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User needs, prosthetic design priorities, and functional movement assessments for children with above/through-knee limb absence in Cambodia: a mixed methods interactive interview

Caitlin E. Edgar^a, Claudia Ghidini^a, Chanthearin Ry^b, Yong Yean^b, Phanith Karng^b, Thearith Heang^b, Sisary Kheng^b and Anthony M. J. Bull^a

^aThe Centre for Paediatric Blast Injury Research, Department of Bioengineering, Imperial College London, London, UK; ^bDepartment of Prosthetics and Orthotics, Exceed Worldwide, Phnom Penh, Cambodia

ABSTRACT

Purpose: Prosthetic user needs for children with above/through-knee (A/TK) limb absence in low-resource environments have not been defined at a discrete component level. This knowledge gap hinders design innovation. Proxy-reports from other stakeholders are insufficient. This study aims to define these user needs through interactive interviews with children in Cambodia.

Materials and methods: Children were recruited across three centres in Cambodia. A novel interactive interview guide including card games provided quantitative and qualitative data. A functional movement assessment provided insight on mobility. Qualitative data underwent thematic analysis. Quantitative data was analysed with descriptive statistics.

Results: Eight children were recruited (87.5% male) with a mean age of 14.1 years (SD = 2.80, range: 9.3–17.4). 75% used polypropylene technology. Seven user need interview themes were identified: prosthesis appreciation; appearance; sport and running; daily activity challenges; articulating knee instability; pain/discomfort; and socket use. The mean functional movement score was 88.0% (SD = 6.7). Children ranked walking faster, kneeling, and being less tired as their top three priorities for change.

Conclusions: Children were successfully engaged through an interactive interview. Design innovation is required for more stable prosthetic joints with a greater range of motion and appropriate appearance. Identified improvements will increase quality of life and access to cultural activities and sport.

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KEYWORDS

Paediatric; prosthetic user needs; low resource environment; above/through-knee limb absence; questionnaires

► IMPLICATIONS FOR REHABILITATION

1. Children with above/through-knee limb absence in Cambodia have called for actionable changes in the design of their prosthetic limbs to support their frequent prosthetic use and active lifestyles.
2. Children want to be able to walk faster, access more stable prosthetic knee joints, and face less pain and fatigue during daily life through increased socket comfort.
3. Rehabilitation and prosthetic design must consider key cultural activities such as kneeling to pray, squatting, and sitting cross legged as well as sport.
4. Appropriate appearance of a prosthetic limb is equally critical to acceptance in low-resource environments and includes cosmesis, sound, and clothing interactions.

Introduction

Effective rehabilitation for childhood limb absence in low-resource environments (LREs) presents unique challenges, requiring innovative, cost-effective prosthetic solutions to ensure optimal mobility and quality of life throughout growth and development. Lower limb absence includes both congenital limb differences and amputations, which may involve partial or complete limb loss. Acquired limb absence (amputation) can occur due to a variety of reasons including sarcoma, disease, or trauma, with trauma forming

CONTACT Caitlin E. Edgar  caitlin.edgar17@imperial.ac.uk  The Centre for Paediatric Blast Injury Research, Department of Bioengineering, Imperial College London, London, UK.

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the most common cause in LREs [1–3]. Although limb absence is relatively rare in high-resource environments, recent conflict escalations – such as those in the Gaza Strip – and humanitarian disasters including the Türkiye-Syria and Myanmar earthquakes, have led to a dramatic increase in the number of children requiring prosthetic rehabilitation globally [4,5]. Crucially, this young cohort will require sustained access to appropriate assistive technology and rehabilitation services.

Above/through-knee (A/TK) limb absence, such as transfemoral or knee-disarticulation (KD) amputation, presents additional rehabilitative challenges compared with below-knee. These children have shorter residual limbs and therefore reduced musculature to actuate a prosthetic device [6]. As a result, both adults and children with above-knee limb absence experience increased energy expenditure in daily activities [6,7]. Additionally, they require extra prosthetic componentry in the form of a knee joint. This poses a further challenge as they must contend with the control of this additional joint which adds complexity to the gait training process post-amputation. Also, the larger neuromechanical loss for this proximal amputation level increases the cognitive load during walking to maintain stability [8].

Children require prosthetic limbs which meet the demands of their active daily lives safely and effectively. The addition of a LRE such as low- and middle-income countries, natural disaster-affected areas, conflict zones, and refugee crises complicate prosthetic provision [9]. Here, children may face limited prosthetic design options, uneven terrain, inconsistent access to care, long travel distances, and harsh weather conditions [10]. A significant number of prosthetic designs are either inappropriate or unavailable for LREs. Componentry including microprocessor control or hydraulic features are prohibitively expensive and often inaccessible due to their lack of durability and complexity (require charging and frequent maintenance) [10]. Moreover, these advanced designs are typically too large and heavy for young children to use. Designs available in LREs, such as the International Committee of the Red Cross (ICRC) polypropylene technology, often fail to meet all the functional needs for the child's daily life [11]. For instance, their monocentric knees frequently lack the stability children require [11,12], while donated components often fail to meet the durability and sustainability requirements of the end environment [13]. Cultural considerations can accentuate the demands on prosthetic design, as children may need to kneel to pray, squat to use a toilet, or indeed hide their prosthesis to avoid stigma [9,14–16].

Given the extensive factors influencing prosthetic provision and rehabilitation, it is essential to listen to children with lower limb absence in LREs to understand their priorities for improvement. Few studies have explored the general lived experiences of children in LREs [17] or included cohorts in high resource environments (HREs) [12]. However, none have comprehensively identified user needs at a discrete component level for children with A/TK limb absence [14]. A detailed understanding of these needs is required to advance user centred paediatric prosthetic design globally. To drive prosthetic innovation researchers must define children's preferences, concerns, and priorities. In this way, technical specifications for design can be developed.

Article 12 of the UN convention on the rights of the child states that “children have a right to be heard” [18]. Although the opinions of parents/caregivers are key for progress, children offer valuable insights and must be provided with a platform to highlight their priorities for care and prosthetic design innovation. To do so requires an effective protocol which engages them in a fun, safe, and positive manner. This work reports results from the protocol of Edgar et al. [14]. This protocol uses an interactive concurrent mixed methods interview for children as well as an objective functional movement assessment to understand their current mobility restraints. Mixed methods allow quantitative measurement of the child's function and user need priorities, while qualitative semi-structured interviews provide capacity for in-depth thematic analysis of user needs. Cambodia is chosen as a representative LRE location being classified as a low-income country [19].

The aim of this work is to identify the user and prosthetic design needs for children with above and through-knee limb absence in Cambodia using a concurrent mixed methods approach.

Methods

This study is reported in accordance with the Mixed Methods Reporting in Rehabilitation and Health Sciences (MMR-RHS) checklist.

Ethics

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). Individual participant assent and written legal guardian consent were collected.

Study design and participants

“Listening to Children with Lower Limb Loss” is a concurrent mixed methods (qualitative and quantitative) protocol investigating the unique user needs for this cohort [14]. This study forms part of this protocol and is focused on the children who use A/TK prosthetic componentry, that is, those who have a form of prosthetic knee joint. This study follows on from a successful pilot as detailed in the original protocol.

Due to the complexity of congenital limb difference, the level of prosthetic componentry supplied is used as a proxy for limb absence level to account for reasons for limb absence such as proximal femoral length deficiency. Children were recruited across three centres in Cambodia spanning three provinces: Phnom Penh, Kampong Chhnang, and Preah Sihanouk. Inclusion criteria required children to be aged 6-18years, have at least one limb absence at the A/TK level, have accessed prosthetic rehabilitation services at least 6 months prior, and be otherwise healthy and active. Data are analysed from the children’s interviews, functional movement assessments, and clinical evaluations, all of which were developed by Edgar et al. and can be accessed here: <https://zenodo.org/records/12806793>.

All measures were collected face to face in Khmer by the child’s treating prosthetist during a scheduled typical appointment (CR, YY, PK).

Children’s interviews

Interview guides were available for children aged above and below 10years. Interviews with children were audio recorded, transcribed, and translated to English by the treating prosthetist to ensure accurate translation and transcription of key terminology. Interviews involved multiple methodologies. Children were asked to draw themselves, their families, and their dream prosthesis. Photos of the drawings were taken. Qualitative data was collected through open ended questions in a semi-structured interview format. Quantitative data was collected through closed ended questions and interactive card games. Five card games were used to answer each of the following questions (abbreviated for clarity):

1. Would you rather have a walking aid or prosthesis?
2. Which daily activities are you able to do?
3. Which prosthetic appearance do you prefer?
4. Which type of socket do you prefer?
5. What are the most important actions you want to achieve in the future?

Functional movement assessment

Each movement was pre-screened by the treating prosthetist before children were asked to perform each activity in the clinic. Movements were typical of routine rehabilitation activities completed as part of the child’s care. The prosthetist scored and filmed each activity. Each activity had a specific total score (e.g., 0–4, or 0–3) depending on the activity type where the larger the score the greater the function. To ensure equal weighting of activities despite differing maximum scores, a % score was calculated for each activity and then averaged across all activities to produce a composite total score. A mean score across the cohort was calculated for individual activities and for the composite total score.

Clinical evaluation

A clinical evaluation was conducted as part of the standard appointment routine to identify the demographics, prosthetic componentry in use, and current K-levels for each child [20,21].

Data analysis

Qualitative data were analysed and reported using the consolidated criteria for reporting qualitative research [22]. Data was thematically analysed following the reflective principles laid out by Braun and Clarke [23]. Analysis was conducted by a researcher with a background in biomedical engineering. Steps included familiarisation, open coding, pattern identification, theme generation, theme review, and theme definition and naming [23]. Two independent researchers checked coding, and the resulting themes were evaluated against the transcription text.

Quantitative data was analysed with descriptive statistics using Microsoft Excel (Microsoft Corporation, 2024). Each quantitative result from the interviews and functional movement assessment is placed in a relevant section of the thematic analysis for flow and to support the integration of mixed methods results as called for in the MMR-RHS checklist.

Results

Eight children with transfemoral or KD limb absence were recruited. The demographics and clinical characteristics of the participants are presented in Table 1. Most children were male (87.5%) and presented with transfemoral limb absence (75%) due to trauma (87.5%). The mean age at time of interview was 14.1 years (SD = 2.8, range: 9.3–17.4). Only one child was below 10 years (9 years), however the above 10 years child interview guide was still used due to the researcher error.

The majority of children (75%) used polypropylene prosthetic componentry designed by the ICRC, while two children used donated modular componentry. The ICRC knee joint was monocentric with friction adjusted swing control. The donated knee joint was polycentric with a spring activated extension assist feature. Both sets of componentry used the same solid ankle cushion heel (SACH) feet and polypropylene sockets with EVA foam liners. EVA foam was also used to create cosmetic covers on all prostheses. Transfemoral prosthesis users additionally required a Silesian belt for suspension.

At the interview, seven themes were identified. These were: prosthesis appreciation; appearance; sport and running; daily activity challenges; articulating knee joint instability; pain and discomfort; and socket use.

Theme 1: Children understand and like their prosthesis, in fact they wear it all the time

It was apparent throughout the interviews that children had a clear understanding of their prosthetic device. They understood each individual component of the limb and the function it provided. Children stated they liked their prosthesis and were happy to use it. The prosthesis allowed them to be

Table 1. Demographic and clinical characteristics.

		Mean (SD)	
Age (years)		14.1 (2.80)	
Age at Time of Acquired Amputation (years)		9.41 (4.17)	
Time Since Amputation (years)		5.31 (2.86)	
Time Since First Clinic Access (years)		2.73 (2.72)	
		Frequency	%
Sex	Female	1	12.5
	Male	7	87.5
Reason for Limb Absence	Trauma	7	87.5
	Congenital	1	12.5
Type of prosthesis supplied ^a	Knee-Disarticulation	2	25
	Transfemoral	6	75
K-Level	2	1	12.5
	3	5	62.5
	4	1	12.5
	Missing	1	12.5
Residence	Rural	1	12.5
	Urban	7	87.5

^aAs a proxy for level of lower limb absence or amputation.

independent and take part in daily activities. They recognised there were certain issues with the prosthesis but were happy because it helped them to walk again.

I am really satisfied with my device because it helps me to walk again, go back to school and play around with friends. It doesn't cause me any problem now. (12years, TF)

When asked if they would prefer crutches or a prosthesis in Card Game 1, 100% picked the prosthetic card as the prosthesis allowed them to walk more easily and use less energy. Additionally, children reported that crutches restricted their hand function whereas prostheses allowed them to help in daily tasks such as housework.

Prosthesis. It is easier to use and wear than crutches, easy for me to walk and use less energy when walking or standing on it too. (17years, TF)

The prosthesis because it does not restrict my hand function as [when] using crutches and it allows me to walk easily and can do some housework for my parents. (12years, TF)

100% of children reported wearing their prosthesis every day. 87.5% of children reported wearing it all day, and 87.5% reported wearing their prosthesis in the home. Children only removed their prosthesis for specific reasons such as bathing, sleeping, and if they were in pain. Children used their prosthesis wherever they went, for community activities, religious occasions, school, and for housework.

Yes, I use my prosthesis every day, ... I take off my prosthesis when I shower and when I sleep. (17years, TF)

I use my prosthesis when going to school, pagoda, and any other place that I want to go. (12years, TF)

As a result of this high activity level, children reported some durability challenges with their components, especially for the Silesian suspension belt and knee joint.

I like my prosthesis, but sometimes the Silesian belt is broken. (17years, TF)

They highlighted their appreciation for the ongoing care provided by the prosthetic rehabilitation centres. Additionally, despite raising issues with prosthetic design, there was some hesitancy to try new designs in case they were difficult to use.

I want Exceed [the organisation providing the prostheses] to continue help me by providing prosthesis for me. (9years, TF)

I used to wear and use this type of prosthesis for a long time and if I change to another design, I feel it is difficult for me to use it. (17years, TF)

Theme 2: Appearance and sound

Sub theme: Children wish to hide their disability by emulating physiological appearance and movements

Children consistently raised it was critical to be able to hide their disability and avoid others noticing their prosthesis. This included emulating physiological appearance with a focus on matching skin colour as closely as possible.

I always feel shy to let people know [about my prosthesis]. Yes, I want it ... similar to my skin colour. (17years, TF)

However, it quickly became apparent appropriate appearance encompassed more than just the cosmesis of the leg but also how it functionally appeared compared to a physiological leg during walking. Children reported dissatisfaction with their appearance when using a locked knee joint as the straight leg did not allow them to emulate physiological movement patterns during gait.

... I want to walk as normal people without locking the knee joint. (14years, TF)

This point on functional appearance was emphasised for sitting on chairs. The addition of a prosthetic knee joint lengthened the femoral segment of the leg resulting in a length discrepancy between the two

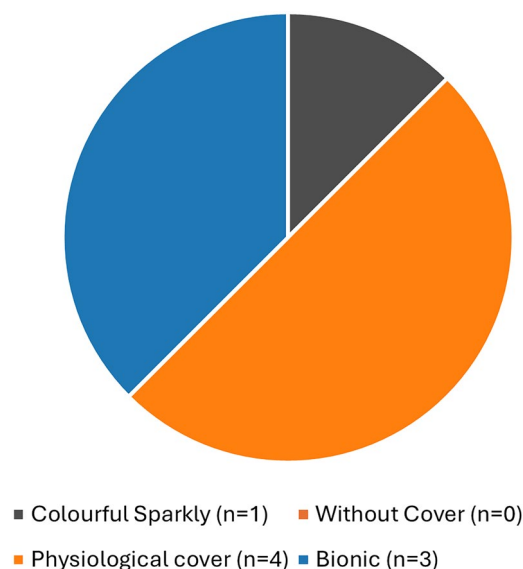


Figure 1. Favourite prosthetic appearance for children identified by Card Game 3. The following four options were given: colourful sparkly, uncovered, physiological cover, and bionic.

legs when sitting with the knee flexed at 90 degrees. This lengthening becomes extremely significant for children with long residual limbs (~10cm). Children wished to minimise this appearance as far as possible.

If possible, I would like the knee joint [to be] equal to the knee joint on the sound leg, to be in line with the knee joint centre, as it looks good when sitting down. (13years, KD)

The combination of cosmesis and functional appearance was seen in Card Game 3 on choice of prosthetic leg appearance (Figure 1). Here, most children chose the leg which matched physiological appearance, and a few chose the bionic leg but stated this would be for functional reasons.

Children also pointed out that noise in a prosthetic leg hindered their ability to hide their disability and was upsetting. They identified that a primary cause of the noise was the knee joint which made them feel uncomfortable.

Yes. When walking it disturbs me and sometimes, I am afraid that people around me will hear the sound. (16years, TF)

Yes, the knee joint has noise during walking and that noise makes me feel uncomfortable [and] unhappy too. (13years, KD)

Despite these concerns, children were positive about the cosmetic appearance of their ICRC legs and cosmetic covers as they effectively emulated physiological limbs. They found the ICRC monocentric knee to be an appropriate size and shape.

The ICRC prosthesis with the cosmetic cover because it provides good cosmesis as it looks the same as a real leg. (16years, TF)

Yes, I like it because the [knee] size is similar to my normal leg. (14years, TF)

Sub theme: Clothing choice must consider several factors of limb loss

It was identified that prosthetic use affects clothing choices post-amputation. Multiple reasons were given for changes to behaviour and there were differences across the cohort. Many children chose to wear long clothing after limb loss to hide their prosthesis from the public eye.

I like using long trousers when going outside. I used shorts when I stay at home but after I became an amputee, I changed my habit. I don't want people to recognise I am an amputee. (17years, TF)

In contrast, some children raised the benefit of wearing shorts. These were easy to put on, did not get in the way of the prosthesis, and allowed children to walk easily without clothes getting caught within the knee joint.

I like wearing short clothes because they are easy to wear and do not get in the way when using the prosthesis. (9years, TF)

Sometimes the pants get folded within the knee joint too. (13years, KD)

The prosthetic limb also prevented many children from wearing clothing they deemed traditional for the Khmer culture.

I never tried any traditional clothes as I am TF. I also think it might be difficult for me to wear and to change the traditional clothes too. (17years, TF)

Yet, despite these clear challenges, children still wished to choose their clothing based on their likes/dislikes in style, appearance, and longevity.

I like wearing jeans with a T-shirt because it makes me look handsome and jeans last [a long time]. (16years, TF)

Theme 3: Taking part in sport and playing with friends and family is important for children

Children were passionate about taking part in sport activities. Sport made children happy, and it was associated with positive time spent playing with friends and siblings.

Yesterday I went to school, rode my E-bike with my brother, and played football with some of my friends at school too. I feel happy when I can play football and table tennis with my friends. (13years, KD)

Children took part in a range of sports with volleyball appearing popular. Some children were able to play all the sports they wished, whereas others could not and sometimes were only able to watch their friends take part. For these children they raised the ability to take part in sport as an important change they wanted from their prosthetic rehabilitation.

In the afternoon, [I] watched friends play volleyball. (17years, TF)

I want to ride a bike and play football like my friends. (9years, TF).

It became clear that a barrier to sport participation was walking fast and running. The ability to walk fast or run was a meaningful change for children to enable their participation in preferred activities. Some children drew prosthetic running blades as their ideal leg ([Figure 2](#)).



Figure 2. Child drawing of an ideal prosthetic leg as a running blade.

I want a prosthesis that allows me to run faster and feel more stable. I like running and play with other children in the community. (9years, TF)

Theme 4: Specific prosthetic design issues prevent children achieving essential movements for daily activities such as kneeling and squatting

In the interview, children highlighted they could not do all the daily activities they wanted to. They wished to be more active in their daily lives.

I cannot do some activities, and I wish to do all these activities in the future. I want to run/walk faster, walk downstairs, kneeling and jumping. (17years, TF)

Children repeatedly raised kneeling and squatting as issues. Squatting enables children to independently use the toilet. Kneeling enables children to engage in culturally relevant activities such as participating in religious activities including at the pagoda. They could not fully achieve these activities due to the limited range of motion at their knees and feet. This was highlighted as a critical area for change.

Yes, I want to do full squatting easily and so it is also easy for me to use toilet. (17years, TF)

Yes, I want my knee joint on the prosthesis to fully bend during kneeling and squatting too. ... [The] prosthesis does not allow for squatting and only 90-degree knee flexion. If the knee joint allows me to do squatting and kneeling easily, I would be happy. Are there any designs of knee joint that will allow me to squat easily, and how much would it cost? (13years, KD)

Range of motion was not the only challenge for kneeling. The addition of the knee joint to the socket system increased the length of the femoral segment such that children with long residual limbs could only balance on the prosthetic side with their intact limb not touching the ground.

I can only kneel on the prosthetic side. (12years, KD)

Another key activity which was unachievable for children was cross-legged sitting. Children would like their knee joint to be able to rotate so that they could sit with their legs crossed.

I can't sit cross legged because it is difficult for me to rotate my leg. I wish the knee joint could rotate so that I can sit cross-legged. (16years, TF)

In the "can/cannot do" Card Game 2, children self-reported the daily activities they could not achieve, which matched those mentioned during the interview (e.g., sitting cross-legged) (Figure 3).

The mean functional movement assessment score was 88.0% (SD = 6.7) across the cohort. The full breakdown of each activity score is shown in Table 2. Similar activities to the self-reported ones were identified as challenging (e.g., sitting cross-legged, kneeling), but additional activities requiring improvement were also identified (e.g., stairs and obstacles).

Theme 5: An articulating knee joint is important to children, but stability is a significant issue which impacts walking speed

Children stated that an articulating knee joint was essential for them. It allowed them to walk more easily due to the flexion and extension. In fact, children with prescribed straight legs were keen to be able to unlock their knees.

I don't want to change anything with the socket, but I want a knee joint that allows me to flex and extend easily. I want to unlock my knee. (14years, TF)

A key benefit of the articulating knee was being able to sit down easily and in multiple positions such as in the classroom. Children were keen to be able to sit in typical positions so as not to stand out.

Yes, because it can help me to sit in different positions, not just standing and also allows me to walk freely. (12years, TF)

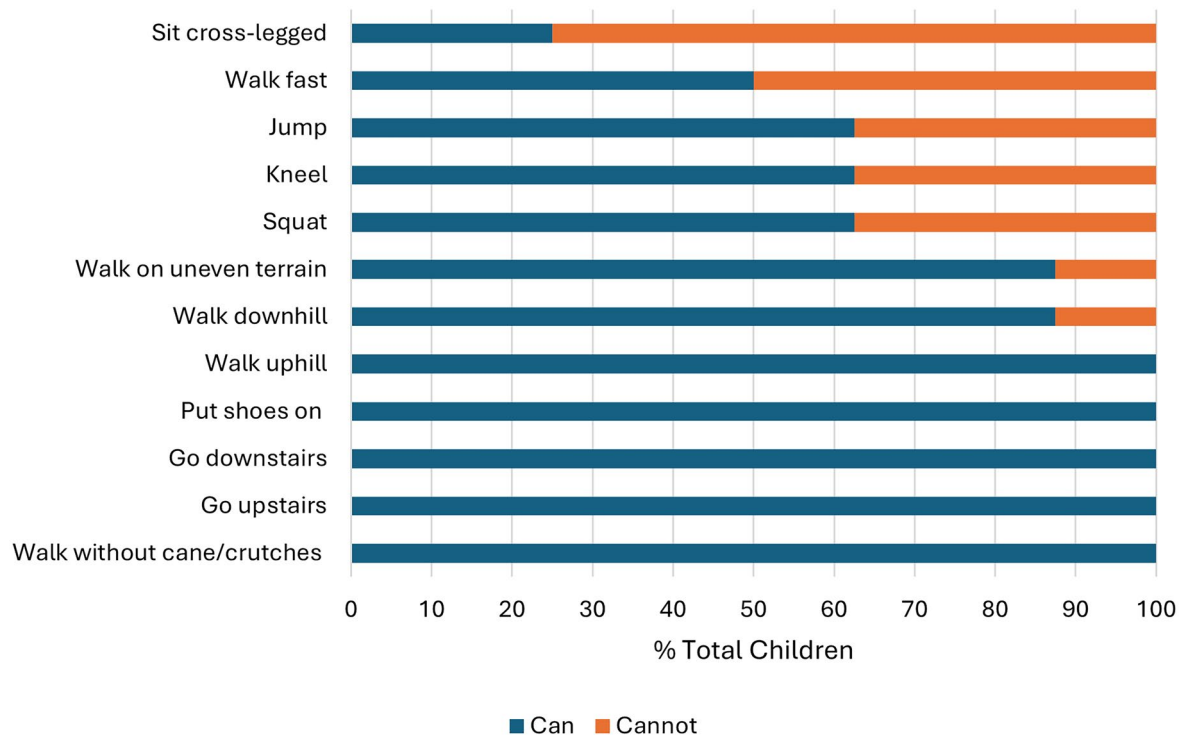


Figure 3. Child self-reported ability to achieve daily activities. Identified through the interactive interview Card Game 2. The game asked children: 'For this next activity we would like you to split this set of cards into two groups, one group is the activities you can do, and the other group is the activities you cannot do. If you do not understand a picture, let me know and I will try and explain.'

Table 2. Functional movement assessment scores for the Cambodian cohort of children with above/through-knee limb absence.

Functional movement activity	Mean % (SD)
Kneel	41.7 (30.0)
Squat	54.2 (43.4)
Sit cross legged	64.3 (37.8)
Walk over obstacle	77.1 (26.6)
Walk downstairs	91.7 (15.4)
Walk upstairs	91.7 (15.4)
Walk down ramp	91.7 (15.4)
Walk up ramp	95.8 (11.8)
Walk freely	96.9 (8.8)
Stand up from chair	100.0 (0.0)
Sit down on chair	100.0 (0.0)
Sit on ground	100.0 (0.0)
Standing balance	100.0 (0.0)
Pick object up from floor	100.0 (0.0)
Walk on uneven ground	100.0 (0.0)
Walk between parallel bars	100.0 (0.0)
Total Score	88.0 (6.7)

However, a significant barrier to walking with an articulating knee joint was instability. Children found their knees unstable even when walking over level ground. Instability was especially problematic for uneven or muddy surfaces as well as stairs and hills.

No, I don't feel stable, sometimes I fall down during walking and when I walk on uneven surfaces such as muddy or slippery surfaces. I want a prosthesis that allows me to run faster and feel more stable. (9years, TF)

Sometimes it feels unstable to go downstairs. Also, I can walk downhill but sometimes I feel instability [at the front]. (17years, TF)

The lack of stability prevented children from walking as fast as they would like or even running.

With my current device I cannot walk fast like I want because I do not feel secure with this knee. I want to run or walk fast but I don't feel stable with the prosthetic knee joint. (17years, TF)

Despite these stability issues, children learnt how to cope with their knee joints and were able to control them most of the time. However, when they lost control, falls could occur.

Yes, I can manage the knee joint stability. Sometimes, I cannot control my knee joint and then I fall down but this happens maybe only every 2 months. (13years, KD)

A method children employed to improve stability, and control was to activate a lock within their knee for certain activities where additional stability is essential. Some children were able to activate this lock on their own, but others required help from family members.

My grandfather always helps me when I want to lock it. I like locking it during walking, and I can run faster and be stable. (9years, TF)

Theme 6: Limb absence and prosthetic use can result in pain, discomfort, and fatigue

Children reported pain and discomfort in their residual limb. 44.4% of children said their residual limb was the first area of their body to become fatigued. As a result, children called for more comfortable prostheses to reduce the pain in the residual limb.

I don't appreciate my device, ... I have pain at the distal end of the stump ... but I am also happy because it helps me to walk. (17years, TF)

I want a device that provide me more comfort, stability, and lighter weight. (17years, TF)

However, pain was not only reported in the residual limb. Children also experienced fatigue and pain in secondary locations such as their hips, lower back, and intact limbs. 55.6% of children reported these intact areas as the first to become fatigued.

I get tired in my hip and lower back. Sometimes it is numbness and very painful. (17years, TF)

After walking for long I feel that my sound side is very tired. (14years, TF)

Sometimes this pain was not simply due to compensatory movement patterns or overuse but due to the suspension system in use. The Silesian belt could be too tight.

I feel pain at my waist on sound side due to the tightness of Silesian belt. (17years, TF)

A frequent issue was the weight of the prosthesis. Children repeatedly requested more lightweight designs to improve comfort and fatigue.

Yes, I want it lighter weight. (17years, TF)

To cope with pain and discomfort, children employed certain coping methods to reduce their pain. These ranged from simple rest to massage.

I solve this problem by taking off the device. After I feel okay, I will continue using the prosthesis. (17years, TF)

Despite this, pain could sometimes impact sleep quality, although 100% of children reported they liked going to sleep.

Yes, I like to sleep at night, because I walk a lot during the day so I need to sleep at night, but sometimes I cannot sleep due to my stump pain. Sometimes [I wake up] when I have pain in my stump. (17years, TF)

Theme 7: Children like their sockets but they have issues with socket fit and sweat

100% of children reported they liked their prosthetic socket. They were positive about various aspects including comfort and good fit.

Yes, I like it, it is easy for me to wear it and not tight and not so heavy. (13years, KD)

Yes, the socket still has a good fit and is comfortable. (14years, TF)

Despite this, children still called for improvements in their EVA foam liner within the socket. They wished for it to be softer.

The only thing I want to change is the liner, I want it to be more soft. (12years, KD)

Additionally, sometimes problems with the socket fit arose. The socket could become too loose over time. To cope with loose sockets, children started to wear more layers of residual limb socks to fill out the volume of the limb to fit the socket.

Sometimes the socket is loose, so I need to come to the clinic. (13years, KD)

When my socket is loose, I add stump socks to 2 layers max. (13years, KD)

Another challenge children raised was that their limbs became sweaty within the socket. In fact, 75% of children reported they struggled with sweat in the socket. This was especially problematic in the hot season and when walking/playing a lot. The sweating was a significant issue which could result in heat build-up, itchiness, and skin redness thus further increasing discomfort.

Yes, sweating after coming back from school when the weather is hot. It happens every day when I come back from school. (12years, TF)

My amputated side easily gets sweat, itchy and redness. [It happens] when I walk for long time and walk so much. (17years, TF)

Another problem children raised is that their growth affected their socket use. They reported they must return to the clinic as they grow, and their sockets become tight.

My current prosthesis does not have any problem; I come to centre just once a year when it becomes tight and short. (9years, TF)

In the Card Game 4 on socket preference, 87.5% chose the adjustable socket. Their reasoning was that it would provide more comfort, support their growth, and allow them to reduce the amount of time they visited the clinic.

I want the socket to be more flexible as it will provide more comfort. [I choose] the adjustable socket because it allows me to make adjustments by myself without visiting the centre. (16years, TF)

The 12.5% of children who preferred the classic socket were concerned the adjustable socket would not allow for good cosmesis and appearance.

Classic socket because I don't need to do adjustments with socket fit and can cover with good cosmesis. (17years, TF)

Despite these problems, children reported that the socket was easy to wear. They did not report any problems with donning/doffing the prosthesis.

Yes, I like it because it is comfortable and easy to don/doff. (12years, KD)

Card Game 5: Rank top priorities for change

Figure 4 shows the ranking of the most important priorities for children in this cohort and provides a comprehensive reflection of the thematic analysis. Walking faster and kneeling were ranked highest. This reflects the importance children placed on walking faster in theme 5 and kneeling in theme 4. In contrast, visiting the clinic less was not identified as a priority and similarly it was not raised throughout the thematic analysis.

Discussion

This work has defined the user needs for children with A/TK limb absence in Cambodia. A previously presented engaging and child-friendly set of outcome measures and protocol were followed to effectively gather key information on paediatric prosthetic design priorities for LREs and current functional movement capacity [14].

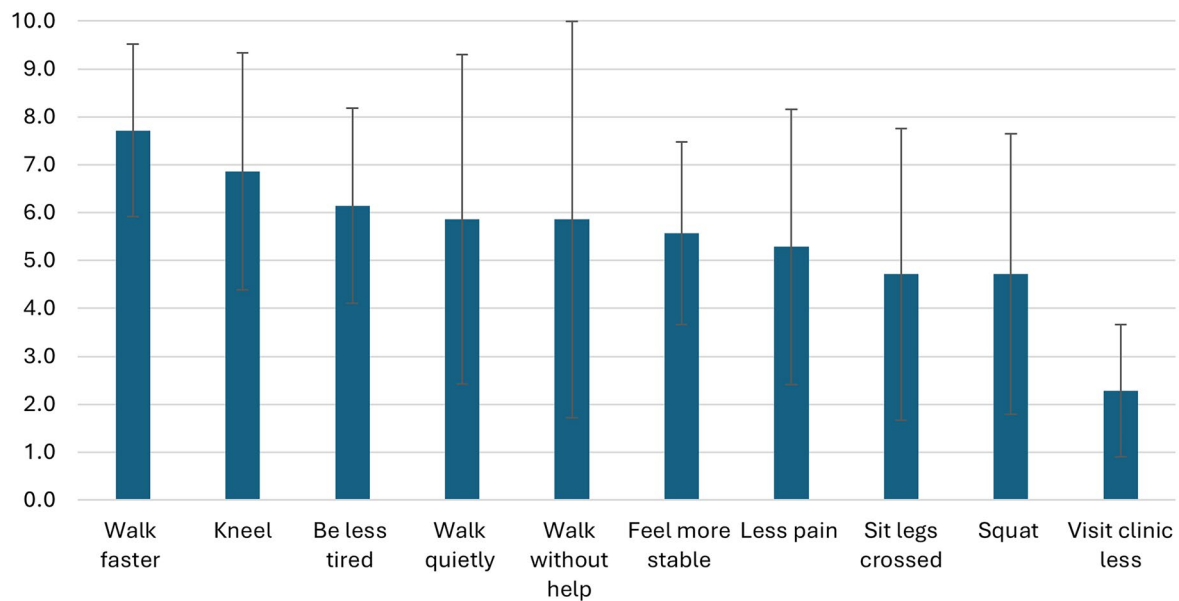


Figure 4. Child self-reported mean ($\pm$ SD) ranking of 10 priorities as identified through the interactive interview Card Game 5. The game asked children: ‘Can you please rank these 10 cards in order of the things that you want the most. The things you want to be able to do or have in your life the most you put at the top and the things you are not interested in you put at the bottom. This is not about what you can or cannot do, but what you want to do. For example, do you want to walk faster more than you want to kneel?’

The recruited sample included children with above-knee absence and KD amputation which provided unique insight into key differences for KD such as the imbalance when kneeling due to the long residual limb combined with prosthetic knee length. Disarticulation amputation is preferred for children to retain the distal growth plates in the long bones [24], therefore it is important for children with KD limb loss to be included in user needs analyses to ensure appropriateness of prosthetic design for this level. Future work could aim to also include children with hip-disarticulation.

Theme 1 identified that children appreciate their prosthetic leg and clearly understand the role of each discrete component. This supports previous calls for children to be more actively engaged in medical device design research with the goal of facilitating codesign [25]. Theme 1 also found that children rely heavily on their prosthesis for independence. Componentry must therefore be sufficiently durable to withstand this high activity level. Additionally, if breakages occur or children grow out of their limb this will have a severe impact on the child who requires almost constant use of their limb for daily life.

Theme 2 identified that children in Cambodia still face challenges on disability stigmatisation with most participants wishing to hide their limb absence and prosthetic leg (Figure 1). This finding emulates previous work with children with below-knee limb absence in Cambodia [15]. To support children in their wish to emulate physiological appearance as far as possible, multiple factors were raised. These included cosmetic appearance such as colour; physiological movement patterns such as walking with free knees and sitting on chairs; and minimising noise especially in the knee joint. For appearance, children stated they liked the ICRC knee joint size and shape. Paediatric prosthetic knees must therefore not simply be minimised in size but instead shaped appropriately to emulate physiological appearance. Clothing was also highlighted as a challenging aspect of appearance. It was often used to cover the limb through long trousers, but this could be a hinderance. Prosthetic componentry should avoid sharp edges or capture points which may tear or damage clothing. It may be necessary to consider adapted clothing for children as has been raised by Al Asmari et al. in a key study for women with limb absence [26].

Theme 3 identified the importance of sport in childhood. It was found to be a facilitator of social activity for children both with friends and family, yet currently available designs for this cohort do not fully support access to sport. As a result, some children were excluded from taking part, only able to watch. Facilitating access to advanced technology such as running blades and sports knees for specific activities would improve sport access for children. However, the cost of these components is prohibitive

for widespread provision in LREs. Additionally, sports knees are not always designed for use in rough terrains and often state they should avoid contact with water/dust/dirt. Finally, the blade design is inherently non-physiological in appearance thus it does not meet the requirements raised in Theme 2. This therefore limits the use of these components to specific scenarios and further work is necessary to understand an appropriate implementation plan.

Instead, at a minimum, children should receive technology which facilitates increased stability and walking speed to improve base level access into sport and active play. These criteria were clearly raised in Theme 5 where knees with greater stability and subsequent walking speed were requested. Balance and stability are always essential especially during the early stages of rehabilitation to ensure confidence and avoid prosthetic limb abandonment. For experienced users, instability can still limit walking speed and sometimes result in falls. However, children clearly raised their preference for articulating knee joints to facilitate easy walking and sitting. Therefore, simply providing a locking mechanism to increase stability may not be sufficient. In fact, it has been shown that providing articulating knee joints from the start of rehabilitation resulted in fewer gait adaptations than the traditional protocol of providing straight legs during early rehabilitation [27]. More complex technologies such as microprocessor knees are unsuitable for use in LREs due to their prohibitive cost and lack of durability [10]. Instead, an affordable paediatric prosthetic knee joint suitable for use in LREs with increased stability is required. Additionally, future work could investigate knee alignment protocols which may influence knee stability.

Theme 4 highlighted that other daily activities also posed challenges. Children repeatedly stated they had difficulties with kneeling and squatting which was supported by the card game results (Figure 3 and Figure 4) and functional movement assessment (Table 2). Kneeling is an important motion for praying in many religions as well for children to play on the ground with friends [28], while squatting is important for children to achieve independent self-care in environments where squat toilets are still in use. Yet these movements are currently limited by the range of motion at the prosthetic knee and lack of joint at the ankle. The current SACH foot system does not have an ankle joint, therefore in full kneeling the child must remain balanced on their toes as there is no capacity for plantarflexion. Additionally, the lack of ankle joint inhibits stable squatting as no dorsiflexion is possible. To fully provide comfort during these movements increased ROM at both the knee and ankle are required. Single axis ankles or design innovation focussed on user-controlled increased range of motion at the ankle for specific activities form possible avenues of future work.

Children also reported issues with cross-legged sitting due to a lack of rotation about the knee joint. Sitting cross-legged is important for children when attending school as it is often the preferred sitting position during group activities such as assemblies. Further research into suitable rotation systems for children in LREs is required.

Themes 6 and 7 found challenges with pain, comfort, and socket fit. Issues existed with the residual limb and the interface with the prosthesis, as has commonly been found for adult populations [29]. Children only had access to EVA foam liners which are typically not as comfortable as silicone liners. However, EVA foam is the most commonly provided liner worldwide for young children as gel liners increase sweating and the need for hygienic practices to avoid the occurrences of skin infections [30]. Indeed, many children already reported that sweating is a significant issue and therefore the use of silicone liners may exacerbate this issue further. Furthermore, other benefits of EVA foam liners include their capacity to be adjusted for growth through addition or removal of padding [31]. It is therefore not immediately apparent which liner system will suit children best and it will likely rely on individual preference and component availability.

Other residual limb issues were pain and sockets becoming ill-fitted over time. They were noted to become too loose over time which may be due to the liner wearing out [32]; larger initial sockets being provided to allow room for growth [31]; or due to muscle atrophy due to compensatory movement patterns [33]. In other occasions, children reported their growth as a cause of socket fit issues which is to be expected given children with A/TK limb absence retain at least one growth plate within their residual limb. Adjustable sockets can form a potential solution for these socket fit issues and although there are multiple existing designs a recent review found none on the market specifically for children [34]. Adjustable sockets designed for LREs would support children to retain their independence throughout growth spurts, especially as access to care

may be limited. These socket designs were positively supported by children as shown by Card Game 4 with their potential for user-controlled adjustment valued. However, it must be considered that these solutions will be likely more complex and thus may increase the number of failure points. Consideration of durability during their design for children is required.

Discomfort was also identified in secondary locations including the intact limbs and lower back. This has been previously shown in the adult population due to the typical compensatory movements used by individuals with A/TK limb absence [35,36]. This is of concern given the years of prosthetic use ahead for these participants and the existing link in adult cohorts between compensation movements, discomfort, and early onset osteoarthritis [37]. Componentry which supports children to achieve their daily activities using healthy movement patterns and reduced energy expenditure is necessary.

Finally, the card-game ranking activity (Figure 4) reflects the thematic analysis results and encompasses every theme. The result provides a clear priority list for actionable change in prosthetic design. In fact, walking faster and kneeling scored the highest, showing the importance of participating in sports and community activities as well as having a functioning/appropriate knee joint (theme 3, 4 and 5). These wishes were followed shortly by “being less tired” which relates to the significant fatigue and high energy expenditure of children with A/TK amputation (theme 6), and “walk quietly” which relates to social stigma and concealing the prosthesis sound (theme 2)

Limitations

The small sample size forms a limitation. The size was sufficient for the interactive interview exceeding that required in the protocol allowing identification of the major themes during qualitative analysis. However, the small sample limits the generalisability of the quantitative analysis and prevented inferential statistical analysis being completed. Yet, the quantitative results mirrored those found in the interactive interview regarding key priority areas and thus the conclusions of this work are well supported.

Furthermore, this sample only recruited children in Cambodia and as such the results may not be generalisable to other LREs and geographical locations. However, the componentry prescribed and used by the children is typical of LREs where a combination of ICRC technology and donated modular components is common. Thus, the learnings on improvements in prosthetic design are likely generalisable across these LRE technologies. Future work should look to recruit more children in a variety of geographical, cultural, and socioeconomic locations.

Only one girl was included in the sample and most children presented with limb absence due to trauma, both of which are typical of the demographics for children in LREs. However, this may limit the findings for female children and those with differing aetiologies of limb absence. Future work should aim to include more girls as it has previously been found in adult cohorts that female user needs may differ from male [38,39].

The interactive interview and card games form patient reported outcome measures which can be subjective, and the use of thematic analysis can introduce bias dependent on the researcher conducting the analysis. The researcher is a biomedical engineer and is therefore well placed to discern themes related to prosthetic design and engineering. However, individuals from other backgrounds may identify additional themes and other focus areas. It would therefore be beneficial for future work to further analyse this extensive dataset through a different lens. Additional bias may have resulted from the fact children were interviewed by their treating prosthetist which could have influenced their ability to share certain viewpoints. However, the benefits of the interviewer being an individual the child knows and is comfortable around cannot be understated for overall enjoyment in research participation and the clarity of discussion.

Conclusion

The unique user needs of children with A/TK limb absence have been defined in a LRE using a novel engaging protocol and interview guide. Children raised key issues regarding current prosthetic design but remained positive about their prosthetic experience. Cultural and environmental factors added additional criteria for design where joint range of motion, stability, and cosmesis are essential. The results provide clear priorities for prosthetic design innovation for a unique cohort in a low-resource environment.

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Author contributions

CRediT: **Caitlin E. Edgar**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing; **Claudia Ghidini**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – review & editing; **Chanthearin Ry**: Data curation, Investigation, Project administration, Writing – review & editing; **Yong Yeon**: Data curation, Investigation, Project administration, Writing – review & editing; **Phanith Karng**: Data curation, Investigation, Project administration, Writing – review & editing; **Thearith Heang**: Project administration, Writing – review & editing; **Sisary Kheng**: Project administration, Writing – review & editing; **Anthony M. J. Bull**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Data availability statement

Interview transcripts and relevant data can be made available through establishment of collaboration/partnership and by adding new researchers to the current ethical approval to comply with data protection.

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