Print your own body parts

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John Nhial was barely a teenager when he was grabbed by a Sudanese guerrilla army and forced to become a child soldier. He was made to endure weeks of walking with so little food and water that some of his fellow captives died. Four more were killed one night in a wild-animal attack. Then the boys were given military training that involved "running up to ten kilometres in the heat and hiding" before being given guns and sent to fight "the Arabs".

He spent four years fighting, bombed from the skies and blasting away on guns almost too heavy to hold against an enemy sometimes less than a kilometre away. "I think, 'If I killed that one it's a human being like me,' but you are forced," he said. One day the inevitable happened: Nhial (not his real name) was injured, treading on a mine while on early-morning patrol with two other soldiers in a patch of Upper Nile state surrounded by their enemies.

"I stepped on it and it exploded," he recalled. "It threw me up and down again – and then I was looking around for my foot. I tried to look for my leg and found that there was no foot. When I saw there's no foot I feel shock. I was really confused. If I was not with the two others I would kill myself because I thought there was no use for me now, so I decide to die."

His comrades carried him back to base camp, but there was hardly any medical care there. It took 25 days before he received proper treatment, during which time he developed tetanus on one side of his body. Finally Nhial was put on a flight to the Kenyan border, his life saved when he was handed over to a Red Cross health team. Now, a decade later, he lives in a Juba refugee camp, having suffered further troubles in the whirlwind of conflict that has engulfed the struggling new nation of South Sudan.

During one outbreak of violence he was rounded up with other Nuer – the country's second-largest ethnic group – and taken to an army barracks. His life was only spared when he was dismissed as "useless" because of his disability. Today he plays wheelchair basketball for his country, although he relies on a prosthetic lower leg to struggle his way round the muddy, sprawling camp that entails long walks to reach the most basic services. It can be difficult to get to training. But at least his hands are free to carry things such as food and water, unlike those on crutches.

Mary Lam (not her real name), 34, who caught polio as a child and today works as a restaurant supervisor in the capital, Juba, explained what it was like growing up reliant on bamboo sticks to haul herself around with a bad leg. She would get up much earlier than her siblings, since it took an hour to get to the classroom and they could rush there much quicker. "It was hard to go with my exercise book to school unless I tie it on my back like a baby," she said. And it limited her use of her arms too. "When two hands are using the bamboos you are not able to do domestic work in the house."

Stories of lives devastated by conflict or disease are all too common across low-income countries. Lack of an arm or leg can be tough anywhere, but for people in poorer parts of the planet, with so much less support and more rickety infrastructure, it is especially challenging. Some are victims of conflict, others were born with congenital conditions. Many more are injured on roads, the casualty toll soaring in low-income nations even as it plummets in wealthier ones. Every minute, 20 people are seriously injured worldwide in road crashes. In Kenya, half the patients on surgical wards have road injuries.

The World Health Organization (WHO) estimates there are about 30 million people like Nhial and Lam who require prosthetic limbs, braces or other mobility devices. These can be simple to make and inexpensive. As one veteran prosthetist told me, his specialism is among the most instantly gratifying areas of medicine. "A patient comes in on Monday on crutches that leave them unable to carry

anything. By Wednesday they are walking on a new leg and on Friday they leave with their life transformed."

Yet more than eight in ten of those people needing mobility devices do not have them. They take a lot of work and expertise to produce and fit, and the WHO says there is a shortage of 40,000 trained prosthetists in poorer countries. There is also the time and cost to patients, who may have to travel long distances for treatment that can take five days – to assess need, produce a prosthesis and fit it to the residual limb. The result is that unglamorous items such as braces and artificial limbs are among the most-needed devices to assist lives. Yet, as in so many other areas, technology may be hurtling to the rescue, this time in the shape of 3-D printing.

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Slowly but surely, 3-D printing – otherwise known as additive manufacturing – has been revolutionising aspects of medicine since the start of the century, just as it has impacted on so many other industries, from cars to clothing. Perhaps this is not surprising, given that its key benefit is to enable rapid and cost-efficient creation of bespoke products. There are, after all, few commercial products that need to suit a wider variety of shapes and sizes than medical devices made for human beings.

Experts have developed 3-D-printed skin for burn victims, airway splints for infants, facial reconstruction parts for cancer patients, orthopaedic implants for pensioners. The fast-developing technology has churned out more than 60 million customised hearing-aid shells and ear moulds, while it is daily producing thousands of dental crowns and bridges from digital scans of teeth, disrupting the traditional wax modelling methods used for centuries. Jaw surgeries and knee replacement operations are also routinely carried out using surgical guides printed on the machines.

So it is unsurprising the technology began to stir interest in the field of prosthetics – even if sometimes by accident. Ivan Owen is an American artist who likes to make "weird, nerdy gadgets" for use in puppetry and budget horror movies. In 2011 he created a simple metal mechanical hand for a steampunk convention, the spiky fingers pulled by loops through his own. He posted a video that – as is the way in our interconnected world – was seen by a carpenter in South Africa who had just lost four fingers in a circular saw accident. They began discussing plans for a prototype prosthetic hand, and soon that came to the attention of the mother of a five-year-old boy called Liam, born without fingers on his right hand.

She wanted a tiny version of their hand. But Owen realised the child would rapidly grow out of anything they made, so he looked at the idea of using 3-D printing. "If we could develop a design that was printable, it would be possible to rescale and reprint that design as Liam grew, essentially making it possible for his device to grow with him," he said. So the artist persuaded a printer manufacturer to donate two machines and developed what has been claimed to be the first 3-D-printed mechanical hand. And crucially, rather than patent this work, Owen published the files as open source for anybody to access, allowing others to collaborate, to use and improve the designs.

This has grown into Enabling the Future, a community with 7,000 members in dozens of countries and access to 2,000 printers, who help make arms and hands for those in need. One school student in California even printed a new hand for a local teacher. Often they are aimed at children, since many dislike the weight, look and hassle of modern prosthetics, which can involve inserting the arm in a silicone sleeve and using straps across the back to hold the device in place. These body-powered hands cost thousands of pounds, yet must be replaced every couple of years as a child grows. The 3-D-printed versions cost about £40, come in any colour and look like a cheery toy, so are often more appealing despite being less sophisticated.

Jorge Zuniga, a research scientist in the Biomechanics Research Building at the University of Nebraska in Omaha, heard about this project on his car radio. He was only half-listening, but arriving home he started playing baseball with his four-year-old son and observed how important the grabbing

of an object was to his own child's development. He spent the next month carefully building a prosthetic model that mimicked the human hand, only for his work to be dismissed instantly by his son. "He told me children wanted a hand that looked like a robot."

From this conversation and the open-source designs available emerged Cyborg Beast, a project being heavily backed by his department to develop futuristic-looking, low-cost prosthetic hands. "You can do anything with 3-D printing," said Zuniga, who now heads a seven-strong team. "We believe it will revolutionise the prosthetics field. It will lower the costs worldwide and gives engineers, patients and doctors the chance to modify prosthetic hands as they want. And they can be any colour."

When I told Zuniga slightly hesitantly that his design looked like a toy, he was delighted. "That's great – we want children to see it as a toy," he said. "This is a transitional device. Many children do not like prosthetics, however good they are these days, because they might have a hook for a hand and the harness needs help to put on, which children dislike. So this is to bridge the gap, helping them get used to the idea as they grow up.

"We have even had a child missing a shoulder. So we developed a device that weighs the same as the missing arm. This meant he not only got a new arm that helped daily life but it also improved his posture and balance, therefore was much better for his spine. This sort of thing can be done much easier with 3-D technology. But of course the difference between a toy and a prosthetic arm is that you need professional involvement to enhance use of the devices and ensure they are fitting properly."

It is remarkable that people who do not even own a printer can obtain a functional child's hand for the price of a theatre ticket within 24 hours. Zuniga says at least 500 Cyborg Beasts are in use worldwide, and the design has been downloaded almost 50,000 times. He has taken it to his native Chile, where he runs a paediatric orthopaedic 3-D-printing laboratory, and has had recent requests for the plans from Nigeria. "My concern at this stage is that some of the materials can melt in higher temperatures. It is not working well there yet, but this sort of prosthetic has huge potential to be used with better materials in the developing world. We are still in the infancy stage at this moment."

Another place that has experimented with this technology is in the cruel, forgotten war cursing the Nuba mountains of Sudan, where an amazing American named Tom Catena has been working as the only permanent doctor for half a million people around his Mother of Mercy Hospital. Fuelled by his religious faith, for almost a decade this brave medic has ignored bombings, lack of electricity and water shortages to do everything from delivering babies to amputating limbs.

"It's demoralising for us to amputate an arm knowing that there is no good solution," Catena told me by email. "We have many arm amputees – both above and below the elbow as a result of the war here and general lack of medical care. This in an agricultural society, where nearly everyone is a subsistence farmer. If one is missing an arm, he is not very functional in this society. They become totally dependent on the family and they have a difficult time getting married (also very important in this society)."

The idea of using 3-D printing to help arose when Mick Ebeling, an American film producer and philanthropist, learned about this work at the same time as he was hearing about the emerging work on low-cost prosthetic hands. Searching for information on Catena, Ebeling read about one of his patients: Daniel Omar, a 12-year-old boy who had wrapped his arms around a tree to protect himself during an aerial attack. His face and body were protected when a bomb exploded nearby – but both the boy's arms were blown off.

Ebeling travelled out with printers and, working with hospital staff, fitted about a dozen people with new arms. "Unfortunately, as time went on, none of the amputees were using the prostheses as they felt they were too cumbersome," said Catena. The doctor concluded that "the 3-D model was good, fairly easy to make and inexpensive… although it hasn't worked out so well here, perhaps with some tweaking, the 3-D printers can be of great use for arm amputees."

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Yet for all the agonies and difficulties associated with arm loss, the bigger problem in low-income countries is when lower limb disability leads to loss of mobility. Wheelchairs are expensive and can be difficult to use when roads are pot-holed, streets are muddy and pavements are non-existent. Without a prosthetic limb, people struggle to fetch water, to prepare food and, above all, to work. This throws them back on their families and communities, intensifying any hardship and poverty.

One group that has spent almost three decades trying to tackle such issues is Exceed, a British charity set up by diplomats and academics at the request of Cambodia's government to help thousands of landmine survivors. It works in five Asian countries, training people at schools of prosthetics and orthotics. In Cambodia, there are still almost 9,000 landmine survivors in need of artificial limbs, although these days traffic accidents are a more likely cause of disability, while children also need braces for a range of common conditions such as spina bifida, cerebral palsy and polio.

"If you wear a prosthesis you are disabled for about ten minutes in the morning while you have a shower, then you put your leg on and go to work. If you do not have one, then your hands are out of use with crutches so you can't even take drinks to the table," said Carson Harte, a 59-year-old prosthetist and chief executive of Exceed. "Without a prosthesis there are no expectations. You just go back and rely on the goodwill of your family."

It is not really cash shortages that deny people these devices, since simplified forms cost little and generic Chinese models are improving fast. The components can cost just £30. The big hurdle is the lack of trained technicians to fit the artificial limbs. In the Philippines, there are estimated to be 2 million people needing prosthetics or orthotics. Yet there are only nine fully trained experts, each able to assist at most 400 patients a year with the time-consuming process of creating and fitting a customised limb, although more are being trained on a new four-year course.

Traditionally, a prosthetist would wrap a stump with plaster of Paris bandages to make a reverse mould and let it dry, then fill it with more plaster that must harden. From this a socket can be forged that fits, with more modifications for precision, to the bone on the stump. Great care must be taken to avoid nerves and tender areas that are not tolerant of pressure. The key for the technician is to understand the pathology of a stump, which differs for each person. This is a cumbersome process that can take a week, especially with gait training for new patients that lasts three days. It can also be messy work, mixing up and moulding the plaster, while a prosthetist visiting a rural area must cart around 20-kilo packs of plaster. But with a 3-D scanner, a digital image can be made in half an hour and sent by email, and there is no mess.

Exceed has begun a seven-month trial of 3-D-printed devices in Cambodia with Nia Technologies, an innovative Canadian not-for-profit organisation. "This technology has the potential to increase the productivity of every technician," said Harte. "It is not about printing off legs, nor does it replace the skills of a well-trained professional, but it has potential to produce a better, faster, more easily repeatable way of doing one key part of the chain. There are no magic bullets, but this may be an important incremental change.

"The key to success so far has been cross-fertilisation: putting engineers and prosthetist orthotists together. Engineers make broad assumptions that are not always right, prosthetist orthotists do not always know what engineers can do. Together we have made more advances in a few months than have been achieved in years, sorting our real problems in real time through collaboration."

Nia is also trialling its 3-D PrintAbility technology in Tanzania and Uganda, where there are only 12 prosthetists to serve a population of about 40 million people – and at the time of writing all six state clinics have run out of materials. Doctors there often deal with children who have lost limbs after falling in open cooking fires, while other youngsters need braces after suffering post-injection paralysis caused by badly administered jabs that damage nerves.

In Uganda their team is working with CoRSU hospital in Kisubi, a specialist rehabilitation centre for children with disabilities. Orthopaedic technician Moses Kaweesa said they found the technology lighter and faster to use, as well as easier for people in remote rural areas. "It used to take five days to have a limb manufactured, with lots of hanging around for the patient. Now it is barely two days, so they spend much less time in the hospital. There is also less waste of material, so for a country like ours this can help so much by cutting down the costs."

The first person to test out a 3-D-printed mobility device was a four-year-old girl who until then had dragged herself across floors and had to be carried around by her family. "When she was born her leg was missing the right foot," said her older brother. "It was very difficult for her to walk, to play with other children. She can be lonely. But when she was given a leg she was able to run with others, play with others."

Matt Ratto, Nia's chief science officer, who led the project's development, admitted that it was only when he saw the serious-looking child in her red dress start to walk that he realised his technology actually worked. But, like Harte, he urges caution. "We are surrounded by the hype of 3-D printing with crazy, ridiculous claims being made," he said. "We must be cautious. A lot of these technologies fail not for engineering reasons but because they are not designed for the developing world. You can't just smash in these new technologies.

"A lot of what we are doing is social innovation. People think you are threatening to replace prosthetists, which is a problem since they can be hesitant to embrace it just like in the developing world. We are trying to develop a bridge between the North and South but we have to work with the people on the ground to build their capacity. They are the experts – and they are deeply interested in doing whatever they can to get the children walking."

Ratto's aim is to use their technology to fit 8,000 people with 3-D-printed mobility devices within five years, across some 20 sites in low-income countries. "My sense if we get this right is that the growth can be exponential. If we iron out the kinks and work out the best way to help clinicians I think we will see something of a hockey-stick curve on the graph. But we must not get it wrong, move too fast nor over-hype the potential."

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One person who shares Ratto's belief in this technology is Claudine Humure, a 24-year-old Rwandan with big ambitions whom I met on a chilly November day at Wheaton College in Norton, Massachusetts. She lost her parents in the genocide, and then at the age of 12, while living in an orphanage, developed a dreadful pain in her right leg that turned out to be bone cancer. "I thought I was going to die when the doctors told me, because that was all I knew about cancer. I thought that was my fate," she said. "Then they said they had to amputate my leg the next day. I was crying so hard. I hated the doctors who were telling me the news since everything was happening so fast."

After the operation, Humure was flown by a US charity to Boston for further treatment, including chemotherapy and surgery to prepare the leg for a prosthetic. She spent almost a year recovering before returning to Rwanda with an artificial leg. But when it broke, she struggled to find a new one and saw the deficiencies of what was available in low-income countries. "I had seen what was possible. A good prosthesis fits well and feels comfortable. You can do anything with it, you feel normal."

Now this affable woman is back in the US, studying biology and business at a prestigious university. She wrote her high-school project on the design of prosthetic limbs and has volunteered at Spaulding Rehabilitation Hospital in Boston, where she spent time with injured victims of the 2013 marathon bombing. "They were very new to the idea of missing a limb, so it was very traumatic for them. You could see they were terrified since it was so sudden. I hope I was a positive influence, an inspiration not to give up hope."

Most significantly, Humure won a biomechatronics research internship at Massachusetts Institute of Technology's Media Lab. Here she met Hugh Herr,

a pioneering figure in prosthetics. He lost both legs after being trapped for three nights in a freezing blizzard while climbing, then designed titanium-tipped artificial feet to let him return to his beloved mountains. She also came across 3-D printing for the first time. "This was life-changing," she said. "My eyes opened. I saw all this cutting-edge research when we had such bad prostheses in Rwanda. I looked at my own prosthetic leg and started thinking."

Now she dreams of opening specialist clinics, first in Rwanda, then across the rest of Africa. And she is designing a socket for prosthetic limbs to be used by people who have had leg amputations above the knee, aimed at low-income nations. "I am making the socket lighter, easier to use and cheaper to manufacture. But what makes the design special is that the user can adjust it to make it more comfortable. In developing countries, people just do not have the time to keep travelling to clinics."

Humure believes such advances can change the world for millions of people like her. "You can have a disability and still be successful. I know I have been lucky in many ways because I met the right people, but I am a positive person and this is the attitude I want to instil in other amputees and people with disabilities, especially the millions of us in developing countries. A good prosthesis does not just help your mobility. It gives you confidence and can change your life. Above all, you forget you are an amputee."

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