Original Article

DOI: https://doi.org/10.4038/jmj.v37i1.234

The legacy of war: improving lower-limb prosthetic design in northern Sri Lanka

[1]Michael A. Berthaume, [2]Sathiadas M G

[1]Department of Engineering, King's College London, London, United Kingdom

[2]Department of Paediatrics, Faculty of Medicine, University of Jaffna, Jaffna, Sri Lanka

Abstract:

The JJCDR provides prosthetics based on ICRC designs, adapted using local materials for better durability in Sri Lanka's climate. However, since the original designs weren't tailored to Sri Lankan users, two collaborative studies were conducted to understand how amputees in the north use their prosthetics. The goal is to co-design improved prosthetics that meet local biological and cultural needs through a multidisciplinary approach called anthroengineering, which combines engineering and anthropology.

The database was first queried for demographic information relevant to prosthetic design. There were 3,665 unique patients who registered with the JJCDR from 1986 – 2018, the majority of which were males.

Of the 555 patients with occupation data, many were housewives (124) or unemployed (85), suggesting a greater need for prosthetics suited for basic mobility rather than heavy labor. The majority of patients lived in the Jaffna peninsula (82.5%) and most amputations occurred in the Northern province (94.3%), primarily due to war. Most amputations were lower-limb, likely caused by landmines and blasts, and were treated at teaching hospitals (65.6%). As JJCDR offers limited upper-limb prosthetics, the actual number of upper-limb amputees may be underrepresented.

Contrary to expectations based on ISO 10328 standards for lower-limb prosthetics, there was little evidence of prosthetic foot fractures. However, it remained unclear whether delamination between the keel and the rubber occurred.

Keywords

Amputee, Jaffna, Jaffna Jaipur Centre for Disability Rehabilitation (JJCDR), prosthetic foot, SACH foot, mechanical failure, ISO10328

Introduction

The civil war in Sri Lanka has left a large legacy population of amputees, most of whom live in the north and the east, where the conflicts took place. When the war was occurring, and for several years after, this attracted the attention of the global humanitarian community, and organizations like the International Committee of the Red Cross (ICRC), Motivation, and Exceed Worldwide provided resources (e.g., training, skilled workers, donations, consumables) to provide prosthetics to help people live more fulfilled lives. As international aid and donations abated, it fell upon national resources (e.g., the government, local hospitals and charities) to fill this gap. One such charity is the Jaffna Jaipur Centre for Disability Rehabilitation (JJCDR).

Established in 1987 to help those who lost limbs during the war, the JJCDR has been a regular provider of prosthetic, orthotic, and mobility services to Sri Lankans for over 35 years. Located in Jaffna, most of its patients come from the Jaffna peninsula, but it has become so renowned for its services that people travel from across the island to take advantage of the JJCDR's prosthetic services.

The prosthetics currently provided by the JJCDR are local variations of the ICRC's prosthetic technology. Focused on local manufacture, these prosthetics largely use local materials which increases their durability and longevity in the hot, humid, Sri Lankan environment. However, the ICRC prosthetics were not designed with Sri Lankans in mind. Instead, they were manufactured for functionality, flexibility, and affordability so they could be used by any across the globe. As part of an ongoing collaboration between UK and Sri Lankan universities, hospitals, and charities, we undertook two studies to better understand the amputee population in

Corresponding author : Michael A. Berthaume, Email: michael.berthaume@kcl.ac.uk, https://orcid.org/0000-0003-1298-242X,
Submitted April 2024 Accepted April 2025

the north and how they were using their lower-limb prosthetic devices. Here, we summarize the two studies, published in other open-access journals, so they are freely available to the international community. The information from these studies will be used to co-design new portions of the prosthetic devices so they better serve the biological and cultural anthropological needs of the local amputee population sustainably. This unique combination of engineering (i.e., design) and anthropology (i.e., culture, biology) is referred to as anthroengineering (1, 2).

Results:

Demographic, medical, and financial statistics from the JJCDR (1987-2018)

First, we reviewed an anonymised copy of the patient records held by the JJCDR. This study was conducted with ethical approval from the University of Jaffna (reference number J/ERC/22/136/NDR/0275) and London South Bank University (reference number ETH2122-0172). To protect patient anonymity, names and identifying information were removed, addresses were anonymised to village level, and birthdays were binned into year and quarter (e.g., 1975.1 would be a person born between January and March 1975, while 1975.4 would be a person born between October and December of the same year).

The database was first queried for demographic information relevant to prosthetic design. There were 3,665 unique patients who registered with the JJCDR from 1986 – 2018, the majority of which were male (n = 2,605 M, n = 1,060 F). As there was missing data, sample sizes for summary statistics are provided. Previous work has shown this discrepancy, with more men receiving prosthetic and orthotic (P&O) services than women, is common around the world (Barth et al., 2021). Unsurprisingly, given the large percentage of war-related amputations, most patients were young at the age of amputation, and consequently young when they registered with the JJCDR (Figure 1).

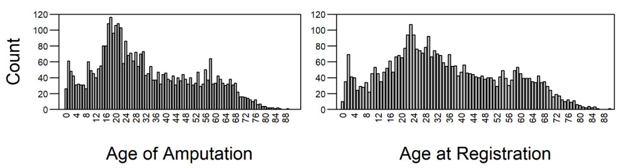

Figure 1: Age at amputation and registration.

Occupations can change with time, but of the 555 patients with occupation data, 124 were housewives and 85 were unemployed, implying it would likely be more important to have prosthetics that were efficient at walking down the street and moving about a house but not experience high, strenuous loads that might be more important to a labourer. Unsurprisingly, most patients lived in the Jaffna peninsula at the time of registration (82.5%, 2,851/3,455 with address information) and most (94.3%, 2,382/2,525) lost their limb(s) in the Northern province.

Most prosthetic patients with reason of amputation recorded (2,556 patients) had war-related amputations (Figure 2), and had their amputations had taken place at teaching hospitals (65.6%, 2,100/3,202). Most of the amputees were lower-limb amputees, which again is unsurprising as landmines and shell blasts tend to results in lower-limb amputations (Table 1). The JJCDR also provides limited upper-limb prosthetics, so it is possible the upper-limb amputee community in the region is higher, and that they do not receive prosthetic services from the JJCDR.

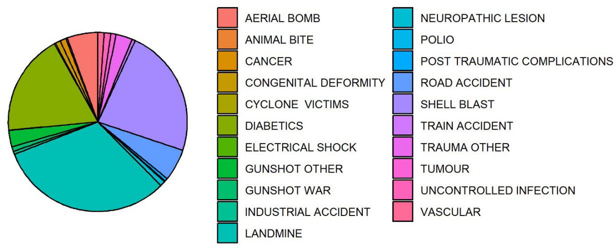

Figure 2: Causes of amputation. The main causes of amputation are shell blast, landmine, and diabetes.

Table 1: Amputation sites. Data on unilateral and bilateral amputees is combined.

Upper limb amputation	Left	Right	Total
Elbow disarticulation	1	1	2
Partial hand	1	1	2
Shoulder disarticulation	0	1	1
Transhumeral	35	35	70
Transradial	47	48	95
Wrist disarticulation	3	5	8
Total	87	91	178
Lower limb amputation			
Hip disarticulation	2	0	2
Partial foot	40	52	92
Transfemoral	243	271	514
Transtibial	904	852	1756
Total	1189	1175	2364

Potentially one of the most important findings is the temporal changes in cause of amputation (Figure 3). Since the war has ended, landmine and shell blast amputations have gone down significantly, although landmine amputations do still occasionally occur due to legacy mines. As in many other countries, diabetic amputations are on the rise: this is unsurprising, given the increase in diabetes within Sri Lanka, and the large percentage of Sri Lankans who have undiagnosed diabetes (3, 4). As the survival rate for those with diabetic amputation is low (largely due to comorbidities with the disease progressing), knowledge and treatment of diabetes is critical for the community.

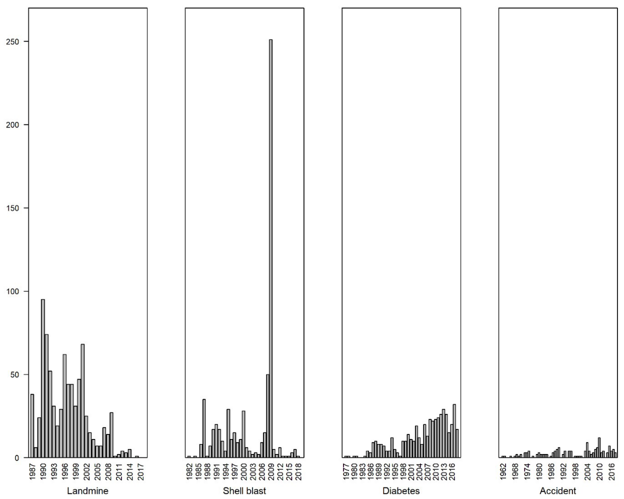

Figure 3: Trends showing changes in cause of amputation through time. Number of amputees (y-axis) is plotted against year of amputation (x-axis) for amputations caused by landmines, shell blasts, diabetes, and accidents.

Finally, when reviewing the financial data, it became clear the costs associated with provision of new prosthetic devices vastly outweighed the costs associated with repairing existing devices. This is important from a design perspective, as it highlights the need for modular prosthetics that can be easily disassembled, repaired, and reassembled quickly and easily (5).

Mechanical failure of prosthetic feet

Working with the JJCDR, we collected 122 prosthetic feet (Nov 2019 – July 2022) that were replaced by the JJCDR due to failure (5). The vast majority (105) were manufactured by the JJCDR, using either fibre-reinforced nylon coated rubber (n = 66, referred to as "string rubber" in the publication) or non-fibre-reinforced nylon (n = 34, referred to as "sheet rubber" in the publication). Five prosthetic feet were worn past the point of identification as string or sheet.

We investigated mechanical failure mechanisms in the 66 fibre-reinforced feet to better understand how the feet were being used, and why they were needing to be replaced. To properly understand how the feet fail requires an understanding of how they are constructed.

The prosthetic feet are the soft ankle cushion heel (SACH) design created by the ICRC. The SACH foot manufactured at the JJCDR consists of three main components: a hard, polypropylene (plastic) keel surrounded by natural rubber, with a nylon layer at the bottom. The keels, manufactured by the JJCDR, are all the same size, meaning the distal end of the keel is closer to the toes in the smaller feet, and relatively closer to the heel in the larger feet. The keel is an important component of the SACH foot, as it provides structural integrity, and allows the prosthetic foot to connect to the ankle component. The rubber acts as a damper and energy storage unit, making it easier for the amputee to walk, and making gait less jarring.

Unlike what would be predicted under the ISO 10328 standards for the design and testing of safe lower-limb prosthetics, we found little evidence of the prosthetic feet fracturing. We were unable to decisively determine if delamination between the keel and the rubber occurred without cutting into the feet, but it was clear from some feet that the keel was moving around freely within the rubber, meaning delamination had occurred.

When we discussed why the feet were replaced with people who worked at the JJCDR, the most common reason given was wear on the bottom of the feet. Essentially, the prosthetic foot would start to wear at the heel and distal end of the keel. When this happened, the keel would start to delaminate from the rubber and push through the bottom of the foot. The keel would then wear away as it rubbed the ground, lessening the structural integrity of the foot and eventually causing the foot to fracture, which could cause the prosthetic user to fall and become injured. Feet were therefore replaced when feet were worn, but before the keel pushed through the bottom of the foot.

Figure 4: The two type of feet manufactured by the JJCDR (top) and plantar surface of a prosthetic foot (bottom) with a grid.

To quantify how the feet were wearing, we developed a qualitative method derived from the study of tooth wear. Pictures of the soles of the feet were taken, and a 20 by 10 grid was placed on top of it (Figure 4). Each square was assigned a score from 0 to 9 (Table 2), with 0 implying the foot was newly manufactured and not yet used, and 9 implying the portion of the foot was completely missing (e.g., a big toe had broken off).

Table 2: Scoring system used by Ranson and colleagues to quantify prosthetic foot wear patterns.

Score	Description of wear
0	No wear (newly manufactured, not yet used)
1	No observable wear
2	First layer of nylon exposed
3	Second layer of nylon exposed
4	0%–33% of rubber under nylon exposed
5	34%–66% of rubber under nylon exposed
6	67%–99% of rubber under nylon exposed
7	100% of rubber under nylon exposed
8	Portions of rubber missing
9	Portions of foot completely missing

The average, standard deviation, and coefficient of variation were calculated for each square across the 66 feet (Figure 5). It was found that, as predicted by those working at the JJCDR, on average, the distal end of the keel and perimeter of the foot were more worn than other portions of the foot. These areas should be structurally reinforced to increase prosthetic foot longevity. The authors also hypothesized that the standard deviation and coefficient of variation may capture differences in behaviour and locomotor biomechanics between individuals, although this has yet to be tested.

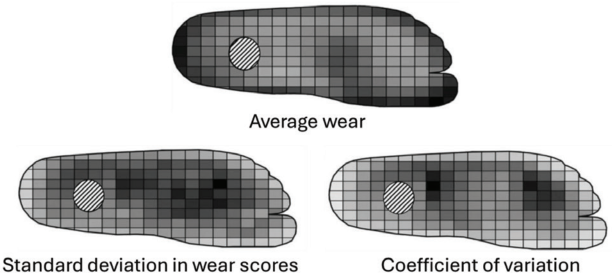

Figure 5: Average wear score (top) – darker areas indicate higher levels of wear. Variation in wear scores is depicted using the standard deviation and coefficient of variation (bottom)

This data helped create a biomechanical model for understanding how these prosthetic feet fail. When walking, the prosthetic user places the heel of their foot against the ground (i.e., the heel strike phase of locomotion). The amputee then shifts their centre of gravity over the prosthetic foot during the midstance phase, eventually lifting the heel of the prosthetic foot off the ground (heel off). When this occurs, the rigid portion of the foot, with the keel, remains fairly stable, but the distal end of the foot bends much like a foot bends around the metatarsophalangeal joint in an intact foot, putting bending moments and large pressures about the distal end of the keel. During toe off, this portion of the foot is rubbed against the ground, causing wear.

One of the big implications of this study is our understanding of how to design prosthetic feet for non-European countries. In countries like the United Kingdom, prosthetic feet must pass the ISO 10328 tests before being sold on the open market. These tests put foot prototypes through a series of mechanical tests (static and dynamic loads), and factors like deformation, delamination, and fracture and investigated to determine if the product is ready for market. Unfortunately, the ISO 10328 tests do not consider factors like foot wear, likely because prosthetic wear is not a factor that needs considering in the countries which sent representatives to help develop the ISO 10328 standards.

In Sri Lanka, there is a culture of wearing open-toed shoes, like sandals, and walking barefoot. This causes the prosthetic feet to wear faster than if they were worn with closed-toed shoes, making wear an important factor in prosthetic feet failing and needing to be replaced. Thus foot wear, which is not considered by the ISO 10328 tests, must be considered when designing prosthetic feet for countries like Sri Lanka (6).

Conclusion:

These are the first of many studies coming out of this research programme, examining how to create culturally relevant, sustainable prosthetics for low- or middle-income countries. While progress in research can be slow, it is our hope that this leads to the co-design and development of new prosthetic devices that help those with limb loss in Sri Lanka.

Acknowledgements

The authors would like to thank Jeya Ganeshamoorthy and members of the JJCDR for their continued support throughout this research. They would also like to thank coauthors of the two studies for their support in this research. Trips to Sri Lanka were funded in part by an NIHR PrOTeCT grant (Award ID 16/137/45) award to Prof Anthony Bull (Imperial College London) and Research England funding awarded to MAB through London South Bank University.

References

1. Berthaume, M. A., & Kramer, P. A. (2021). Anthroengineering: an independent interdisciplinary field. *Interface Focus*, *11*(5), 20200056. https://doi.org/10.1098/RSFS.2020.0056
2. Barth, C. A., Wladis, A., Blake, C., Bhandarkar, P., Aebischer Perone, S., & O'Sullivan, C. (2021). Retrospective observational study of characteristics of persons with amputations accessing International Committee of the Red Cross (ICRC) rehabilitation centres in five conflict and postconflict countries. *BMJ Open*, *11*(12), e049533. https://doi.org/10.1136/bmjopen-2021-049533
3. Amarasinghe, S., Balakumar, S., & Arasaratnam, V. (2015). Prevalence and risk factors of diabetes mellitus among adults in Jaffna District. *Ceylon Medical Journal*, *60*(3), 107. https://doi.org/10.4038/cmj.v60i3.8191
4. Katulanda, P., Constantine, G. R., Mahesh, J. G., Sheriff, R., Seneviratne, R. D. A., Wijeratne, S., Wijesuriya, M., McCarthy, M. I., Adler, A. I., & Matthews, D. R. (2008). Prevalence and projections of diabetes and pre-diabetes in adults in Sri Lanka—Sri Lanka Diabetes, Cardiovascular Study (SLDCS). *Diabetic Medicine*, *25*(9), 1062–1069. https://doi.org/10.1111/j.1464-5491.2008.02523.x
5. Berthaume, M., Barnes, S., Hettiaratchy, S., Clasper, J. C., Kumar, A., Sathiadas, G., & Ganeshamoorthy, J. (2023). Demographic, medical, and financial statistics from the Jaffna Jaipur Centre for Disability Rehabilitation (JJCDR) database, 1987-2018: a prosthetics, orthotics, and mobility clinic in northern Sri Lanka. *Journal of Global Health Reports*, *7*. https://doi.org/10.29392/001c.88105
6. Ranson, G., Morley, M., Corsial, N., Sathiadas, G., Ganeshamoorthy, J., & Berthaume, M. (2023). The mechanical failure of locally manufactured prosthetic feet from the Jaffna Jaipur Centre for Disability Rehabilitation (JJCDR), Sri Lanka. *Prosthetics & Orthotics International*. https://doi.org/10.1097/PXR.0000000000000242