Junior researchers

ახალგაზრდა მკვლევარები

Vol. 3 Issue 5, 2025

https://doi.org/10.52340/jr.2025.03.05.20

Congenital Hand Anomalies: Neural Adaptation After Surgical Reconstruction

Arjun Jay Prakash[1], Chaithanya Subramanya[2], Hiruni Nethma Dissanayake[3], Devni Chanuththara Athuldoraarachchi[3], Mariam Namgaladze[1], Basmala Diab[4], Hena Anvar[3],

[1]MD, Ivane Javakishvili Tbilisi State University, Georgia;

[2]MD, Georgian National University SEU, Georgia;

[3]MD, Yerevan State Medical University after Mkhitar Heratsi, Armenia;

[4]MD, Tbilisi State Medical University, Georgia.

***Corresponding author:* Arjun Jay Prakash, MD, Ivane Javakishvili Tbilisi State University, Georgia, arjunatschool@gmail.com, Mobile: +97466191967

***ORCID:* Arjun Jay Prakash: 0009-0002-2063-0192; Chaithanya Subramanya: 0009-0003-6672-2946; Devni Chanuththara Athuldoraarachchi: 0009-0001-5748-8452; Basmala Diab: 0009-0001-2792-2692; Hena Anvar: 0009-0005-0245-6874; Hiruni Nethma Dissanayake: 0009-0002-3237-0025; Mariam Namgaladze:0009-0004-2910-4820.

Abstract:

Congenital hand anomalies, such as syndactyly, amniotic band syndrome (ABS), and congenital amelia, significantly modify hand structure, compromise functional abilities, and contribute to altered organization within the central nervous system. Reconstructive surgery seeks not only to restore anatomical form and fine motor capacity but also to facilitate the reintegration of reconstructed digits into existing cortical representations. Postoperative neural adaptation is primarily mediated through use-dependent plasticity, with magnetoencephalography studies demonstrating that somatosensory cortical maps can reorganize rapidly, even in mature brains. Timely surgical intervention leverages enhanced developmental plasticity, promoting more effective incorporation of reconstructed digits into functional sensorimotor pathways, whereas severe or complex anomalies may restrict the degree of achievable cortical reorganization. Advanced microsurgical techniques, including staged reconstructions and vascularized toe-to-hand transfers for ABS, offer sensate and functionally robust units that support both anatomical restoration and neuroplastic recovery. Structured postoperative

rehabilitation further strengthens these adaptive cortical processes, underscoring the essential relationship between surgical technique, neural mechanisms, and functional outcomes. This review integrates current evidence on congenital hand anomalies, emphasizing cortical adaptation, postoperative function, and the translational relevance of surgical timing, operative strategy, and rehabilitation protocols.

Keywords: Congenital hand anomalies, Syndactyly, Amniotic Band Syndrome (ABS), Congenital amelia, Cortical plasticity, Neural adaptation, Toe-to-hand transfer, Sensorimotor rehabilitation.

Abbreviations:

Central nervous system - CNS

Amniotic Band Syndrome - ABS

Magnetoencephalography - MEG

Metacarpophalangeal joint- MCP

Proximal Interphalangeal joint - PIP

Distal Interphalangeal joint - DIP

Manual Ability Classification System - MACS

Introduction:

Congenital hand anomalies encompass a spectrum of developmental malformations, ranging from skin dimpling and constriction rings to complete amelia (absence) of distal digits. They significantly disrupt hand morphology, compromise psychosocial well-being, restrict upper limb function, and alter the organization of neural pathways within the central nervous system (CNS) [1,5,6].

Syndactyly, Amniotic Band Syndrome (ABS), and congenital amelia of digits, are the most commonly encountered congenital anomalies in clinical practice. Syndactyly is a congenital condition where adjacent fingers are fused, limiting functionality and necessitating surgical intervention. ABS is a severe syndrome involving the presence of constricting rings and tissue

synechiae. These can lead to deformities and multiple digit loss. Congenital amelia arises from disruptions in early limb bud formation or blood supply during embryogenesis. These conditions significantly disrupt hand function and daily life, posing a challenge in pediatric surgery and neurorehabilitation [1,3,4,5,6].

Historically, congenital hand anomalies have been challenging to treat as they involve two primary challenges: High surgical complexity, and properly enabling cortical adaptation. Surgical intervention

needs to establish adequate web spacing, achieve proper digit alignment, and preserve fine motor skills necessary for age-appropriate activities [5,6]. Cortical adaptation is particularly complex in congenital cases as the brain has never received normal somatosensory input from the affected limb, making reorganization difficult [1,3,4]. This review aims to compile the current literature on congenital hand anomalies, with a focus on neural reorganization and plasticity post-correction surgery.

Methodology:

This literature review synthesizes contemporary evidence on congenital hand anomalies, with particular emphasis on neural adaptation, cortical reorganization, and functional recovery following surgical reconstruction. The analysis encompasses a range of conditions—including syndactyly, amniotic band syndrome (ABS), and congenital amelia—while also examining reconstructive techniques, microsurgical interventions, and neuroplasticity-driven mechanisms of sensorimotor recovery. Relevant publications were identified through systematic searches of PubMed and PMC using keywords such as “Congenital Hand Anomalies,” “Syndactyly,” “Amniotic Band Syndrome,” “Cortical Reorganization,” “Sensorimotor Plasticity,” “Magnetoencephalography,” “Toe-to-Hand Transfer,” “Neuroplasticity,” and “Congenital Amelia.” Inclusion criteria comprised full-text, English-language, peer-reviewed studies that addressed congenital upper-limb anomalies and provided empirical data on cortical organization, neuroplastic processes, surgical reconstruction, or functional outcomes. Studies involving adult-onset or acquired limb loss, non-surgical case descriptions, non-human models, or insufficient methodological detail were excluded. Abstracts were initially screened for thematic relevance, after which eligible articles underwent full-text evaluation. Final study selection was based on methodological rigor, conceptual alignment with neural adaptation following reconstruction, and clarity of reported outcomes, with disagreements resolved through reviewer discussion and consensus.

Neural Organization in Congenital Limb Differences:

The organization of the sensorimotor cortex shows differences between individuals with congenital hand amelia and those with amputations, revealing the significant role of early life experience and development in establishing and maintaining the neural architecture. In amputations, the cortical representation of the missing hand within the primary somatosensory and motor cortices persists, even after long term reduction of peripheral stimulation. This indicates that constant sensory feedback is not required to maintain this organization. Additionally, individuals with congenital hand amelia do not show the individuated digit representation seen in controls or amputees [3,4]. Also, while in amputees, the cortical region

previously assigned to the amputated part, becomes responsive to stimulation from other body parts, this reorganization was not observed by Victoria et al. in the case of congenital digit amelia [2]. These findings highlight the crucial role developmental experience plays in affecting the organization of the primary sensorimotor cortex.

Individuals with congenital hand amelia were instead observed to develop compensatory mechanisms, relying on other body parts, such as their feet or mouth. This functional replacement is exhibited by significant changes in the association cortex, particularly within the inferior parietal lobule and the anterior intrapetal sulcus. This suggests that the brain region represents the goal of an action (e.g., grasping, manipulating) regardless of the body part used to perform it. In individuals born with digital amelia, this region shows elevated and selective preference for foot movements. However, this compensatory mechanism is limited, especially within the primary sensorimotor cortex as it is more strongly activated by adjacent, non-compensatory body parts, such as the shoulders and the abdomen [3,4].

Cortical refinement after congenital hand reconstruction is predominantly driven by use-dependent plasticity, the principle that repeated motor activity strengthens and reshapes sensorimotor representations. Repetition of finger movements, for example, induces measurable reorganization within the somatosensory cortex, improving the efficiency with which the action is subsequently performed. Mogilner et al. [1] demonstrated this mechanism in adults with congenital syndactyly: MEG mapping before and after surgical separation revealed that postoperative cortical changes represented a refinement of an existing fused map, rather than the creation of a novel representation derived from a different effector. These findings indicate that the cortex retains a latent but functional template for individual digits, which becomes unmasked and reorganized through postoperative sensorimotor use [1].

A critical distinction must be made between developmental plasticity, which establishes initial cortical architecture, and experience-dependent plasticity, which reshapes it later in life [3,4,6]. Wesselink et al. [3] compared cortical organization in adults with acquired upper-limb amputation to those with congenital hand absence. Individuals who lost a limb later in life maintain a persistent representation of the missing hand decades after amputation, despite the absence of peripheral input. In contrast, individuals with congenital absence lack a typical “hand area,” indicating that this representation never formed or formed atypically due to absent early-life sensory experience. The authors propose that early sensory input is essential for the development of canonical somatosensory maps, but not necessary for their long-term maintenance [3].

In congenital absence, the deprived primary somatosensory cortex does not reorganize according to compensatory effectors such as the foot. Instead, it becomes responsive to adjacent body regions, for example, the shoulder or abdomen, highlighting that the primary sensory cortex is constrained by topographical proximity. This limitation does not extend to higher-order association cortex. In the same individuals, the inferior parietal lobule and anterior intraparietal sulcus exhibit function-based plasticity, showing selective representation of compensatory foot use during complex tasks [4].

Cortical Plasticity after Syndactyly Surgical Separation:

Syndactyly refers to the congenital fusion of adjacent digits and is among the most common congenital hand anomalies. It compromises hand function and may also impact psychosocial development. Surgical correction involves meticulous separation of fused web spaces and reconstruction using skin flaps and grafts from well-vascularized donor sites such as the groin or thigh, employing techniques including Z-plasty, rotational flaps, and triangular flaps [5]. These reconstructive procedures serve as clinically relevant models for understanding sensorimotor plasticity in the developing brain [5].

Magnetoencephalography (MEG) has demonstrated that appropriate cortical map redifferentiation follows surgical separation. In healthy individuals, somatosensory representation of the digits in the postcentral gyrus is arranged sequentially from digit 1 to digit 5. Mogilner et al. [1] identified abnormal cortical maps in patients with congenital syndactyly, characterized by reduced interdigit cortical distances and non-somatotopic organization. Postoperative MEG repeated several weeks later revealed reorganization of the cortical hand map, with newly separated fingers adopting distinct cortical territories and normalization of the thumb-finger distance [1]. These findings highlight the brain's capacity to reorganize tactile representations following structural repair.

Timing and Extent of Plastic Recovery:

Cortical plasticity following congenital hand reconstruction is influenced by both the severity of the malformation and the age at intervention. Mogilner et al. [1] demonstrated this in two contrasting cases: a child with syndactyly due to constriction band syndrome showed rapid restoration of a near-normal somatotopic map, whereas a child with Apert-related complex syndactyly demonstrated only partial recovery. Although cortical hand area increased after surgery in both cases, the complex form retained shortened and non-somatotopic interdigit distances, emphasizing that deeper skeletal and soft-tissue fusion, particularly in Apert syndrome, limits the degree of cortical remapping. In comparison, simpler forms of syndactyly with clearly identifiable anatomical boundaries show more robust postoperative plasticity [1].

These findings align with a retrospective cohort of 52 pediatric syndactyly patients [5], where 90% achieved full manual dexterity (MACS Levels 1-2). Surgeries were commonly performed at 6-18 months of age, a timeframe classically associated with substantial neuroplastic potential. Although cortical imaging was not conducted in this cohort, the authors emphasize that plasticity remains clinically meaningful beyond infancy, extending the therapeutic window for reconstructive intervention [5].

Functional and Clinical Outcomes After Reconstruction:

The primary aim of syndactyly reconstruction is to restore functional hand use that supports normal fine-motor development [5]. Syndactyly may occur alone or as part of syndromic conditions such as Amniotic Band Syndrome (ABS), where constriction rings can result in a spectrum of deformities,

including skin dimpling, lymphedema, acrosyndactyly, or auto-amputation [6]. Evaluation of surgical outcomes typically focuses on the degree of digital separation, formation of functional web spaces, thumb opposability, and restoration of joint motion crucial for grasp and precision tasks [5,6].

In the Phan et al. cohort [5], 90% of children regained full dexterity, while the remaining cases exhibited mild persistent limitations due to severity of the underlying anomaly or syndromic associations. Web spacing, a key predictor of postoperative functional capacity, was satisfactory in 94% of patients. Only three required secondary surgery for postoperative contracture release, and overall, children demonstrated age-appropriate fine-motor skills [5].

Chiu et al. [6] reported similarly favorable outcomes in eight children with ABS undergoing staged reconstruction before age two. The protocol included release of constriction bands and acrosyndactyly (stage 1), thumb reconstruction (stage 2), creation of a functional hand using second-toe transfer when necessary (stage 3), and later refinements for web deepening or scar management (stage 4). Functional outcomes included full MCP joint extension with 40-70° active flexion, and 30-60° PIP flexion; DIP stability was preserved [6].

Postoperative care, including splinting, scar modulation, and individualized rehabilitation, plays a critical role in preventing contractures and optimizing long-term hand use. Continuous sensorimotor activity and guided therapy likely reinforce adaptive cortical processes, contributing to durable functional recovery [5].

Microsurgical Reconstruction and Neural Acceptance:

Severe congenital hand anomalies may require microsurgical reconstruction, such as toe-to-hand transfer, to restore structural integrity, dexterity, and sensibility. In ABS, the second-toe transfer provides a vascularized, sensate osseous–soft tissue composite while minimizing donor-site morbidity [6]. Preservation of volar anatomy and neurovascular pedicles facilitates integration of the transplanted digit, particularly when performed early, promoting optimal cortical acceptance [6].

MEG findings from Mogilner et al. [1] show that neuroplasticity persists into adulthood. Adult patients developed distinct somatotopic finger maps within weeks of syndactyly separation, indicating rapid cortical refinement. In contrast, neurovascular island flap transfers for nerve injuries exhibited persistent sensory mislocalization, where stimuli applied to the thumb were perceived as originating from the donor ring finger, demonstrating that sensory relocalization requires anatomical congruence [1]. Toe-to-hand transfers, which restore a complete functional unit, enable coherent cortical reintegration [1,6]. These findings indicate that reconstructive surgery initiates dynamic neuroplastic adaptation, allowing both developing and mature cortices to incorporate reconstructed digits into functional maps and support long-term sensorimotor recovery.

Amniotic Band Syndrome (ABS): Pathophysiology, Surgical Reconstruction, and Neural Integration:

ABS encompasses a broad spectrum of anomalies resulting from amniotic bands that constrict developing fetal digits, producing outcomes ranging from superficial indentations to acrosyndactyly or digital amputation [6]. Severity depends on the depth and tightness of constriction, and presentations often include skeletal and neurovascular compromise. Acrosyndactyly, characterized by fused digits with distal fenestrations, requires early surgical correction for functional restoration [6].

Reconstruction is typically staged and performed before age two, optimizing structural outcomes and leveraging heightened developmental plasticity [6]. Initial surgery releases constriction bands and separates acrosyndactylous digits. Subsequent procedures reconstruct the thumb and, when necessary, utilize second-toe transfer to replace absent digits, offering a vascularized

and sensate functional unit. All 16 transferred toes in the series survived fully, and children achieved stable grasp and pinch function [6].

Neural integration is central to successful reconstruction. Early surgery enables the developing cortex to incorporate transferred digits into functional sensory and motor maps. Chiu et al. [6] demonstrate that timely reconstruction enhances both structural growth and cortical adaptation, ultimately supporting stable long-term fine-motor performance. This underscores that ABS is not merely structural but a neurofunctional condition that demands coordinated surgical and developmental planning.

Translational and Clinical Implications:

Contemporary management of congenital hand anomalies increasingly recognizes surgical repair as the first phase of a broader neurofunctional restoration process, rather than a solely structural correction. Integrating neuroimaging into surgical planning and postoperative care provides objective insight into somatosensory organization and the brain's adaptive response to reconstruction. MEG, for instance, reliably maps somatotopic organization in healthy individuals and has revealed rapid cortical reorganization in adults following syndactyly release [1]. Such tools can help align surgical techniques with expected patterns of cortical reintegration, thereby optimizing strategies for restoring functional utility.

Microsurgical reconstruction, particularly toe-to-hand transfer, can produce a vascularized, sensate, and mechanically functional hand even in severe congenital deficits such as ABS [6]. However, postoperative success depends heavily on targeted sensory re-education and task-specific rehabilitation, which reinforce the adaptive cortical changes initiated by surgery. Because cortical maps reorganize within weeks of reconstructive procedures [1], early initiation of structured therapy is critical for consolidating sensorimotor pathways and maximizing long-term function.

This neurocentric framework is grounded in the observation that congenital cases retain latent

neuroplastic capacity that can be revealed through appropriate surgical and rehabilitative stimuli. Even when congenital fusion results in reduced or non-somatotopic cortical hand representations, the somatosensory cortex demonstrates rapid and substantial reorganization after anatomical correction [1]. The robust sensory reintegration seen after pediatric toe-to-hand transfers further underscores the brain's capacity to incorporate newly constructed anatomy into functional maps [6]. Importantly, this plastic potential is not limited to infants: older pediatric patients also benefit from surgery, with postoperative afferent input driving improved dexterity and participation in daily activities [5]. Collectively, these findings support a holistic model of congenital hand reconstruction, one in which surgical intervention, neuroimaging-guided planning, and structured rehabilitation function synergistically to harness neuroplasticity and restore meaningful hand function.

Conclusion:

Surgical reconstruction for congenital hand anomalies highlights the brain's substantial, though not unlimited, capacity for functional adaptation and cortical reorganization. Findings from Mogilner et al. demonstrate that, following syndactyly release, the somatosensory cortex is capable of re-differentiating previously merged representations, restoring discrete tactile maps and sensory organization even after prolonged structural fusion or congenital absence. The degree of neural recovery is closely linked to both the complexity of the malformation and the age at which reconstruction occurs; earlier intervention generally enables more complete cortical remodeling, although meaningful use-dependent plasticity remains evident even in older patients, underscoring the persistence of adaptive potential beyond early developmental periods. Early reconstruction in syndactyly and amniotic band syndrome is central to restoring fine motor abilities, as achieving appropriate digit separation, web formation, and joint mobility creates the structural basis for effective rehabilitation and subsequent cortical adaptation. Moreover, early microsurgical toe-to-hand transfers provide vascularized, sensate functional units that support both motor and sensory recovery while promoting accurate cortical integration and reducing the risk of sensory mislocalization.

Collectively, these surgical approaches illustrate that operative repair does more than restore anatomy; it actively drives cortical reorganization, harnessing latent neuroplasticity to enhance long-term functional outcomes. Integrating neuroimaging with postoperative assessments and optimizing rehabilitation strategies will be essential for refining surgical timing, improving operative techniques, and maximizing recovery trajectories in future clinical practice.

References:

1. Allison T, McCarthy G, Wood CC, Jones SJ, Luby M. Somatosensory cortical plasticity in adult humans revealed by magnetoencephalography — separation of syndactyly. *Exp Brain Res*. 1993;96(2):367–378.https://pubmed.ncbi.nlm.nih.gov/8386377/
2. Root V, Muret D, Arribas M, Amoruso E, Thornton J, Tarall-Jozwiak A, Tracey I, Makin TR. Complex pattern of facial remapping in somatosensory cortex following congenital but not acquired hand loss. *eLife*. 2022;11:e76158. https://pmc.ncbi.nlm.nih.gov/articles/PMC9851617/

3. Striem-Amit E, Vannuscorps G, Caramazza A. Obtaining and maintaining cortical hand representation as evidenced from acquired and congenital handlessness. *Proc Natl Acad Sci U S A*. 2018;115(30):7801–7806. https://cogneuro.psychology.fas.harvard.edu/publications/plasticity-based-compensatory-effector-use-association-not-primary
4. Striem-Amit E, Vannuscorps G, Caramazza A. Plasticity based on compensatory effector use in the association but not primary sensorimotor cortex of people born without hands. *Proc Natl Acad Sci U S A*. 2018;115(30):7801–7806. https://pmc.ncbi.nlm.nih.gov/articles/PMC6065047/
5. Lőrincz A, Nudelman H, Kormos EI, Józsa G. Delayed surgical management of congenital syndactyly improves range of motion: a long-term follow-up. *J Clin Med*. 2025;14(9):3200.https://pmc.ncbi.nlm.nih.gov/articles/PMC12072538/
6. Chiu DTW, Patel A, Sakamoto S, Chu A. The impact of microsurgery on congenital hand anomalies associated with amniotic band syndrome: toe transfers and functional reconstruction. *Plast Reconstr Surg Glob Open*. 2018;6(4):e1657. https://journals.lww.com/prsgo/fulltext/2018/04000/the_impact_of_microsurgery_on_congenital_hand.6.aspx