

Enabling Conditions and Sequencing for Sustainable Prosthetic and Orthotic Care: Development of the ROOTS Framework through Realist Evaluation in Post-Conflict Sierra Leone

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Method Article

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Abstract

Background

Prosthetic and orthotic (P&O) care remains severely constrained in post-conflict and resource-limited settings despite sustained external engagement. Efforts to expand access have centered patient volume as the primary success metric, producing a recurring pattern: inputs arrive without the required foundational conditions, outcomes do not persist, and systems remain dependent rather than strengthened. No empirical framework exists for understanding what local capacity conditions must precede volume-oriented quality and consistent care, or in what order those conditions must be built.

Methods

Massachusetts Institute of Technology (MIT) and the Sierra Leone Ministry of Health (MOH) conducted a longitudinal mixed-methods assessment of their P&O system strengthening strategy (2023–2026), applying realist evaluation to identify the contextual conditions and sequencing logic that determined whether implementation outcomes held. Data sources included semi-structured interviews (interest holders $n = 10$; P&O users $n = 4$), infrastructure assessment, program documentation, and thematic analysis of 105 weekly meeting records. CMO configurations were generated inductively through iterative analysis across all four data streams.

Results

Four CMO configurations were identified, each creating the enabling conditions the next required: infrastructure, supply chain reliability, workforce development, and systematic technical quality assurance of clinical materials and equipment. Prospective analysis of 105 weekly meeting records confirmed this sequence through staged shifts in dominant programmatic concern, consistent with threshold-based domain activation. These configurations are synthesized in the developed ROOTS (Readiness assessment, Ordering by dependency, Ongoing vetting, Threshold recognition, Sustainable trajectory) framework.

Conclusion

Lasting P&O outcomes require local capacity before volume, and local capacity has a dependency structure that cannot be shortcut. ROOTS offers program designers, government partners, and funders an empirically grounded sequencing framework: it identifies which foundational conditions must be established before expanded care can be activated, and in what order. When sequencing follows that logic, investment produces outcomes that persist.

Key Message

What is already known on this topic: Prosthetic and orthotic (P&O) systems in post-conflict and resource-limited settings face compounding barriers across the domains of infrastructure, supply chain, technology, and workforce. External programs have repeatedly delivered devices, training, and equipment without producing outcomes that persist after support withdraws. The sequencing logic - that determines which domains must be established before others can function, has not been empirically described.

What this study adds: This study introduces the ROOTS framework, an empirically grounded implementation framework derived from a longitudinal realist evaluation of the SITE strategy (supply chain, infrastructure, technology, education) in Sierra Leone. ROOTs demonstrates that in Sierra Leone, infrastructure, supply chain, workforce development, and P&O technology quality assurance had to be established in that order, each domain creating the conditions the next required. This study documents an early observable milestone of sustainable trajectory: a system strengthened in the necessary components and the necessary order developed the capacity to evaluate and decline a substandard external actor without external prompting, demonstrating a shift in power configuration made possible by system strengthening.

How this study might affect research, practice or policy: ROOTS offers program designers, government partners, and funders an empirically grounded tool for identifying the dependency structure of their own health system context, translating that logic into actionable sequencing guidance. It demonstrates that implementation domains must be established in dependency order, each creating the conditions the next requires, and that this sequence must be discovered through systematic assessment rather than assumed. Operationalizing observable milestones of sustainable trajectory is identified as a priority for future research.

1. Introduction

1.1 P&O need in resource-limited settings

Prosthetic and orthotic (P&O) care remains among the most inaccessible rehabilitation services in settings where health systems have been weakened or destroyed by conflict, poverty, or sustained crisis. An estimated 57 million people globally live with limb loss [1], the majority in countries where P&O services are severely constrained or entirely absent; the full population requiring orthotic and prosthetic care is substantially larger. The inverse relationship between need and capacity is most acute where conflict, crisis, and underdevelopment have generated the highest concentrations of P&O need [2, 3].

Blast injuries, landmine contamination, and conflict-related limb loss occur disproportionately in countries where P&O systems were fragile before conflict began and have not recovered in its aftermath [4, 5]. Sierra Leone illustrates this trajectory: a civil conflict from 1991 to 2002 produced one of the highest per-capita rates of conflict-related amputation in sub-Saharan Africa, and subsequent crises

including the 2014–2016 Ebola outbreak compounded existing system weaknesses. Two decades after the conflict's end, P&O service capacity had not recovered to pre-conflict levels despite sustained engagement by international organizations during and after the war [6, 7].

1.2 External engagement and the challenge of lasting results

International engagement with P&O needs in these settings has been sustained and substantive. A range of government, nonprofit, and academic actors have worked in conflict-affected and resource-limited countries for decades, delivering devices, training clinicians, supplying materials, and in many cases developing long-term country partnerships oriented toward government handover and sector sustainability [8, 9]. These engagements have produced real benefits for the individuals and communities they reached [4, 5].

A defining feature of this external engagement has been its orientation around patient volume as the primary metric of program success. Devices delivered, patients seen, and practitioners trained per visit are the indicators most commonly reported in the P&O provision literature and most legible to funders and governments [4, 8]. Infrastructure, supply chain continuity, and workforce retention do not map cleanly onto visit-based reporting and are systematically underweighted relative to countable outputs. This dynamic is documented in Sierra Leone's own policy record, which notes that the predominance of NGO-led provision operating without government coordination produced ineffective investments, duplication, and high abandonment rates for assistive products [7, 10]. Unaccredited, piecemeal, or device-specific training produces certificate holders without transferable clinical competency, and certificate accumulation can substitute for professional development in program reports without producing equivalent clinical capacity [11, 12].

The literature documents a persistent gap between the scale of external engagement and the degree of lasting system change it has produced [2, 3, 5, 13]. In settings where health system foundations are absent or severely degraded, even well-designed interventions cannot produce outcomes that persist if those foundations are not established first [13, 14, 15].

Existing frameworks characterize the components of a well-functioning P&O system [1], but none empirically specifies the sequencing and dependency logic that determines in what order those components must be established for outcomes to persist.

1.3 The implementation gap: from barrier knowledge to sequenced action

A substantial body of literature characterizes barriers to P&O access in resource-limited settings: workforce shortages, inadequate supply chains, infrastructure deficits, weak governance, and limited financing [2, 3, 5, 16, 17]. This knowledge is necessary but not sufficient: knowing which domains require strengthening does not specify how to build them so that improvements persist, in what sequence

investments should be made, or how to recognize that a domain has reached sufficient function before expanding clinical services.

Implementation science provides frameworks for studying how evidence-based approaches are adopted, implemented, and sustained in real-world settings [18, 19]. The Consolidated Framework for Implementation Research (CFIR) is among the most widely applied [22, 23], but was developed for contexts where basic service delivery infrastructure can be assumed. In weak and destroyed health system contexts, the enabling conditions for implementation are themselves the object of intervention; standard health system frameworks require adaptation for settings where system foundations are not yet in place [14, 20].

Realist evaluation [21] is suited to this question. Its central analytical unit, the context-mechanism-outcome (CMO) configuration, asks what contextual conditions enabled what mechanisms to produce what outcomes, addressing conditionality and sequence directly: mechanisms do not activate in the absence of enabling context, and the order in which context is established determines what can follow. Applied to P&O system strengthening, realist evaluation can identify not only what worked but what had to be true first, providing the empirical basis for a sequencing framework applicable in other contexts.

1.4 This study: SITE, ROOTS, and the Sierra Leone partnership

This study is the second in a sequence of analyses of P&O system strengthening in Sierra Leone. Prior work applied the Systems-level Assessment of Barriers and Interventions (SABI) framework and Multi-level Architecture for P&O Strengthening (MAPS) to characterize barriers across individual, service delivery, and health system levels, and to translate that assessment into a domain-specific strengthening strategy, identifying four domains requiring intervention: Supply chain, Infrastructure, Technology, and Education, formalized as the SITE strategy in a five-year MIT-MOH Memorandum of Understanding (MOU) signed in January 2023 [22]. This study addresses the implementation questions that assessment and strategy design leave open: in what order must domains be established, what conditions must each domain reach before dependent domains can activate, and how does the order of investment determine whether outcomes persist. The ROOTS (Readiness assessment, Ordering by dependency, Ongoing vetting, Threshold recognition, and Sustainable trajectory) framework does not replicate or replace the assessment function; it takes assessment outputs as its starting point and specifies the sequencing logic that transforms a strengthening strategy into durable local capacity. The connection between the assessment, design, and subsequent steps described by ROOTS framework, presented in this paper, is visualized in Fig. 1.

This study presents a longitudinal mixed-methods realist evaluation of the SITE strategy (2023–2026), generating two contributions: the ROOTS framework, an empirically grounded sequencing guide for P&O system strengthening; and evidence that a system strengthened in necessary domain and order develops the capacity to evaluate and decline substandard external provision without external prompting.

1.5 Study context: Sierra Leone

Sierra Leone is a resource-limited post-conflict setting whose civil conflict (1991–2002) produced lasting damage to health infrastructure and workforce capacity. P&O care has no dedicated budget line in the MOH operating budget [23, 24]. P&O services are delivered through two MOH-operated clinics, the National Rehabilitation Centre (NRC) in Freetown and the Bo P&O Clinic in the south, plus a currently non-operational facility in Koidu. At program inception in January 2023, the NRC had one internationally certified clinician approaching retirement, no clinicians in any formal training pipeline, non-functional fabrication equipment, and no formal supply chain for materials; the Bo clinic operated under equivalent constraints.

2. Methods

2.1 Study design

This study uses a longitudinal mixed-methods design to evaluate implementation of the SITE strategy within the MIT-MOH partnership in Sierra Leone (2023–2026). The primary analytical framework is realist evaluation [21], which asks what works, for whom, and under what circumstances, and organizes findings as context-mechanism-outcome (CMO) configurations. CMO configurations address conditionality and sequence directly: mechanisms do not activate in the absence of enabling context, and the order in which context is established determines what can follow. Realist evaluation was applied retrospectively to program data.

2.2 Setting

P&O services in Sierra Leone are delivered through two Ministry of Health and Sanitation (MOH)-operated facilities: the National Rehabilitation Centre (NRC) in Freetown, the Bo P&O Clinic, and the Koidu Clinic (currently non-operational), and one privately operated facility in Makeni. Prior to the MIT-MOH partnership, a systematic assessment documented severe, compounding barriers across individual and community, service delivery and clinic, and health system and policy levels [22]. The SITE strategy was developed through evidence-based translation of that assessment and formalized in the MIT-MOH MOU in 2023.

2.3 Data sources and collection

Three data streams informed this analysis, collected during a field visit to Sierra Leone in March 2026 and supplemented by remote interviews and program documentation spanning the full partnership period (2023–2026).

Semi-structured interviews were conducted under MIT Committee on the Use of Humans as Experimental Subjects (COUHES) Protocol #2512001889, approved March 18, 2026, and Sierra Leone Ethics and Scientific Review Committee (SLESRC) approval (No: 024/03/2026). Interest holder interviews (n = 10)

were conducted with MOH clinicians, program staff, education partners, and students in the assistive and prosthetic orthotist (APO) training program directly involved in SITE implementation. Interviews with users of P&O care (n = 4) were conducted with individuals who had received prosthetic or orthotic care at the NRC. All interviews were conducted in English (the official language of Sierra Leone), the majority in person at the NRC in Freetown, with two interest holder interviews conducted remotely. Interviews were audio or video recorded with participant permission and transcribed using automated transcription software. The lead researcher (FRA) conducted all interviews, with selected interviews conducted by co-investigators (TM, CH). A semi-structured guide informed by CFIR domains [25, 26] ensured thematic consistency across interviews. All participants are identified by code throughout; participant codes and characteristics are provided in Supplemental Table S2.

Infrastructure assessment data were collected through repeat application of the 0–25 point rubric developed during the 2021–2023 baseline assessment at the NRC [22], enabling direct longitudinal comparison across classification bands.

Weekly program meeting records spanning the full partnership period (2023–2026) were analyzed as a fourth data stream. Records from 150 + MIT-MOH weekly meetings were subjected to anonymized thematic analysis [27] to identify patterns in topic frequency and binding constraint shifts over time. This analysis was conducted under existing COUHES and SLESRC protocols; records were stripped of identifying information prior to analysis and no individual-level data are reported.

Patient and public involvement

People who use P&O devices were included as interview participants in this study. Several interest holders who participated in their professional roles as clinicians, program staff, or students also have personal experience as users of P&O care and spoke to both dimensions in their interviews; four additional participants were recruited solely as users of P&O services at the NRC. Participants were not involved in developing the research questions, designing the study, or selecting outcome measures. Findings will be disseminated to participants and MOH partners through existing program channels (e.g., in-person meetings at the NRC and direct communication through Sierra Leonean program staff). Sex and gender data were not collected as individual-level demographic variables, as they are not relevant to the implementation outcomes analyzed in this study.

2.4 Analytical approach

CMO configurations were generated inductively through iterative analysis of data across all four streams. The analytical process proceeded in three stages. First, each data stream was analyzed independently: interview transcripts were coded thematically using a codebook developed from initial close reading, with codes organized by SABI level (individual and community, service delivery, health system and policy) and WHO Health System Building Block; infrastructure re-assessment data were analyzed longitudinally by rubric domain; and weekly meeting records were analyzed by dominant topic per meeting, with each record assigned a primary domain code from five categories (infrastructure,

supply chain, education and workforce, vetting and quality of care, and sustainable trajectory). Second, patterns across streams were triangulated to identify candidate CMO configurations: cases where contextual conditions, mechanisms, and outcomes were consistently co-present across at least two independent data sources. Third, configurations were refined through member-checking with Sierra Leonean co-authors to confirm that the mechanisms and outcomes identified were recognizable from practitioner experience. Four CMO configurations emerged from this process.

2.5 Positionality

The lead researcher holds a dual role as both researcher and program implementer. This introduces inherent risk of confirmation bias, addressed through triangulation across four independent data streams, inclusion of perspectives from users of P&O care external to the program design, and co-authorship with Sierra Leonean practitioners whose contributions are independent of the program's academic framing. One co-author participated as both an interest holder and a co-author contributing contextual expertise and substantive review; a second co-author assisted with data collection and was also interviewed as an interest holder. These dual roles are acknowledged as transparency considerations and, where applicable, as methodological strengths in centering practitioner knowledge. The lead researcher's positionality as a biomedical engineer with graduate training in health systems and specialization in global health and development informed both the implementation of the vetting function and the analytical lens applied in this evaluation; a full reflexivity statement is provided in the Supplemental section.

3. Results

3.1 Counterfactual baseline: the provision-without-foundation pattern

Prior to the MIT-MOH partnership, the NRC and Bo clinics had received repeated external engagement without lasting system change. Interview data and program documentation identified a consistent pattern: inputs were provided without the enabling conditions those inputs required to take effect (Table 1).

Following the exit of the country's largest P&O program funder in the early 2000s, both sites operated without a formal supply chain for approximately fourteen years. Thermoplastic sheeting, a critical component used in P&O device fabrication, was sourced from a single informal contact at the NRC until that source was exhausted; the Bo clinic relied on residual donated materials, then on short-term external missions (Interest Holder 6 (IH), IH4, IH7, IH8). Clinical output was largely limited to repairs; new fabrication required users to self-fund raw materials. Device quality during this period was described as below acceptable standard (IH6, IH4, IH8).

During the supply-absent period, both sites received visits from multiple external organizations; none produced lasting system change. External actors arrived, delivered a time-limited input calibrated for the

visit rather than the system, and departed without establishing supply continuity or a workforce development pathway (IH6, IH10).

Table 1 summarizes all external organizations active in the sector during the documented period; none established a formal supply chain or produced a clinician in accredited P&O education. The same clinicians received the same certificate across multiple visits while the training was presented as reaching new participants each year (IH6). In at least one year, students enrolled in ISPO-accredited education were removed from scheduled sessions to attend a non-accredited workshop instead (IH3).

Clinical harm from episodic provision was documented individually: poorly fitted devices caused physical injury in at least one case and led to permanent refusal of prosthetic care (IH6). A participant who later received care from an ISPO-certified clinician identified, retrospectively, the assessment steps a prior non-accredited clinician had omitted and their consequences for fit and function (Prosthesis User 1 (PU)).

The consistency of this pattern across two clinic sites, multiple organizations, and more than a decade is not explained by the absence of effort or resources. Each engagement was organized around discrete, countable outputs (devices fitted, practitioners certificated, equipment donated) without establishing the foundational conditions those outputs required to function or persist. This structural pattern, in which donor-driven accountability rewards visible outputs over system foundations, has been identified as a defining feature of externally led global health programming more broadly [13, 28].

Table 1

CMO configurations: SITE strategy implementation, MIT-MOH partnership, Sierra Leone, 2023–2026.

SITE Domain	Context	Mechanism	Outcome	Key Evidence*
Infrastructure	NRC below functional threshold at program inception: non-functional fabrication equipment, unreliable power, absent running water, insufficient storage. Infrastructure score: 10/25 (severely constrained).	A facility at or above functional threshold creates the physical necessary physical conditions for consistent clinical P&O care and for practical learning to occur. Below threshold, clinical production cannot be reliably planned and improvised workarounds compound skill gaps.	NRC reaches functional threshold for clinical operations and dependent domains. Infrastructure score: 21/25 (operational with limitations) at re-assessment, March 2026. Residual gaps: running water (water tower pending) and reliable electricity.	IH6, IH1, IH2, IH3, IH4, IH5; infrastructure rubric scores; program documentation
Supply chain	No formal supply chain for P&O materials at either site for approximately 14 years prior to program. Materials improvised from non-standard substitutes or sourced through informal channels with no continuity.	When standard materials are available in sufficient quantity and on a predictable resupply schedule, clinical P&O care can be delivered consistently and students develop transferable competency using internationally standard processes. Supply reliability, not merely supply presence, is the enabling condition.	Consistent clinical service delivery enabled. Practical education advanced from foundational to applied modules. Device quality improved. Clinical output shifted from repairs to new fittings.	IH1, IH3, IH4, IH5; supply order and delivery records; program documentation
Education (workforce)	Functional infrastructure and reliable supply chain in place. No clinicians in accredited P&O education at program inception; one Category I clinician approaching retirement with	Sustained accredited education in a functional clinical environment with reliable materials produces clinicians with transferable competency, professional identity, and the capacity to evaluate clinical practice against an internalized standard.	Expanded clinical P&O capacity: 11 clinicians in accredited education (10 Category II, 1 Category I) from a baseline of zero. Clinical lead role assumed by program-trained clinician on predecessor's retirement in 2025 with no	IH6, IH1, IH2, PU1, IH3, IH4, IH5, IH8; educational records; program documentation
*IH= Interest Holder; PU = Prosthesis User				

SITE Domain	Context	Mechanism	Outcome	Key Evidence*
	no successor in pipeline.		service interruption. Emergent self-protection capacity (see § 3.3).	
Technology (vetting)	Technologies, equipment, and materials entering the country required evaluation against clinical safety, compatibility with standard fabrication processes, and fitness for a low-resource environment.	Interdisciplinary quality review of incoming components, materials, and equipment conducted by a team whose expertise collectively spanned biomedical engineering and global health systems, infrastructure and workshop development, P&O technology, supply chain, and in-country clinical leadership, with local confirmation by Sierra Leonean clinicians and government coordination for import, installation, and storage, identifies and corrects quality failures before they reach clinical use.	Supply and equipment quality maintained throughout program period. Quality failures identified and corrected: storage conditions improved after materials were damaged; non-functional consumables in initial shipment identified, prompting establishment of local procurement channel.	Program documentation; field observation records; supply order records
*IH= Interest Holder; PU = Prosthesis User				

3.3 Self-protection as an observed outcome of system strengthening

One finding that emerged from the CMO analysis was not planned as an outcome of the SITE strategy: a trained workforce with functioning infrastructure and reliable supply developed the capacity to evaluate and decline a substandard external actor on professional grounds, without external prompting. It is reported separately because it documents a shift in the power configuration between the system and its external partners and constitutes the earliest observable evidence of sustainable trajectory in this evaluation.

At the time of data collection, the NRC's posture toward Organization A (Table S1) had changed. Senior clinical staff described a recognition that the model was extractive: outcomes were documented and fundraised in Sierra Leone's name while the clinic could not sustain the work after each visit (IH6, IH4).

Once the program had established its own students, supply chain, and clinical standards, practitioners had both the alternatives and the professional knowledge to evaluate what was being offered, and a different mechanism became available: selective non-participation (IH6, IH4, IH9).

This shift was not a formal institutional decision. It was a practitioner-level posture change that program leadership registered and did not override. The clinical lead withdrew from active participation in Organization A's visits and communicated a changed standard for external engagement. Organization A did not visit in the most recent year.

Before these conditions existed, the mechanism was not available. As one participant described the prior situation: "anything was better than nothing" (IH6). The SITE strategy changed those conditions; the mechanism followed.

The cognitive basis for self-protection was observable across multiple participants independent of the Organization A finding. A participant described, by reference to formal education content, why a prior 3D-printing activity with a non-clinical government agency had been clinically problematic: it had omitted assessment steps that ISPO training defines as prerequisites for device fabrication (IH1). A participant who had previously received care from a clinician trained outside an ISPO-recognized program compared the two assessment processes, identifying specific omissions and their consequences for fit and function (PU1). In both cases, the critique was produced by education, not intuition. Workforce-initiated self-protection of this kind does not appear to have been previously documented as a mechanism or outcome indicator in the P&O or rehabilitation systems strengthening literature [4, 8, 5, 11, 12].

3.4 The ROOTS framework

The four CMO configurations presented in the Results may be captured in a generalizable implementation framework: the ROOTS framework (Readiness assessment, Ordering by dependency, Ongoing vetting, Threshold recognition, Sustainable trajectory) (Fig. 2). ROOTS does not prescribe which domains to address; that function is served by validated system assessment tools such as SABI and MAPS [22]. ROOTS specifies how to implement whichever domains an assessment identifies, making sequencing and dependency relationships explicit and operational for program designers, government partners, and funders in weak and destroyed health system settings.

The global P&O literature documents a recurring pattern: external programs provide devices, train practitioners, or upgrade facilities episodically, and outcomes do not endure after external support withdraws [4, 28, 29]. ROOTS is a response to that pattern, grounded in longitudinal empirical evidence from a setting where the sequencing of enabling conditions determined whether outcomes held.

Each component of ROOTS addresses a distinct implementation challenge.

1. **Readiness assessment** precedes implementation. Drawing on the outputs of SABI and MAPS (or equivalent system assessment tools), readiness assessment characterizes not only which domains are weak but how weak, and what dependency relationships exist between them. In Sierra Leone, a

quantified infrastructure baseline (10/25 on a validated rubric) established the foundational investment required before supply chain and education could be addressed.

2. **Ordering by dependency** translates readiness findings into an implementation sequence determined by logical and temporal dependency relationships, not by funder preference or conventional program design. Infrastructure must exist before supply chain inputs have somewhere to go; supply chain must be reliable before education can produce transferable clinical competency, because a discipline learned on non-standard substitute materials does not transfer to standard clinical practice. The sequence is not prescribed in advance; it is discovered through sustained attention to what is blocking progress.
3. **Ongoing vetting** is a continuous technical quality assurance function running in parallel with all implementation phases. It evaluates whether incoming components, materials, and equipment meet clinical safety standards, are compatible with standard fabrication practice, and are suited to the clinical environment. It requires interdisciplinary expertise, physical verification where feasible, and confirmation by local clinical leaders and government partners. In Sierra Leone, this function encompassed every item entering the country, with local confirmation and government coordination for import and storage. Physical site visits identified quality failures that remote management would not have detected. As the system matures, an emergent internal quality assurance capacity develops alongside the designed program function; both are necessary and neither substitutes for the other.
4. **Threshold recognition** is the judgment that a domain has reached sufficient function that dependent domains can activate, not that it is complete or without residual gaps. In practice, threshold manifests as a domain dropping off the critical agenda: it ceases to be the primary constraint because it has been resolved sufficiently for dependent domains to progress. In Sierra Leone, the infrastructure threshold was crossed not at a declared milestone but when infrastructure ceased to be the binding constraint on supply chain and education. Residual gaps remained at re-assessment (21/25); threshold recognition requires sufficiency, not completion.
5. **Sustainable trajectory** is the horizon toward which the other four components are building. A system on a sustainable trajectory has developed sufficient agency, professional judgment, and institutional standing to determine what external support it needs and on what terms. What changes is not dependence on support but the power configuration: the system becomes a partner capable of evaluating, negotiating, and where necessary refusing, rather than a recipient that accepts whatever arrives. Progress along this trajectory is observable; the self-protection finding reported in this study represents an early milestone. Operationalizing a validated set of trajectory milestones is identified as a priority for future work.

[Add Fig. 2: The ROOTS framework: components, sequencing, and enabling conditions]

4. Discussion

The following sections situate the ROOTS framework and CMO configurations in the broader implementation science literature.

4.1 Infrastructure as prerequisite foundation

Infrastructure occupies a foundational position in the ROOTS sequence that interview data alone would underrepresent: participants spoke less about infrastructure than other domains because targeted investment was undertaken early and its effects had become the assumed baseline of clinic function by the time of data collection. This absence from discourse is analytically meaningful rather than indicative of lower importance. The NRC's infrastructure score increased from 10/25 to 21/25 on a validated rubric, reflecting the degree of foundational investment required before dependent domains could progress. Infrastructure investment is not a parallel track; it is a precondition.

One finding has direct design implications: in fragile state contexts, infrastructure improvements through locally contracted labor degraded faster than expected because contractors substituted lower-specification materials. Infrastructure threshold is not a one-time investment; quality oversight of contracted work belongs within the **Ongoing vetting** function throughout the program lifecycle.

4.2 Supply chain reliability and the pedagogical dependency

Supply chain reliability is both an enabling condition for clinical service delivery and a prerequisite for practical education. A single shipment establishes supply presence; a predictable resupply rhythm establishes the reliability that enables clinical planning and sustained educational progression. The pedagogical dependency is clinical: a prosthetist or orthotist learns to fabricate by fabricating, using standard thermoplastics and components. Without those inputs, training produces theoretical knowledge that cannot transfer to clinical practice. Supply order records document this threshold directly: practical clinical education advanced from foundational to applied content following confirmed supply availability at each site.

Implementation findings from this phase identify pre-arrival planning and receiving conditions as critical: a single-consignment shipment created a warehouse bottleneck on arrival, and unusable consumables in the initial shipment required establishing a local procurement channel. Both findings locate the ongoing vetting function in receiving and storage conditions, not only procurement.

4.3 Sequencing, threshold recognition, and sustainable trajectory

The thematic analysis of 105 weekly program meeting records provides prospective evidence of the sequencing logic that the CMO configurations describe retrospectively. Table 2 documents a staged shift in dominant programmatic concern across six implementation periods: infrastructure occupied the plurality of meeting attention in the first period (48%, April–September 2023), giving way to workforce development as the primary concern by the second half of 2023, which in turn gave way to vetting and quality of care from late 2024 onward, with sustainable trajectory emerging as a documented programmatic priority from October 2024. This progression was not planned in advance as a fixed

schedule; it reflects the organic resolution of binding constraints as each domain reached sufficient function. A domain ceased to dominate meeting discussion not when it was complete but when it was no longer the primary obstacle to program progress, which is the operational definition of threshold recognition that the ROOTS framework formalizes.

Threshold recognition is therefore not a formal assessment event but an observable shift in where program attention concentrates. Each transition in Table 2 corresponds to a domain reaching sufficient function that dependent domains could activate. Residual gaps remained at each transition; the infrastructure score of 21/25 reflects outstanding gaps in running water and electricity. Threshold is defined by sufficiency for dependent domains, not by completion. This distinction is grounded in realist evaluation’s principle that mechanisms activate only when enabling contextual conditions are met, not when context is complete or ideal [21].

Table 2
Primary programmatic concern by six-month implementation period, MIT-MOH weekly meeting records (n = 105)

Period	n	Infrastructure	Supply Chain	Workforce Development	Clinical Quality Assurance	Sustainable Trajectory
Apr–Sep 2023	23	48%	30%	22%	—	—
Oct 2023–Mar 2024	18	39%	11%	44%	6%	—
Apr–Sep 2024	17	6%	6%	65%	18%	6%
Oct 2024–Mar 2025	14	—	14%	36%	36%	14%
Apr–Sep 2025	20	—	5%	30%	55%	10%
Oct 2025–Feb 2026	13	—	—	15%	62%	23%
<i>Note. Primary domain assigned per meeting using five coded categories. Bold indicates the plurality domain for each period. n = total meetings coded per period.</i>						

The structural dependence that volume-first accountability produces cannot be resolved by volume-first investment. The pattern is not unique to P&O: the short-term medical mission literature documents that visit-calibrated provision, organized around discrete countable outputs, reproduces rather than resolves dependence on external support by bypassing the foundational conditions that would enable local systems to sustain what external actors provide [30, 28]. What this study’s longitudinal data document is the point at which that structural condition changed in Sierra Leone, and what produced the change.

The emergence of sustainable trajectory as a programmatic concern from late 2024 onward is significant because it precedes and contextualizes the self-protection finding reported in § 3.3. This instance of a trained workforce declining a substandard external actor without external prompting reflects a broader directional shift documented in the program record rather than an isolated incident. The capacity for that response was structural, enabled by the contextual conditions the SITE strategy had built in the necessary sequence. Other milestones of sustainable trajectory can be expected to emerge as the system matures; operationalizing a validated set across settings is identified as a priority for future work. Adjacent fields have developed staged maturity models with observable, validated indicators of system development: public health sustainability frameworks specify domains and factors that determine whether programs persist [31, 32], and digital health has produced staged adoption models in which each level constitutes an observable, verifiable milestone of system maturity [33]. No equivalent exists for P&O system strengthening.

Investment in foundational capacity, built in dependency order, is what makes device and workforce investment lasting [31, 32]. The field's persistent concern about P&O care limitations despite sustained effort may be partly answered by attending to the power configuration between systems and their external partners. Capacity strengthening in global health has historically been externally driven and oriented toward project implementation, often producing disempowerment of local organizations rather than local ownership [34, 13]; systems that cannot protect their practitioners from substandard engagement cannot consolidate the gains that external programs intend to produce.

4.4 Limitations

This study has several limitations. Data collection was concentrated primarily at the NRC in Freetown; findings may not fully represent conditions at provincial facilities, though members of the Bo and Koidu Clinics participated in the interviews. The lead researcher's dual role as program designer and evaluator introduces inherent risk of confirmation bias, addressed through triangulation across three data streams and co-authorship with Sierra Leonean practitioners whose contributions are independent of the program's academic framing. The interest holder sample skews toward clinicians and students in the education domain; user perspectives are included but the sample is small ($n = 4$). The retrospective application of realist evaluation means CMO configurations were generated from data not originally collected with this framework in mind [35]. The ROOTS framework is derived from a single country program; multi-site validation is required before generalization without adaptation.

5. Conclusion

Volume metrics capture the visit; they do not capture whether a system can sustain what those visits produce. Prior engagement in Sierra Leone and settings like it has repeatedly delivered inputs without the foundational capacity to absorb them, and the outcomes did not hold [30, 28].

This study documents the foundational conditions for sustained P&O care, in what order they must be built, and what becomes possible when they are. Local capacity has a dependency structure: each

domain had to reach threshold function before dependent domains could activate, with the order of investment determined by dependency relationships rather than convention or funder preference.

The ROOTS framework emerges from this analysis as an empirically grounded implementation framework for program designers, government partners, and funders in post-conflict and resource-limited settings. It translates sequencing and dependency findings into planning guidance adaptable to other settings: the sequence is not prescribed in advance but discovered through systematic assessment of the dependency structure of the context at hand.

The self-protection finding reported here, that a trained workforce declining a substandard external actor without external prompting, is one observable early milestone of sustainable trajectory, reflecting a broader directional shift. It documents the power configuration change that system strengthening made possible. Operationalizing validated milestones of sustainable trajectory across settings is identified as a priority for future work.

Sustainable P&O care in resource-limited settings requires local capacity established in dependency order before volume-oriented provision can persist. ROOTS offers an empirically grounded tool for identifying and following the dependency structure of a given system context.

Declarations

All adults interviewed provided informed consent to participate in the study under research protocols approved by the MIT IRB and the Sierra Leone Ministry of Health Ethics Board.

Data availability statement

Interview transcripts are not available for public sharing; participants were recruited under protocols that did not include data sharing provisions, and disclosure could identify individuals in a small professional community. Program documentation used in the weekly meeting analysis is similarly restricted.

Aggregate quantitative data supporting the findings of this study (infrastructure rubric scores, supply order records, educational enrollment and progression records) are available from the corresponding author on reasonable request, subject to applicable ethics restrictions.

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Author contributions

FRA: Conceptualization, methodology, data collection, formal analysis, writing (original draft), writing (review and editing), project administration, funding acquisition, program implementation. TM: Data collection (interviews), writing (review and editing). CH: Data collection (interviews), program administration (education program oversight, Sierra Leone), investigation, participation in weekly program meetings. AK: Program oversight (full implementation, Sierra Leone), investigation, participation in weekly program meetings. PK: Program oversight (implementation and education, Bo clinic), investigation, participation in weekly program meetings. NK: Investigation (clinical care oversight, NRC), participation in weekly program meetings. CP: Program administration (education program and curriculum delivery), investigation, participation in weekly program meetings. NMB: Investigation (education program monitoring, curriculum delivery, clinical quality review), participation in weekly program meetings. DD: Investigation (infrastructure implementation oversight), participation in weekly program meetings. VA: Supervision, writing (review and editing). RA: Supervision, methodology (questionnaire development), writing (review and editing). HMH: Supervision, conceptualization, funding acquisition, writing (review and editing), oversight of research and implementation activities.

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Figures

FIGURE 1

Implementing P&O system strengthening: a decision-making process

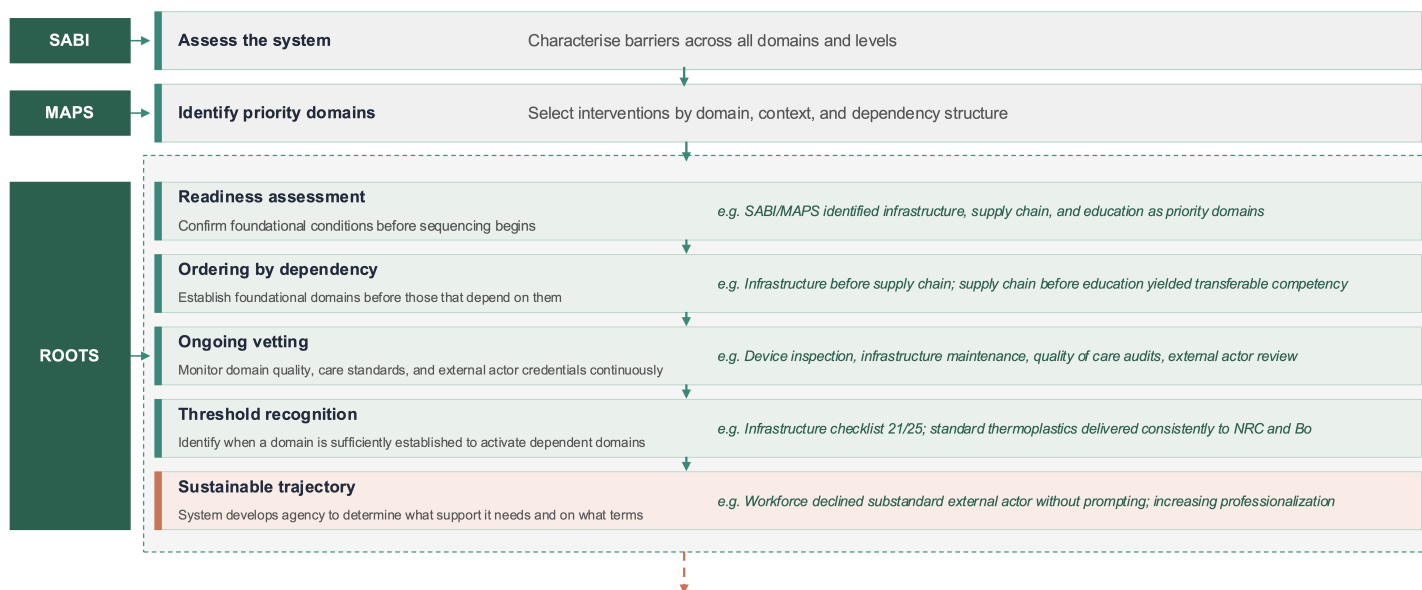


Figure 1

Implementing P&O system strengthening: a decision-making process

The integrated P&O system strengthening methodology: situating ROOTS within assessment and strategy design.

P&O system strengthening requires three sequential steps before sustainable implementation can begin. The Systems Assessment for Barrier Interactions (SABI) characterizes barriers across all domains and levels of the system, producing a multilevel barrier profile. The Multi-level Architecture for P&O Strengthening (MAPS) translates that profile into a prioritized set of interventions organized by domain, context, and dependency structure. ROOTS (Readiness assessment, Ordering by dependency, Ongoing vetting, Threshold recognition, Sustainable trajectory) governs the implementation phase that follows: it is not the first step in strengthening a P&O system, but the structured process by which an implementer who has completed assessment and strategy design executes, sequences, and monitors intervention in dependency order. The Sierra Leone examples shown illustrate how SABI and MAPS outputs fed directly into the starting conditions for ROOTS. P&O, prosthetic and orthotic; NRC, National Rehabilitation Centre.

FIGURE 2

The ROOTS framework: components, sequencing, and enabling conditions

Component	What implementers do	Enabling conditions	Sierra Leone evidence
Readiness assessment	Characterise which domains are present, absent, or partial; map dependency relationships between them	Systematic assessment tools; access to multi-level stakeholder data; government partnership	<i>SABI/MAPS identified infrastructure, supply chain, and education as foundational priority domains</i>
Ordering by dependency	Sequence interventions so foundational domains are established before those that depend on them	Assessment findings revealing dependency structure; program flexibility to phase by findings	<i>Infrastructure established first; supply chain before education; each creating conditions the next required</i>
Ongoing vetting	Continuously monitor domain quality across infrastructure, supply chain, care delivery, and external actors	Sustained program presence; in-country leadership with authority to evaluate and act on findings	<i>Device inspection, infrastructure maintenance tracking, quality of care audits, structured external actor review</i>
Threshold recognition	Identify when a foundational domain is sufficiently established to activate dependent domains — sufficiency, not completion	Pre-defined sufficiency criteria; embedded monitoring capacity; authority to make sequencing decisions locally	<i>Infrastructure checklist reached 21/25; standard thermoplastics delivered consistently to NRC and Bo</i>
Sustainable trajectory	The system develops sufficient agency to determine what support it needs and on what terms — a direction, not an endpoint	All prior components in place; trained and retained workforce; professional identity and institutional confidence	<i>Workforce declined substandard external actor without prompting; increasing professionalization and institutional confidence</i>

Figure 2

The ROOTS framework: components, sequencing, and enabling conditions

The ROOTS framework: components, operational guidance, enabling conditions, and Sierra Leone implementation evidence.

ROOTS comprises five components applied in sequence by implementers who have completed system assessment (SABI) and strategy design (MAPS). For each component, the framework specifies what the implementer does, what enabling conditions must be in place for that component to function, and the corresponding evidence from the Sierra Leone implementation (2023–2026). Readiness assessment confirms which domains are present, absent, or partial and maps their dependency relationships before sequencing begins. Ordering by dependency establishes foundational domains, infrastructure, then supply chain, then education, before activating those that depend on them. Ongoing vetting continuously monitors domain quality, care standards, and external actor credentials throughout implementation. Threshold recognition identifies when a domain has reached sufficient function to activate dependent domains; sufficiency, not completion, is the operative standard. Sustainable trajectory describes the direction toward which a system builds: the capacity to determine what support it needs and on what terms, observable when a workforce acts to protect care standards without external prompting. ROOTS is a direction, not an endpoint; the Sierra Leone evidence column documents early observable milestones rather than a completed trajectory. SABI, Systems Assessment for Barrier Interactions; MAPS, Multi-level Architecture for P&O Strengthening; NRC, National Rehabilitation Centre; P&O, prosthetic and orthotic.

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