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Durability challenges and mitigation strategies for paediatric prostheses - cambodian prosthetist experiences and clinical casefile analysis

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ABSTRACT

Purpose: Prosthetic component durability challenges can form a significant barrier to the successful rehabilitation of children with lower-limb absence in low-resource environments. This work aims to define these challenges and understand current mitigation strategies to support improved design and service delivery.
Materials & Methods: A convergent mixed methods approach was employed. Qualitative interviews were conducted through purposive sampling with 6 prosthetists in Cambodia. Thematic analysis was complemented with data from 62 retrospective paediatric clinical casefiles detailing prosthetic component problems, failure points, and repair solutions. Descriptive and inferential statistics were applied with a significance level of $p < 0.05$.
Results: At interview, 5 themes were identified: the challenge of prosthetic component durability; prosthetic knees; SACH feet; repairs require professional expertise; and local supply/repair of componentry is beneficial. Clinical casefiles revealed component failure points. The distribution of knee problems was design specific and showed significant differences between local polypropylene and donated modular componentry ($p < 0.001$). Repair solutions are provided for knee and feet designs.
Conclusion: Prosthetists provided critical insight which was supported with clinical evidence. Durability is a significant challenge which can be partially alleviated through inclusion of spare parts and mobile outreach repairs. Clarity on current design shortcomings provides evidence for designers and manufacturers.

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IMPLICATIONS FOR REHABILITATION

- Through their extensive experience, prosthetists in Cambodia identified multiple challenges with paediatric prosthetic component durability in low-resource environments.
- Prosthetists, clinicians, and NGOs should recognise the potential for positive impact within their consistent maintenance of clinical case files and subsequent dissemination of durability trends, areas for design improvement, and donor best practice.
- Specific component problems show the importance of the global "Right to Repair" initiative for assistive technology and prosthetists should be supported to call for the inclusion of spare parts.
- Prosthetic clinics should consider the durability of donated componentry and the benefits of local manufacturing.

Introduction

Prosthetic limb provision for childhood lower limb absence (LLA) is a challenging rehabilitation process requiring highly skilled professionals and complex technology [1,2]. Multiple stakeholders are involved including prosthetists who prescribe and fit the most appropriate prosthetic limb for successful rehabilitation [3]. Prosthetists have a wealth of experience which can be harnessed for positive change in prosthetic provision and design [1,4–6], especially for children in low-resource environments (LREs).

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Children form a unique cohort who pose additional rehabilitation challenges due to growth and development including limb length discrepancies due to height increase, and socket fit issues due to residual limb volume changes [7,8]. Further to this, children have high activity levels [9]. These factors place significant strain on prosthetic components. In some LREs, this challenge is further compounded by demanding environmental conditions, requiring componentry to withstand regular use on uneven ground, exposure to challenging weather conditions, mud, and water submersion among other factors [10–13]. This combination necessitates experienced prosthetists and durable componentry to effectively provide prosthetic care.

Following initial limb fitting, children must regularly return to the clinic for prosthetic component repairs and replacements [14]. If frequent repairs and component failures occur, this can form a significant barrier to access due to repeat costs, long travel distances to clinics, a shortage of qualified prosthetists, and the time children and their parents must spend away from education and work, respectively [10,15].

The frequency of repair is often dependent on the design of the prosthetic component, with more complex components associated with greater durability challenges [16]. Componentry donated from other locations can require additional repairs due to their unsuitable design for the end environment [17,18]. In LREs this can be combined with inconsistent supply chains which hinder the repair and replacement of donated componentry. Instead, locally manufactured devices and supply chains can provide more consistent care. In fact, a "Right to Repair" [12] initiative is ongoing globally which calls for assistive technology (AT) designers to consider the repairability of their products.

Prosthetists can provide valuable insights into current best practice for mitigating durability challenges in paediatric prosthetic componentry. Previous work used interviews and international surveys to harness this knowledge more generally and for adult cohorts, but none has focused specifically on children [12,19]. This previous work identified durability and repairability as a key challenge in provision, especially for prosthetic knees and feet, but lacked detail for prosthetic design improvement [12]. Hussain et al. [11] raised paediatric component durability as a specific area of interest for prosthetists in Cambodia. Without clarity on the current challenges and mitigation strategies for children, prosthetic designers and service providers lack the information required to effectively rehabilitate children in LREs. In fact, a study by Sattari et al. [20] revealed that children utilising AT reported their lowest satisfaction with repair and maintenance. Exploring the experiences of paediatric prosthetists is a crucial first step in addressing this issue.

Oldfrey et al. [12] raised a critical issue regarding the gap in long term data collection after first prosthetic delivery. "Data is often not collected beyond first provision, and impact is displayed only in numbers of devices handed out. This means that issues around repair and maintenance … become invisible to decision makers and therefore continue to not be addressed." Kenney at al [21]. confirmed this challenge and recognised that clinical datasets can form a suitable evidence base as they detail prosthetist actions and solutions to address repair and maintenance challenges. Prior work from Ghidini et al. [18] began addressing this problem by identifying the paediatric prosthetic componentry with the greatest wear issues in Cambodian clinical casefiles. However, further detail on the specific failure locations and repair solutions is missing. This paper seeks to fill these gaps by providing specific detail on reasons for repair and repair type to inform prosthetic manufacturers of the potential current design shortcomings.

This work therefore aims to define the prosthetic component durability challenges and mitigation strategies for children in LREs by employing a convergent mixed-methods approach. Prosthetists' knowledge will be harnessed through interviews, while clinical casefile datasets will be analysed to examine specific repair types.

Specific objectives are to:

1. report the experiences of Cambodian paediatric prosthetists in managing durability challenges associated with two distinct technologies, and
2. analyse retrospective longitudinal clinical casefiles of prosthetists' notes for children in three Cambodian prosthetic centres to identify component failure locations and repair strategies.

Methods

This was a convergent mixed methods study, combining qualitative interviews results with quantitative data from clinical casefiles. Ethical approval was obtained from the National Ethics Committee for Health Research of Cambodia (NECHR_24) and the local institutional ethics committee in the UK (ICREC_6609720).

Qualitative interviews

This paper reported on prosthetist interviews, utilising the protocol and structured interview guide described by Edgar et al. [19]. Six prosthetists were recruited through purposive sampling across 4 prosthetic rehabilitation centres in Cambodia. Three centres were affiliated with the Department of Prosthetics and Orthotics (DPO) supported by Exceed Worldwide. The International Committee of the Red Cross (ICRC) supported 1 centre. Exceed is a key non-governmental organisation (NGO) in the prosthetics and orthotics sector which has been operational in Southeast Asia since 1989 [22]. The NGO focuses on training for local P&O professionals, delivery of prosthetic limbs, enablement and empowerment of disabled individuals, advocacy for disability rights, and research and innovation. Their regional and global impact is significant with over 500 trained professionals and 60,000 custom made devices supplied to date [22].

Inclusion criteria stated that prosthetists must currently or recently (in the last 6 months) have experience working with children with LLA. Advice was taken from each centre to identify the most appropriate prosthetists who could provide in-depth experiences of working with this cohort. Written informed consent was obtained from all participants. Three interviews were conducted in person at the prosthetist's clinic and 3 interviews were conducted remotely over video call. Prosthetists with less than 5 years of post-graduation clinical experience were defined as junior prosthetists, all others were senior.

The interview guide spanned many domains, including prosthetic durability and component repairs. Interviews were conducted by 2 researchers (CE & CG), audio recorded, and then transcribed before thematic analysis was conducted. The reflexive thematic analysis principles, as laid out by Braun and Clarke [23], were employed. Steps included familiarisation, open coding, pattern identification, theme generation, theme review, and theme definition and naming. All steps focussed on the objectives of understanding current durability challenges and solutions. Two independent researchers (CE & CG) checked coding, and the resulting themes were evaluated against the transcription text.

Quantitative casefile analysis

The 3 prosthetic centres supported by Exceed Worldwide systematically collect clinical casefile data for each patient to guide ongoing rehabilitation. A digital and hard copy system existed, with greater detail found in the hard copies. 62 physical casefiles were manually hand scanned by 2 of the investigators (CE and CG) for children aged <19 years with major amputations due to any aetiology. Major amputation was defined as occurring proximal to the ankle joint. Clinical casefiles contained entries from 2005 to 2023. A casefile contains information on demographics and clinical notes dictating the reason for every visit and the solutions to any problems identified. The notes contain details on the type of prosthetic componentry and specific repairs completed on each component during a visit. Individual participant consent and legal guardian consent were waived because the study used anonymised clinical data.

Data were coded and digitised by 2 independent researchers (CE & CG). Visits which were written in English and that documented a prosthetic component problem were analysed. Analysis focussed on identifying the durability problems and repair solutions associated with each prosthetic component. Data entry from 2 casefiles was jointly reviewed, and coding decisions were agreed upon by both investigators. A standardised protocol for systematically coding clinical notes was established to ensure consistency. Individual codes were developed for each component problem/failure type, e.g., “Axis Loose,” as well as each repair solution implemented, e.g., “Replace Screw.” Codes were combined where necessary as detailed in respective results figure captions.

Descriptive and inferential statistics were applied using Excel and IBM SPSS statistics version 28.0 (Armonk, NY: IBM Corp) [24]. For categorical variables, the Chi-square test for independence was run to assess if the distributions were equally distributed [25]. If the Chi-square test for independence assumption regarding the lowest expected cell frequency was violated, the Fisher's Exact Probability test results were used. The significance level was set at 0.05.

Quantitative results are placed in the most relevant thematic results section.

Results

Prosthetists had a mean of 8.6 ± 6.6 years experience working with children with LLA, and all but one were actively involved in prosthetic delivery for children at the time of interview.

All centres provided locally available polypropylene prosthetic technology free of charge, while the Exceed centres also provided donated modular metal componentry from an international charity (Figure 1). The interface between the residual limb and prosthesis was achieved using a socket and liner system (Figure 1a). The local liner was made from Ethyl-Vinyl-Acetate (EVA) foam (3 or 6 mm thickness), while the donated liner was a cushion silicone liner. In most cases, the prosthesis was self-suspended on bony prominences, except in transfemoral cases, where a Silesian belt was used (Figure 1b). The polypropylene technology included a monocentric knee joint and was welded together after alignment (Figure 1c). The donated modular componentry included a polycentric knee joint (Figure 1d). Polycentric knee joints provide more stability due to the use of multiple links to form an instantaneous centre of rotation which is more superior and posterior than the monocentric knee joint centre of rotation [16,27]. A monocentric knee acts as a hinge joint. Both included a solid ankle cushion heel (SACH) foot, sourced from two different providers (local and international). The full prosthesis was then covered with a cosmetic cover made from PE-lite foam to emulate physiological appearance.

At interview, 5 themes were identified. These were: prosthetic component durability; the prosthetic knee; SACH feet; repairs require professional expertise; and local supply and repair of componentry.

Theme 1: Prosthetic component durability

The prosthetists consistently emphasised the need for increased durability in children's componentry. Discussions included how often children needed to return to the centre for repair or replacement of specific components. In fact, it was made clear that follow-up appointments were scheduled for children every 6 months to address any durability or growth challenges. Children were advised to come back to the centre before then if any changes were needed.

> I think between one month or three months they need some adjustment because you know the kid when they walk, they are not walking the same as adults are, right? They are very active. So sometimes the foot is broken, sometimes the strap is broken. They use it heavily, yes, yes. (Senior Prosthetist)

Prosthetists raised high childhood activity levels as a key problem for durability. Children love to be active and play, resulting in an increased demand on their prostheses which accentuates any durability shortcomings in design.

> When they come back the prosthesis is almost completely broken because they are very active, they play a lot. (Senior Prosthetist)

All limb absence levels faced durability challenges. The need for improvement spanned all componentry including the liners, cosmetic cover, and suspension belts. Prosthetists stated that children found silicone liners difficult to look after and keep clean, and therefore regularly chose to remain using PE-lite foam liners instead.

> In our experience, most of the child prosthetic users doesn't want the silicone liner because they normally like to play a lot, and it is difficult to take care of silicone. (Senior Prosthetist)

Few issues with the PE-lite liner durability were raised by the prosthetists, however, the casefile results showed the main issue with this component was socket loosening (Figure 2a).

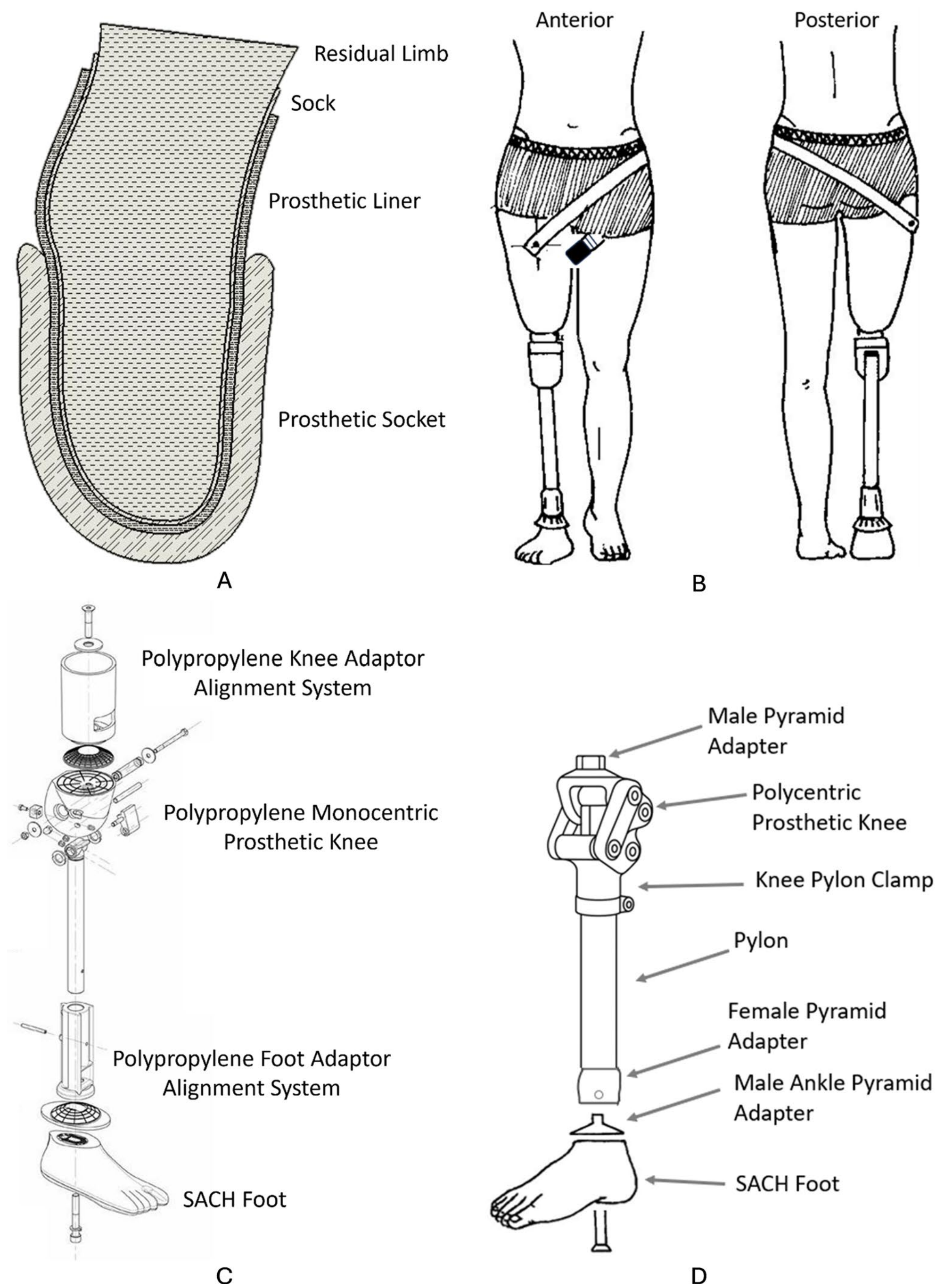

Figure 1. Prosthetic componentry. (a) Interface between residual limb and socket. (b) Example Silesian belt suspension system for transfemoral children (c) Polypropylene technology. (d) Donated modular technology. Image A was produced by the authors. Image B is reproduced with permission from Exceed Worldwide. Image C is reproduced with permission from the ICRC [26]. Image D was produced by the authors using one figure (knee) generated using DALL·E, an AI image generator by OpenAI (2025). Prompt created by the author.

For children with transfemoral amputation, prosthetists raised the inadequate quality of the Silesian belt suspension system stating it often caused problems, and children complained of frequent breakages and repairs.

> Well, suspension is a big complaint, especially for the transfemoral. Here we use Velcro Silesian belt which we get for free from the government, but the quality is not the best. And also, the rivet between the socket and the belt is not very good as it normally breaks, and it comes out. (Senior Prosthetist)

Casefile results supported the highlighted issue of poor belt durability, and revealed the belt could break in multiple distinct locations, primarily the belt itself and the buckle (Figure 2b). Due to the nature

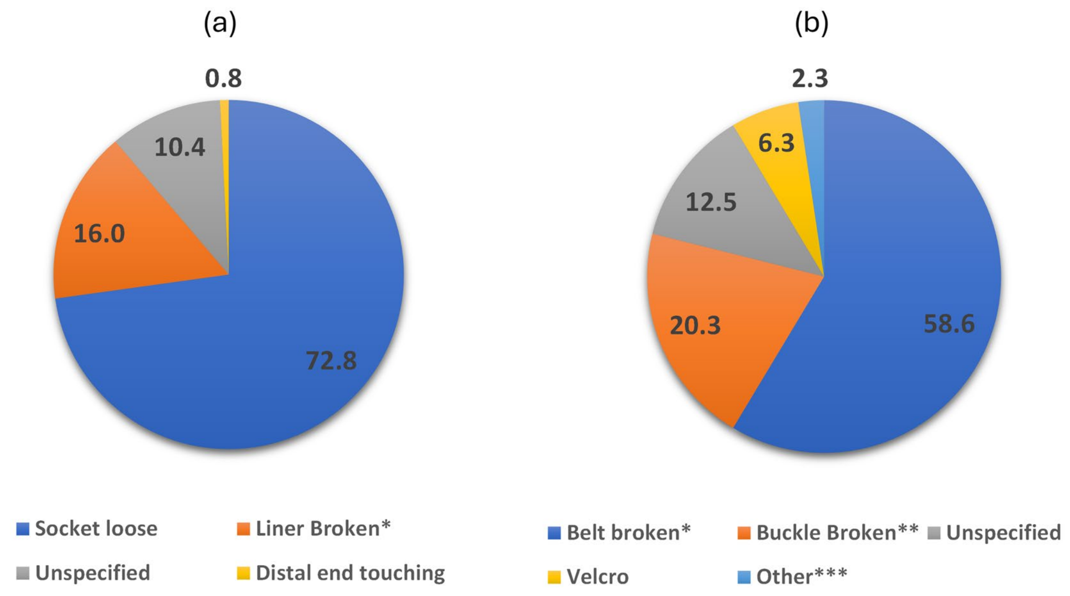

Figure 2. Casefile analysis of socket suspension system failure points. (a) Liner. *Liner broken includes tears in the liner. (b) Silesian belt. *Belt broken includes failure at socket attachment. ** Buckle broken includes buckle rivet broken. *** Other includes loose fit and friction on the skin.

of the problems, they often resulted in full Silesian belt replacement or replacement of the relevant sections i.e. buckle, belt, or Velcro.

Although all children chose to cover their prostheses with a cosmetic cover, and the casefile analysis identified some specific durability challenges (tears, detachment, and dirt), the prosthetists did not highlight any durability issues.

> For the child if they keep it properly, they just wear it to go to school and do some housework so the cosmesis is not a real concern. (Senior Prosthetist)

Theme 2: Prosthetic knee durability and repair strategies vary with design

Children with above- or through-knee limb absence faced additional durability challenges due to the knee joint component which is required for their effective rehabilitation. Prosthetists raised many durability issues for the knees (loose adapters and axes, noise, and complete component failure). Durability was an issue for both designs –monocentric polypropylene and donated modular polycentric - as also identified in the casefile results in Figure 3. The distribution of problems between the 2 knee designs was statistically significantly different ($p < 0.001$, Fishers Exact). Therefore, both knees are analysed separately below.

Monocentric polypropylene knee

Prosthetists stated the monocentric polypropylene knee showed greater durability than the donated modular polycentric knee joint but still posed some issues (Figure 3). Although few ultimate failures of the knee were noted, it often needed repairs. These typically focused on the extension stop damping mechanism which was made from a rubber pad and used to reduce noise and terminal impact, as well as issues with the monocentric axis.

> Mostly I can say the [monocentric polypropylene] does not break. (Senior Prosthetist)

> [Repairs are required] on the axis and also the extension stops for [the monocentric polypropylene]. (Senior Prosthetist)

Noise was a significant issue. Noise impacted both social integration and play as children were not necessarily able to conceal their prosthesis when, and if, they wanted to.

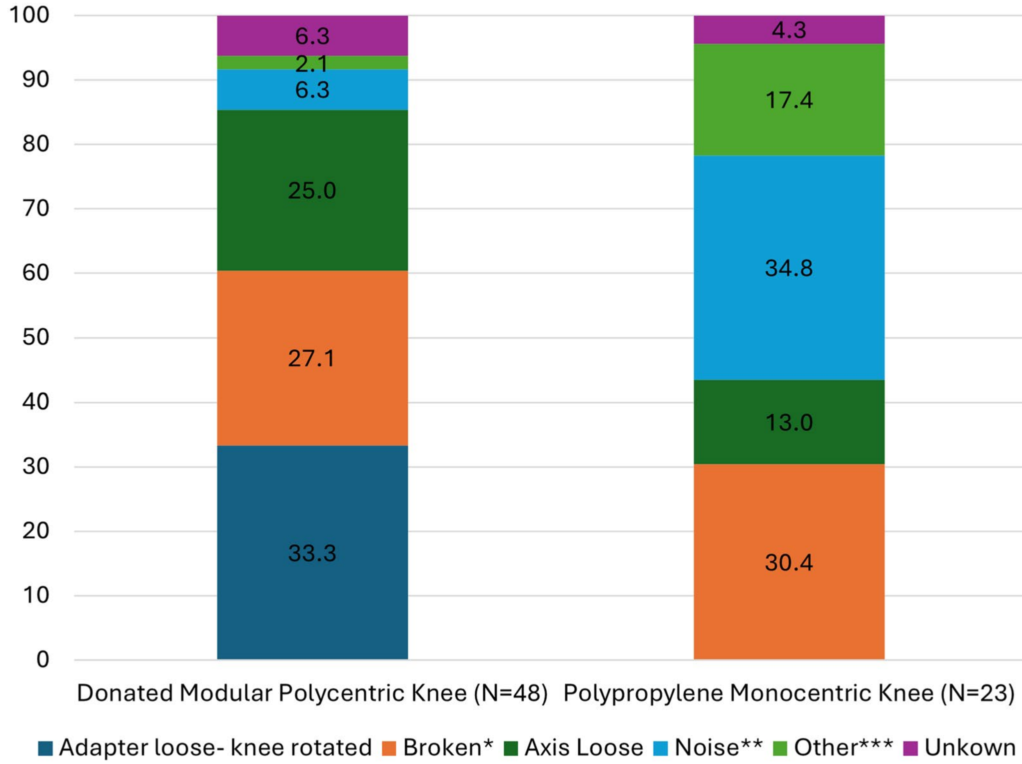

Figure 3. Percentage knee problems per design. N represents the total number of knee problems. *Monocentric knee "noise" includes reports of extension rubber breaking. ** Monocentric knee "broken" includes cracking and socket connection breaking. *** Monocentric knee "other" includes lock breaking and difficulty to flex the knee. Donated other includes sharp edges cut trousers.

Table 1. Repair solutions for most common monocentric polypropylene knee problems.

Problem		Noise (%, $N = 8$)	Broken (%, $N = 7$)
Repair Solutions (% Problems)	Add EVA Pad	12.5	0
	Oil	12.5	0
	New Rubber	50.0	0
	Unknown	25.0	14.3
	Weld Connection	0	14.3
	Tighten Screw/Bolt	0	14.3
	Add Polypropylene	0	14.3

Solutions for "Other" problems included grinding the socket, oiling the knee, replacing the pylon, and changing the lock mechanism in the knee.

> So, some of the clients they want less noise. That is the real experience that the child tells me. When they go to school and then at the break time, they don't want to go outside the classroom and play because of the sound. (Senior Prosthetist)

Interestingly, prosthetists said that children with knee-disarticulation amputation often experienced more problems with noise at the knee joint. In fact, they had to return more frequently to the centre than TF children for issues regarding noise.

> So that's why, especially for KD oh that is very noisy. Yes. Bang bang bang. (Senior Prosthetist)

Prosthetists tried to mitigate the noise due to wear with multiple solutions as indicated by the casefile results (Table 1).

> …now the knee joint is not strong like before, especially the bumpers stop of the [monocentric polypropylene] that wear out very fast, so after only two months they need to be replaced. (Senior Prosthetist)

Another cause of noise was related to the bolt and nut used in the monocentric polypropylene knee to connect it to the socket. Here, loosening could result in additional noise.

Additionally, for the monocentric knee joint they use the bolt and nut to do the attachment and make it tight, and after six months the noise is coming from that, it is not the swing impact. (Senior Prosthetist)

Donated modular polycentric knee

The durability of the donated modular polycentric knee joint was stated to be less than the monocentric polypropylene knee. The donated knee had significant durability issues resulting in frequent repair and replacement.

They can do only six months or seven months and then they will come to change. (Senior Prosthetist)

We have one knee component that we receive from another donor that it's quite easy to damage. (Senior Prosthetist)

The main problem identified in this design centred around the screws becoming loose. Loosening of different screws affected various parts of the knees (the proximal adapter to the socket, polycentric axes, the swing phase control mechanism) and caused different problems to the user.

I think for the knee only the screw breaks or have problems. Sometimes the screw will get loose. So sometimes the client also comes without screw as they lose it as the screw just comes out. (Senior Prosthetist)

The [donated modular polycentric] knee has a problem when the screw that controls the swing mechanisms breaks, and you cannot tighten it anymore and you have too much friction. It breaks after you tighten it many time. (Senior Prosthetist)

Prosthetists had to make frequent repairs to solve the multiple problems caused by screws loosening in the donated knee. Casefile analysis showed prosthetists had little repair solutions available - mainly tightening and replacing screws (Table 2). Prosthetists reported trying to mitigate this by adding glue to the screws.

We also tried to put the glue to prevent the screw from coming out but if you wear it for long time it is still coming out. I don't know why. (Senior Prosthetist)

Another specific issue was the polycentric axes coming loose leading to a full replacement of the prosthetic knee.

Yes, in the [donated modular polycentric] knee, sometime the axes are completely apart from each other. (Senior Prosthetist)

If the axis gets loose, it cannot be repaired, needs to be replaced. (Senior Prosthetist)

Additionally in some cases, for the distal connection between the knee and the shank/pylon, the pylon clamp was incorrectly sized and therefore did not fit tightly around the pylon.

So, this is the [donated modular polycentric] knee, you can see the shank/tube is broken at the clamp…the adaptor is not tight. Maybe because the tube does not perfectly match the clamp side and sometimes it gets loose even when tight. So, the size of the tube is not completely fit with the clamp. (Senior Prosthetist)

Finally, prosthetists raised it could be a challenge to identify wear issues. Due to the use of cosmetic covers around the prosthesis it was hard to access the knee joint either to identify or complete repairs. The monocentric polypropylene knee was not covered, which gave the advantage of checking and repairing the knee more easily.

Table 2. Repair solutions for most common donated modular polycentric knee problems.

Problem		Adapter Loose (%, $N = 16$)	Broken (%, $N = 13$)	Axis Loose (%, $N = 12$)
Repair Solutions (% Problems)	Tighten Screw/Bolt	62.5	7.7	50.0
	Replace Screw	12.5	0	8.3
	Unknown	12.5	15.4	0
	Adjust and Tighten Axis	0	0	16.7
	Adjust Extension	0	0	8.3

… you can cover it so that it looks like the intact leg, even if it will be difficult for you as a prosthetist to do the adjustments or repairs later on. And it is also difficult for the client also to check their knee joint on their own, see if it is okay and they can walk with it. For the [monocentric polypropylene] knee joint we cannot cover it, we can only cover the socket and shank so the client can easily and properly check it, clean it etc. (Senior Prosthetist)

Theme 3: SACH feet failure points

It was common for children to complain to their prosthetists about the durability of their SACH foot as it often broke resulting in repeat visits for replacement. The foot could not be repaired as ultimate failure typically occurred.

You cannot fix it; you need to replace the foot. (Junior Prosthetist)

Failure usually occurred at the toe break where the hard keel inside of the foot stops (Figure 4).

… it breaks in the forefoot because the soft part is longer than the hard heel inside and it breaks where the hard part stops. (Senior Prosthetist)

Differences in durability were found between manufacturers (Table 3). The locally manufactured feet showed increased durability compared to the donated option, although this came at the cost of heavier weight.

If it is the SACH foot from our clinic, not [the donated one], it is a bit heavy, but they can last a long time. But [the donated one] is a little bit lighter but they cannot use for long time, it is easy to damage. (Senior Prosthetist)

A child- and culture-specific challenge existed in the fact children did not always wear shoes with their feet. Barefoot usage resulted in increased wear and a reduction in durability compared to shod feet.

When they go out, they wear the shoes and at home they don't, so the SACH foot wears out. (Senior Prosthetist)

Prosthetists also raised challenges with the modular attachment/connection methods between the foot and the shank/pylon of the modular components (as mentioned previously for the connection mechanism of the donated modular polycentric knee joint). The modular componentry used a pyramid and clamp attachment mechanism whereas the polypropylene technology used a bolt and welding

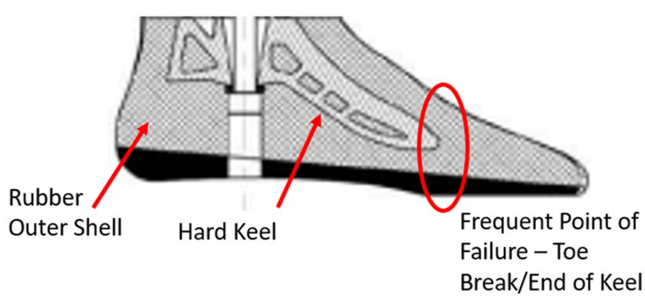

Figure 4. SACH foot with hard keel inside and bolt attachment method. The red circle indicates a frequent point of failure at the toe break/end of keel (Image reproduced with permission from the ICRC [26].

Table 3. Repair/replacement rates and repair methods for donated modular and polypropylene ankle adapters.

Ankle Adapter Type		Donated Modular	Local Polypropylene
Problems		Ankle Adapter Loose (%, $N = 16$)	Ankle Adapter Loose (%, $N = 8$)
Repair Solutions (% repairs)	Tighten Screw/Bolt	77.3	66.7
	Replace Screw	9.1	22.2
	Glue Screw	6.8	0
	Drill Extra Screw	2.3	0

method (Figure 1c & d). There were issues with the quality of the pyramid system resulting in poor fixation.

> The pyramid attachment is not the standard pyramid attachment, so the angle is not proper, sometimes the pyramid is not square and when you tighten it, it is not strong. (Senior Prosthetist)

Indeed, this issue was supported by the casefile results, which showed the donated modular ankle adapter repair solutions focussed on simply tightening screws/bolts to address pyramid attachment issues (Table 3). More repair options were employed to fix the donated modular ankle adapter compared with the polypropylene adapter.

Theme 4: Repairs require professional expertise

Prosthetists made clear that families were instructed to return to the centre if there were any problems with the prosthesis and not to complete any adjustments/repairs at home.

> … of course they need to come for the adjustments. (Senior Prosthetist)

Families may want to adjust at home to avoid the travel back to the centre and the significant costs this would incur. However, this protocol was to avoid any issues if incorrect changes were made which could have affected the child's health and wellbeing.

> But of course, when they come to get the device, we always advise them to come to the clinic if they have any problem and they should not do it by themselves. They have to bring the kid with the device back to the centre because if we advise them and then they do something not correct and then it will cause problems for the kid. (Senior Prosthetist)

To help with more frequent repairs in the local community, mobile repair services were established by some of the centres. These units visited the community on a prearranged schedule which they communicated with the chief of each commune to share the word with relevant families. This helped alleviate the need for regular travel to the centre and allowed the rehabilitation clinicians to maintain contact with the families and check the status of the prostheses.

> We have the mobile service repair…. once a month. So, we have a schedule. So, if when we go to the commune there is a kid needing to have some repair, we also can do in the community as well. (Senior Prosthetist)

The mobile units were only able to conduct small repairs. If the repair required was too large, they had to come back to the centre as not all equipment was available in the mobile unit.

> … they can repair for the small repair only not the big repair. Not the big one. (Senior Prosthetist)

Small repairs included changing easily accessible components such as the foot, Silesian belt, or residual limb socks. Large repairs included prosthetic leg length changes, knee repairs and significant socket fit issues. Even if the required repair was too large for the mobile unit to achieve, the team could still ensure the child was safe and able to mobilise before they could travel to the centre.

> So, it's like for change the foot, change the strap, give them more stump socks and so on. So, we can do it in the Community, but if it is major repair like if the socket too tight or the prosthesis is too short and so on, they need to come back. … but we can do something to make sure the device is safe while they are waiting for coming to the clinic. (Senior Prosthetist)

Theme 5: Local supply and repair of componentry

Prosthetic componentry was sourced from different suppliers. The polypropylene technology including knee joints and socket adapters etc. was sourced from a factory owned by the Persons with Disability Foundation (PWDF) of the Ministry of Social Affairs, Veterans and Youth Rehabilitation (MoSVY), Cambodia. The Cambodian SACH foot was also sourced locally through a different independent factory and used local rubber to create the feet.

> Yeah, we take [the feet] from our local factory. (Senior Prosthetist)

> So actually, we have a [polypropylene] factory here in Cambodia. So, most of the component we can get from the factory that is owned by the ministry of social affairs. (Senior Prosthetist)

The other design options were donated modular componentry. The donated modular components were not manufactured in Cambodia and had to be ordered from the central source. Benefits of local manufacturing and supply were raised. Local componentry could be repaired more easily in country as replacement parts could be sourced, whereas the donated componentry had been difficult to repair and maintain due to a lack of spare parts.

> For the [monocentric polypropylene] knee joint, we can easily find that component to fix it, but for the donated component we cannot replace the screw. (Senior Prosthetist)

> But the modular knee the small screw breaks and we need to change the knee because we don't have screws for replacement. (Senior Prosthetist)

Prosthetists suggested the inclusion of spare screws would allow them to successfully repair the knees.

> If we have screws for replacement, that's good. Everything is OK. If we can only replace that screw, then it is okay. (Senior Prosthetist)

Another supply chain challenge was raised for the donated componentry. It was not instantly available to order, and therefore incorrect estimation of user need may result in children lacking access to the appropriate componentry.

> But for the [donated components] we usually we got the order yearly and then they will supply for annually and then if the component is finished and then we have to wait for the next year order. (Senior Prosthetist)

The inability to instantly access new componentry may necessitate component reuse where possible. However, reusing returned components with other children was highlighted to be difficult and context specific. The quality of the used component was difficult to assess. It was easier with simple componentry such as the SACH foot, but the knee could only be harvested for parts, it could not be reused as a whole component.

> So, when we check the quality of the component if it's still in good condition, we have to keep it and we can use for another. … We might be able to do like the pylon or the foot. I think usually we do not really re-use the knee. But yeah … some other part. Just for like for repair. So far, we did not use the whole set of the component for the child who came to receive the service, but we keep it in case like we need to change some small part for another client, yeah. (Senior Prosthetist)

Apart from quality, a barrier to reuse with the same child was prosthetists did not wish to take the child's prosthetic limb away while they made a new cast and swapped components.

> Usually, we do not re-use it because when we are making the socket at the same time when we make the prosthesis the kid is still using their current prosthesis. So, until the new prosthesis is ready, then we will deliver that to the kid. And then we take the old one back. (Senior Prosthetist)

Yet, it was identified that if supply chains did not function and componentry was difficult to acquire, reuse was an important aspect of provision.

> … because the material for the paediatric clients is really limited. So, we need to consider about the component use as well. If the components can be re-used, we just keep it. (Junior Prosthetist)

This was especially apparent for less common amputation levels such as hip-disarticulation where componentry was difficult to source.

> [For] one HD we already re-use that component for [them] because it's hard to find that one for [them]. (Senior Prosthetist)

Discussion

This paper described the specific durability challenges paediatric prosthetists in Cambodia face and their strategies to mitigate current component design shortcomings. Prosthetist experience has been combined with clinical evidence in the form of casefile repair analysis, with 5 themes arising. The results provide key learnings for service providers, prosthetists, and prosthetic component designers.

The first theme accentuated the significant overall durability challenge for children. In fact, prosthetists caring for children should expect durability problems and proactively schedule regular follow up appointments. Children display higher activity levels than adults which should be encouraged and supported for general physical health and social inclusion [9,28,29]. However, prosthetic designers need to consider this increase compared to adults and implement additional measures. Current lower limb prosthetic component strength and durability testing standards (ISO 10328) do not include child specific protocols or bodyweight ranges [30]. Additionally, they provide a single value for adult cyclic fatigue testing which may be insufficient for children. Further work is needed to characterise activity levels of children with LLA and standardise international durability testing protocols. This may mitigate the current durability shortcomings and account for increased activity levels.

Challenges associated with suspension/liners, particularly silicone liners, included poor durability and the need for frequent user maintenance. Silicone liners require daily washing due to the buildup of sweat, which is necessary to prevent infections and other residual limb related issues [31–33]. However, given the evidence on improved comfort and function gained through silicone liner use, future work should focus on removing the maintenance barriers for children and improve durability [34,35]. The wear issues of the PE-lite liner derived from the clinical casefiles may be due to the repeated donning and doffing of the socket combined with the high activity level. The result is a loss of the required snug fit and increased relative movement between the residual limb and the socket. It is not immediately apparent what improvements can be made with the PE-lite material to alleviate this and therefore removing the barriers to silicone liner uptake may be beneficial.

For transfemoral children, the Silesian suspension belt was also a challenge. However, prosthetists did not mention this theme as often as would be expected given recent findings showed the belt to have the highest frequency of repairs and replacements [18]. This may be because the belt repairs are relatively inexpensive, quick, and simple for the prosthetist to perform. However, the lack of durability may still result in disuse of the prosthesis and additional clinic visits which require time off work and school to achieve. The Silesian belt is used less often in high-resource environments where liners are prescribed with either locks, lanyards, or passive seal suspension [36].

The second theme explored the challenges associated with prosthetic knee durability. The 2 unique designs showed a significantly different distribution of durability problems from the casefile data resulting in key learnings for each. The donated modular polycentric knee joint was stated to have poorer durability than the monocentric polypropylene knee as confirmed by Ghidini et al. [18]. This may not have been surprising due to the added complexity of polycentric axes compared to monocentric single axis designs, as suggested by previous research [16,37]. However, the concerning aspect of poor durability was the substantial number of adapter issues and the fact many of the polycentric knee problems could have been improved with higher quality adapters or screws. So, although this is a component challenge, it does not seem to be related to the knee design itself, but to the quality of materials and manufacturing processes. The inclusion of spare screws to avoid wasting full components is critical. In line with the UN Sustainable Development Goals on climate change and responsible production, component wastage should be minimised [38]. These results therefore call for the inclusion of spare parts in all component sales and donations as a step towards the "right to repair" goal thus empowering prosthetists to increase the lifespan of each component and reduce clinical burden on children, their families, and clinicians themselves [12].

The monocentric polypropylene knee displayed a durability issue with noise due to the failure of the rubber extension stops. The avoidance of noise was shown to be critical to the child's happiness and wellbeing with noise forming a key barrier to social inclusion. Designs must consider visual appearances, walking patterns, and noise if the end user wishes to emulate physiological appearance. However, the overall prosthetist opinion of the monocentric polypropylene knee durability was positive.

The third theme highlighted the durability challenges with SACH feet. The foot itself is typically unrepairable due to its solid one-piece structure. Durability enhancements could be found from material choice as was seen by the improved durability in the local rubber compared to the donated SACH foot. In fact, the centres included in this study now solely provide SACH feet from the local Cambodian factory and do not receive the donated SACH feet. A study by Jensen et al. [39] compared the mechanical strength of SACH feet from multiple LREs showing significant differences in quality. Durability challenges have been especially apparent at the end of the hard keel in the forefoot [40]. Yet, interestingly, a significant quality issue was identified with the proximal modular attachment mechanism for the donated SACH foot. Modular attachment mechanisms are intended to provide an easy and fast alignment method to attach componentry together thus allowing for quick changes and removal of broken components. But this time saving benefit is quickly lost if the attachment mechanism itself constantly requires repair and repeat visits. In contrast, the more time-consuming method of welding polypropylene in the polypropylene components seemed to offer clear durability benefits. Despite the permanence of the welding method, it also provides easy initial alignment prior to weld and key learnings can be drawn from this simple but effective system. However, its application is currently limited to polypropylene technology, and it may be of interest to prosthetic designers to propose new compatible technologies for this alignment system. Further work is required to compare these alignment systems.

The fourth theme highlighted that repairs could only be completed by qualified prosthetists, however examples of "failed" repairs made by non-qualified individuals were not given. The health and safety rationale for this is clear, inexperienced individuals may make mistakes when attempting to repair or adjust the child's prosthesis. However, this does mean families must travel to the centres regularly which costs money and requires time off school and work to achieve. This may form a significant barrier to access [14,41], which can prevent children from entering education, result in increased social stigma, and decreased quality of life [10,42]. Prosthetic designers could aim to include more easily repairable features with clear instruction sets to empower users and their families to conduct small, standardised community-based repairs potentially in widely available mechanical/bicycle repair workshops and thus meet the global "right to repair" goal [12]. The Exceed centres have reduced this patient burden by implementing mobile outreach clinics. These present the additional benefit of information dissemination which may help to improve the concerning statistic that only 5-15% of individuals in LREs have access to AT [14]. This strategy for repair could be implemented in other locations as shown by the case study examples in the ATScale 2020 report [14].

The final theme showed the positive impact of local manufacturing capacity. The local polypropylene technology factory is an example of successful return from charitable manufacturing to local businesses. The factory began as an ICRC initiative and has since been handed over to the PWDF MoSVY with great success as shown by the increased durability of their components compared with donated technology. This is impressive with NGOs often struggling to implement successful exit strategies [43]. The local supply of polypropylene technology and SACH feet helps alleviate prolonged delays often associated with the donation pathway and can become a more sustainable method. This is important considering component reuse is challenging when remaining quality cannot easily be assessed. Additionally, local manufacturing allows for greater durability. The donated technology discussed here often used parts that were not easily accessible, namely the screws which necessitated full component replacement and thus significant waste of time and resources. Where possible, designs should only use parts that are typically globally accessible. Cambodian rehabilitation centres have previously collaborated closely with their donor and reported component failures to identify and address areas for improvement (e.g., including spare screws for the knee as part of a spare limb kit). This ethos was reflected in this work as these results have also been shared directly with the donor to ensure positive change can be enacted. This component monitoring model serves as an example for other donors as well as prosthetic manufacturers, emphasising the importance of field feedback to improve provision.

Reflecting on the relative merits of differing component designs, the compromise between function and durability is highlighted. For example, the local SACH foot showed greater durability, but this came at the cost of increased weight. Although designers and service providers can implement techniques and design changes to bring these two requirements as close together as possible, a balance must be struck. It is therefore essential to listen to prosthetic users, in this case children, to understand their unique needs and provide appropriate care and design innovation [19]. In this location, prostheses were provided free of charge to users and thus repeat costs for repairs were not a priority for consideration; in other locations this may not be the case and as such durability may take precedence over function.

Including prosthetists, users, engineers, and manufacturers who are familiar with the environment, resources available and context from the start can ensure prosthetic components are developed for the intended environment and avoid premature design failures. This work forms a call to action to conduct further durability analysis including both longitudinal description of component failure points and discursive engagement of key stakeholders. Accurate maintenance of clinical casefiles can provide an invaluable source of evidence and harnessing existing retrospective databases from global providers, NGOs, and local clinics can effect positive change. Future work should compare these results with adult provision and paediatric provision in high-resource environments to separate common areas for improvement from LRE and paediatric specific challenges. Further to this, comparison with other datasets would enable manufacturers to draw from the failures or success of differing component design strategies. Specifically, it would be pertinent to assess monocentric and polycentric knee design durability with consistent adapter mechanisms to extrapolate whether significant differences in durability truly exist. Finally, a larger evidence base for paediatric component durability challenges would support calls for standardised durability testing across the paediatric prosthetic field and encourage donors to consider quality management within their supply chains.

There are certain limitations to this work. The use of qualitative interviews in the data collection of prosthetist experiences can result in potential bias. However, this paper partially mitigated this limitation by combining qualitative interviews with hard clinical evidence in the form of casefiles. Additionally, this dataset focused on one geographical location which may limit the generalisability of the results. However, the learnings on polypropylene technology and donated modular technology can be applied to other locations where these componentry are used.

Conclusion

This work aimed to define the key durability challenges prosthetists face for children with LLA. The first objective was met through detailing prosthetist strategies and solutions to cope with design durability shortcomings in the form of shared experiences. The second objective was achieved through the use of hard evidence from clinical casefiles to identify specific component failure points and repair solutions. The results lay out key learnings for improvements in design and service provision. Best practice including local supply and mobile outreach clinics should be emulated as far as possible in other locations.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability

Post-processed casefile data are available on 10.5281/zenodo.12805856.

Author contributions

CRediT: **Caitlin E. Edgar**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing; **Claudia Ghidini**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources,

Visualization, Writing – original draft, Writing – review & editing; **Carson Harte**: Writing – review & editing; **Sisary Kheng**: Project administration, Writing – review & editing; **Anthony M. J. Bull**: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing.

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