Aadeel Akhtar *CEO and founder, Psyonic, Champaign, IL*

Editor: Nirupam Roy

3D-PRINTING HANDS THAT FEEL

Amputation is always a devastating experience. In addition to the loss of function or sensation, the lowered body image leaves deeper emotional impacts on the victims and their loved ones. For various reasons, traumatic injuries and vascular diseases like diabetes [4] are common for particularly upper limb loss. According to the World Health Organization, there are more than 10 million people with hand amputations worldwide, 80% of whom are in developing countries. Unfortunately, only less than 3% have access to affordable prostheses [1-3]. Over the past few decades, there have been major advances in commercial prosthetic hands, enabling control over six degrees of freedom (flexion/extension in all five digits and thumb rotation). However, there is still a great number of needs from users of prosthetic hands. These include:

1) A hand that can conform to and quickly grasp a variety of objects: The most commonly used hand prosthesis is a shoulder-controlled mechanical hook, technology that has changed little since the 1800s. Multiarticulated bionic hands can grasp a larger variety of objects in a more natural and intuitive way.

2) A hand that is robust to impacts: One of the most common problems with multiarticulated prosthetics is their fragility. Users typically report damage, which often limits the hand functionally (such as a finger breaking) within weeks to months of first receiving their hand due to impacts that

Illustration, istockphoto.com

occur during activities of daily living. For example, one patient reported to us that she broke five multiarticulated hands within two years of wearing it. Additionally, users must wait long periods without a prosthesis while the hand is away for repairs.

3) A hand that can manipulate delicate objects and gives touch feedback: Prosthesis users often do not have confidence grabbing fragile objects, as prostheses often have high grip forces and users have a limited ability to regulate the force they exert. This limitation prevents users from performing important daily tasks (for instance, holding a plastic cup full of water). Restoring this sensation, even in a limited form (i.e., vibration motor) not only improves the usability of the prosthetic device but also improves device embodiment.

4) A hand that is waterproof to enable easy washing and cleaning: This feature is important to users to allow for easy cleaning and the performance of tasks that require interaction with water, such as washing dishes or using a garden hose. Other hands have addressed this issue by using silicone gloves worn over the prosthesis, which are insufficient due to frequent ripping and tearing, as well as the increased load placed on the fingers, which reduces hand strength, speed and energy efficiency.

5) An intuitive customization/calibration interface for both clinicians and end-users: A graphical user interface of some form must be provided to access the many features and settings of a multiarticulated bionic hand. This application is particularly important to clinicians to tune control parameters to individual users. It also allows users to easily switch between functional modes, preview grips, and to download and install updates to the hand firmware.

6) A hand that is reimbursable by insurance: Many users who desire a multiarticulated prosthetic hand are unable to obtain one due to the high cost and rejection rates from insurance companies. Ensuring our hand is easily reimbursable by insurance means that more customers that want to use our hand can obtain it.

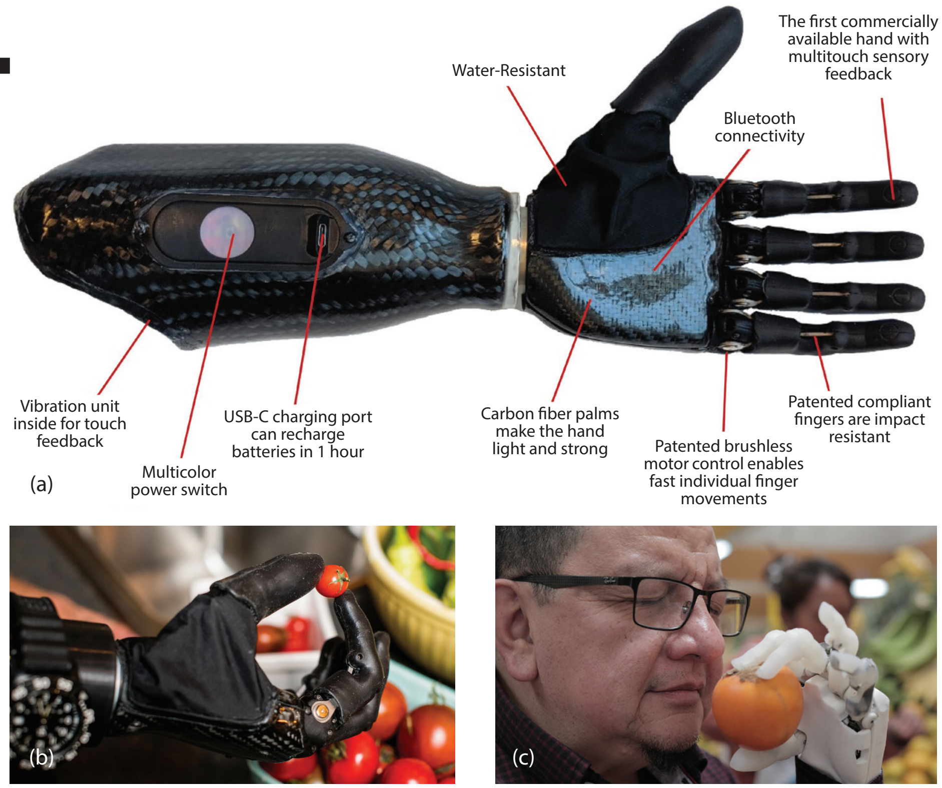


FIGURE 1. (a, b) One of the latest models of the Ability Hand developed by Psyonic. (c) An early prototype of the Ability Hand.

THE ABILITY HAND

In 2016, we started a project at the University of Illinois Urbana Champaign (UIUC) to develop prosthetic hands that are affordable, yet meet the requirements mentioned above. Later, Psyonic, a prosthetic device company formed by the alumni of this research group, advanced the idea to create the *Ability Hand* — a compliant, robust, sensorized prosthetic hand to be used by people with upper limb amputations (Fig. 1).

Psyonic is the first company to develop the commercially available bionic hand capable of multitouch feedback. The Ability Hand is multiarticulated, meaning all five digits flex/extend and the thumb rotates both electrically and manually. The compliant fingers made of a semi-flexible polyurethane and nylon bone enveloped in silicone allow the hand to withstand blunt force impacts to the fingers, while the carbon fiber palm makes it lightweight (460 g). The Ability Hand uses brushless DC motors with field-oriented control and the fingers can close 90 degrees in 200 ms. Moreover, the bionic hand is waterproof and can sense pressure from the fingertips, finger pads, and lateral edges of the index finger, pinky finger, and thumb, which is mapped to a vibration motor. It uses a standard electronic quick disconnect and integrates with third-party commercially available muscle control (i.e., myoelectric) systems. Smartphone apps are available to configure the hand over Bluetooth as well as make firmware updates. Most importantly, due to its low cost, it is covered by Medicare in the United States, which serves as the gold standard for other insurers including VA, Workers' Compensation, and managed care plans.

In this article, we present the fundamental design of this prosthetic hand and discuss the key technical contributions that make it possible to create an affordable bionic hand without compromising on the functionality. This article is a brief overview of the system; elaborate design details can be found in our publications cited in this article.

Fundamental Design of the Bionic Hand Hardware

The Ability Hand consists of six brushless DC motors with planetary gearboxes and encoders. Flexion/extension of each of the digits is accomplished through a non-backdrivable worm gear, which allows for energy savings when the finger reaches a specific position. However, the thumb rotator motor is backdrivable so that the user may position it either manually or electrically. The printed circuit board (PCB) in the hand consists of six STM32 F3 microcontrollers used to control gate drivers for each of the motors, and grips are coordinated through a central nrf52 Bluetooth low energy microcontroller. The pinky, index, and thumb digits contain flexible PCBs with four MPL115A1 pressure sensors that communicate to the STM32 microcontrollers over UART. The hand PCB communicates with the USB-C charging PCB in the socket over I2C. Torque, velocity, and position of all six motors as well as sensory feedback information from all pressure sensors in all digits can be streamed over I2C to an external receiver. Torque, velocity and position commands can also be sent to each of the motors using this protocol. The hand is powered by two 3.7V 2200mAh Lithium Polymer cells in series. On normal usage, the batteries should last a full day of operation, with charging done overnight. Figure 2 shows the general layout for the open-source prototype of the Ability Hand.

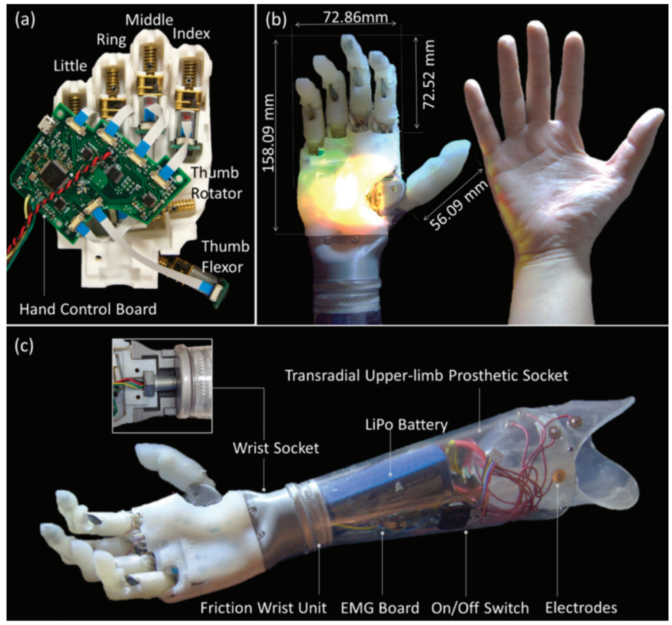


FIGURE 2. Open-source prototype of the Ability Hand, showing: (a) Six DC motors assembled in a 3D-printed dorsal palm. (b) The hand has 50th percentile female hand anthropometry. (c) The fully assembled hand.

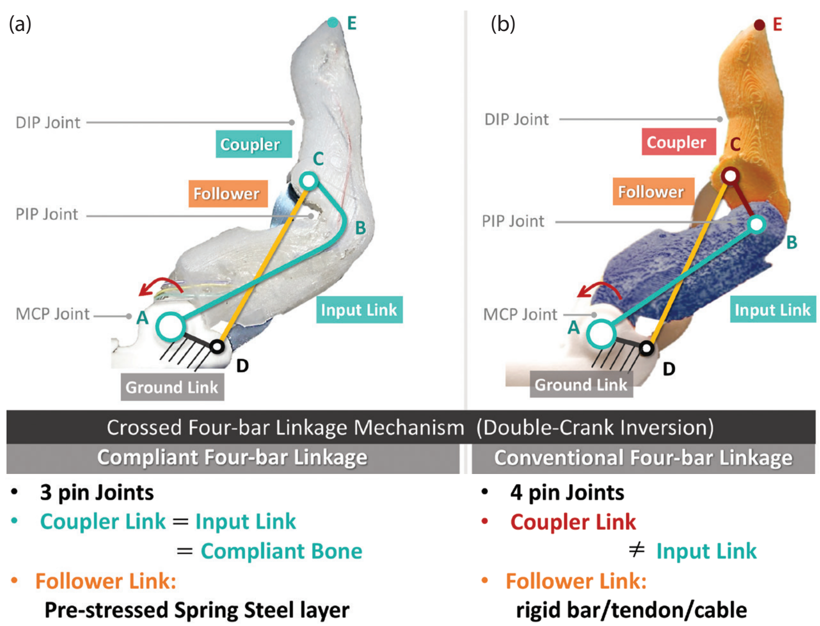


FIGURE 3. (a) Psyonic's compliant four-bar linkage mechanism. (b) Conventional rigid four-bar linkage mechanism. [5]

Impact-Resistant Mechanical Design

Repeated mechanical failure due to accidental impact is one of the main reasons why people with upper-limb amputations abandon commercially available prosthetic hands. To address this problem, we designed a compliant four-bar linkage mechanism that makes the fingers of a prosthetic hand more impact resistant [5]. Results from free-end and fixed-end impact tests show that, compared to those made with a conventional four-bar linkage, fingers made with our design absorb up to 11% more energy on impact with no mechanical failure.

Surveys have shown that people with upper limb amputations place high priority on the need for their prostheses to be impact-resistant [6]. In fact, a study by Biddiss, et al. [7] reported 91% of surveyed people with upper limb amputations who rejected their prostheses stated a lack of impact resistance as the primary reason for rejection, despite having advanced functions like myoelectric control and multi-articulated fingers in their prosthetic hand. The problem of mechanical failure due to a lack of impact resistance is even more apparent with workers in jobs that require intense manual labor, who frequently forgo the use of advanced myoelectric prostheses because they are more susceptible to becoming damaged [8]. Despite the reported need for prosthetic hands that are impact-resistant, few studies have focused on this measure of performance. In the past five years, researchers have worked to increase impact resistance in robotic hands by introducing compliance, such as in the iHY hand [9] and the PISA/IIT soft hand [10]. The impact resistance of these hands was evaluated through qualitative methods, such as striking the fingers with a blunt instrument and showing that the hand still functions properly. The DLR hand [11] was one of the few in which impact resistance was evaluated quantitatively by measuring

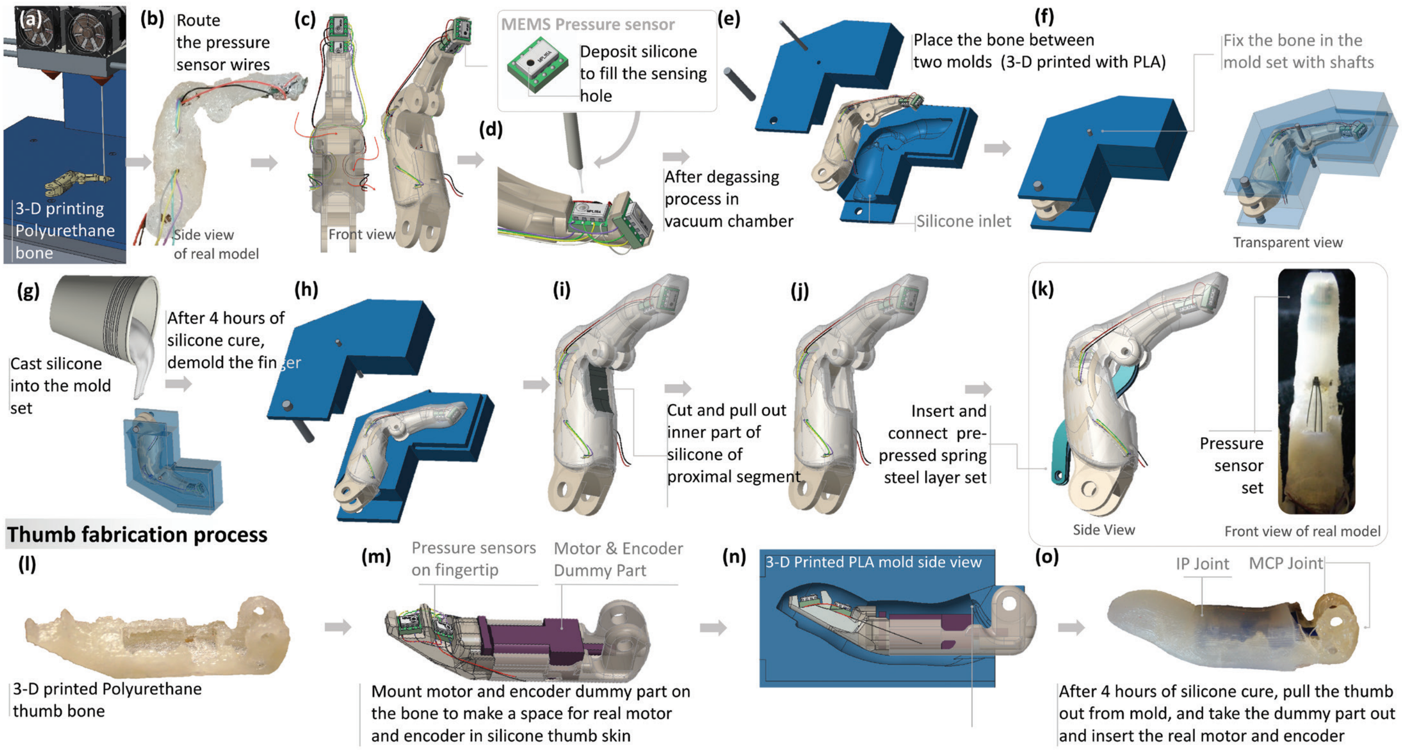


FIGURE 4. The fabrication process of the fingers and thumb with embedded barometric pressure sensors in the open-source prototype of the Ability Hand. The barometric pressure sensor (c) is embedded into a bone structure (top middle) and overmolded with silicone in the final finger (d).

the energy absorbed by a finger upon impact on the dorsal side of the finger.

We designed a compliant four-bar linkage mechanism that makes the fingers of a prosthetic hand more impact-resistant. Four-bar linkages are widely used in robotic fingers (e.g., TBM, Remedi, SSSA-MyHand) [12-13]. Most commercial prosthetic hands use fingers with four-bar linkages (e.g. Vincent, iLimb, Bebionic) [14]. Our design replaces both the rigid input and coupler links with a monolithic compliant bone and replaces the follower link with spring steel. This design behaves like a conventional four-bar linkage but adds lateral compliance and eliminates a pin joint, which is a main site of failure on impact. Fig. 3 shows the overall design of the Ability Hand's compliant finger.

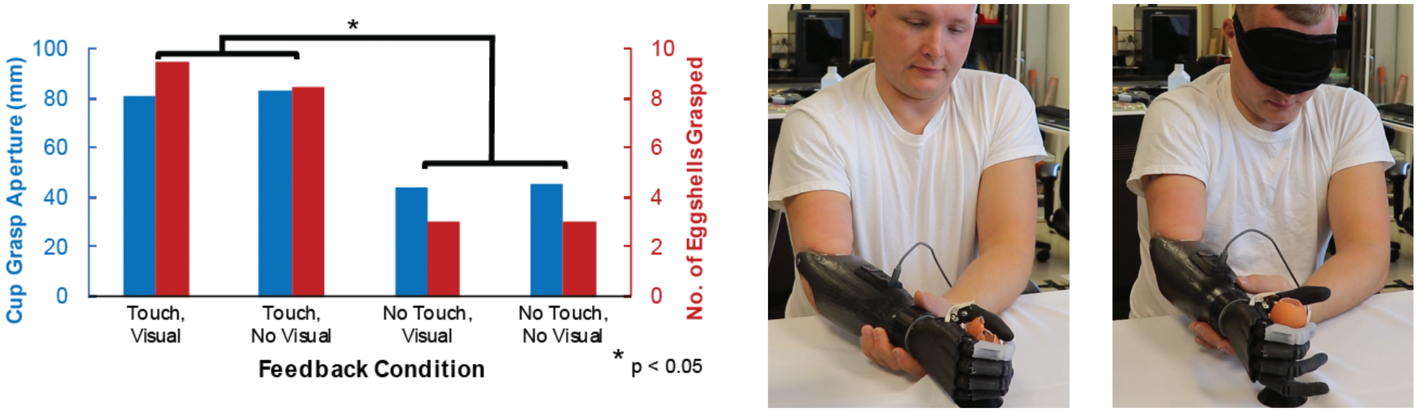
Impact tests showed that our compliant finger design absorbed at least 10x more energy on impact when compared to fingers using a conventional rigid four-bar linkage. There was no mechanical failure upon impact from a 5.99 kg weight with a maximum impact velocity of 4.15 m/s on the volar, dorsal, or lateral aspects of the finger. In addition, we characterized the compliance of our finger through static load tests. An individual finger can hold up to 35 lbs when flexed, 40 lbs when extended, and a hand power grasp can hold 50 lbs.

Sensory Feedback

Poor manipulability due to the lack of sensory feedback is a leading cause of prosthesis abandonment [15-16]. The lack of sensory feedback forces prosthesis users to rely on visual feedback alone in manipulating objects, and often leads to abandonment of the prosthesis in favor of the user's unimpaired arm. In 2005, US Army Sgt. Garrett Anderson lost his right arm below his elbow due to a roadside bomb in Iraq. He received a muscle-powered (myoelectric) prosthetic hand. In his own words: *"After receiving my first myoelectric hand, I went to shake my grandmother's hand and ended up crushing it because I couldn't easily control how much force was being applied by my prosthetic."* This underscores a serious issue with the lack of sensory feedback in prosthetic limbs. There is a critical need to enable people with upper limb amputations to be able to receive sensory feedback from their environment.

Recent efforts by SynTouch have evaluated the usefulness of contact reflexes in improving myoelectric control of devices [17]. They do this by using a sensor (Numatac) that is priced at >$1000 to detect pressure, vibration, and temperature in the fingertips of the hand. When the finger contacts an object, the speed of the finger movement slows down significantly to allow the user to manipulate the object without crushing it. We have used this same technique with low-cost barometric pressure sensors. The idea of using barometric pressure sensors coupled with silicone to be used for touch sensing was developed and open-sourced by the group of Robert Howe at Harvard University [18]. Each pressure sensor can be built for less than $5 and can be easily integrated in the hands.

The Ability Hand provides sensory feedback to users by repurposing low-cost barometric pressure sensors embedded in its compliant finger design. The pinky, index, and thumb digits detect pressure using four MPL115A1 barometric pressure sensors (Freescale, Austin, TX). Using the low-cost, open-source method described by Tenzer,



(a) (b) (c)

FIGURE 5. (a) Results from cup and eggshell grasping tests. (b) Cracking of an eggshell when not receiving touch feedback while seeing the eggshell. (c) Successfully grasping the eggshell when receiving touch feedback while blindfolded. [20]

et al. [18], we cast the sensors in silicone (Dragon Skin 20, Smooth-On, Macungie, PA) to turn them into highly sensitive touch sensors when depressing the silicone. Our original design used rigid printed circuit boards (PCB) with wires running down the polyurethane bone (Fig. 4).

We placed the sensors over common areas of contact when making power and lateral grasps (fingertip, finger pad, and two on the lateral side of the finger). The sensors communicate over SPI to an STM8 microcontroller, which processes the data and sends it over UART to an STM32 microcontroller on the hand PCB. The pressure readings from each sensor are scaled to a value between 0 and 1, and we detect contact when the pressure value exceeds a threshold of 0.2. If contact is detected in any of the six pressure sensors, a *contact reflex* takes place, in which the speed of the hand is reduced to 30% of its current speed to provide the user with finer control in manipulating the contacted object without damaging it [19]. The sensor providing the highest pressure value is mapped to a vibration motor, whose amplitude changes with the pressure applied.

We evaluated the sensorimotor capabilities of the Ability Hand on subjects with below elbow amputations. Using sensory feedback with contact reflexes, there were statistically significant performance improvements when grasping a plastic cup and hollowed eggs (eggshells) [19-20]. Prosthetic hand users were given four feedback conditions in which both

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touch feedback and a blindfold were either on or off. Results are shown in Fig. 5. Users were able to grasp the cup without crushing it when given touch feedback, having a statistically significantly greater grasp aperture even blindfolded. They were also able to grasp statistically significantly more eggshells without cracking them when given touch feedback, again, even blindfolded.

Fabrication

Fabrication of the Ability Hand's open-source prototype design, as shown in Fig. 4, consists of two parts: building a monolithic bone structure (Figs. 4a-4d) and molding a silicone skin (Figs. 4e-4j). The monolithic bone is 3D-printed (M2, Makergear) using a flexible thermoplastic polyurethane filament (Cheetah, NinjaTek) and nylon (Alloy 910, taulman3D). MEMS barometric pressure sensors (MPL115A1, Freescale, Inc.) are embedded in the distal fingertip of the bone, used to detect contact forces perpendicular to the fingertip surface [16]. To detect contact forces, the sensing hole of the pressure sensor is filled with silicone (Dragon Skin 20, Smooth-On, Inc.). Next, the bone with pressure sensors is inserted between two 3D-printed molds (Fig. 4e). After cutting a hole in the silicone skin (Fig. 4i), the spring steel is connected to joint C (Fig. 3a) and the ground joint (joint D, Fig. 3a) of the dorsal palm (Figs. 4j-4k). Figs. 4l-4o show how the thumb is fabricated. The thumb bone is constructed of the same polyurethane material as the fingers. The interphalangeal joint of the thumb is set to 20° as in the distal interphalangeal joints of the other four fingers. The palm is 3D-printed in two pieces (dorsal and volar) using polylactic acid (PLA) filament. The volar palm is embedded in silicone (EcoFlex 30, Smooth-On, Inc.) and snap-fits on to the dorsal palm. ■

Aadeel Akhtar received his PhD in Neuroscience and MS in Electrical & Computer Engineering from the University of Illinois at Urbana-Champaign in 2016. Akhtar received his BS in Biology in 2007 and MS in Computer Science in 2008 at Loyola University Chicago. In 2016, he won the Illinois Innovation Prize. His research is on motor control and sensory feedback for upper limb prostheses, and he has collaborations with the Bretl Research Group at Illinois, the Center for Bionic Medicine at the Shirley Ryan AbilityLab, the John Rogers Research Group at Northwestern University, and the Range of Motion Project in Guatemala and Ecuador.

Q&A

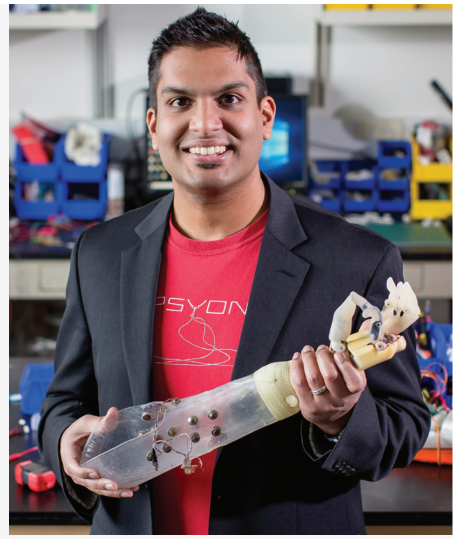
Nirupam Roy interviewed Aadeel Akhtar; following is an excerpt of the interview.

Q: What inspired you to build Psyonic?

The idea of Psyonic started when I was a child. My parents are originally from Pakistan, but I was born in the States, and I was visiting [Pakistan] when I was seven years old. There I met someone with a limb difference. She was my age, living in poverty on the streets of Karachi, and missing her right leg and using a tree branch as a crunch begging for money. It was that event that inspired me to want to go into this field of prosthetics and making them affordable and accessible for everyone around the world.

Q: How did your early life and education help you in this endeavor?

I grew up in the suburbs of Chicago. I went to Loyola University, Chicago, where I received my undergraduate degree in biology. I was pre-med at Loyola, and it was my sophomore year of undergraduate when I took my first computer science class. I thoroughly enjoyed this subject. I realized that if I became just a straight-up MD, I wouldn't get to do any of the cool stuff that I learned in my computer science classes. I wanted to figure out a way to combine those two passions. Right down the street from Loyola and downtown Chicago, there's a hospital. It's now called the Shirley Ryan AbilityLab. It used to be called the Rehabilitation Institute of Chicago and they have been the number one rehabilitation hospital in the United States for the last 30 years. About 2007, they made some breakthroughs in mind-controlled bionic limbs. I thought to myself, this is exactly what I want to do. This is the perfect combination of engineering and clinical medicine rehabilitation. The big problem was that all the prosthetics that they were building and using cost hundreds of thousands of dollars. It turns out that 80% of the world's amputees are in developing nations, and less than 3% have access to affordable prosthetics.



Q: What is the cost of other prosthetic hands?

It can be anywhere between $50,000 to $100,000 dollars.

Q: What is the difference in functionality between a higher- and a lower-end product?

Well, you can get a hook with a socket that is molded to your residual limb for around $3,000. The highest end would be closer to $100,000, and it will have individual finger movements. Only a few insurance companies or workers' compensation would pay for those high-end devices. We wanted to make a high-end device that Medicare would cover. We have made it possible for 75% of the upper limb amputee population to afford multiarticulated prostheses where all five digits can move.

Q: How much importance will you give to talking to the users and knowing the requirements in developing solutions?

When we started taking business courses at the university, we had to start interviewing hundreds of customers and clinicians to find out what their biggest issues are. The number one thing that I heard from every single one of them was that there are $100,000 bionic hands that are breaking within months, and not because they did something crazy with it. They accidentally hit it against the side of the table. Because the fingers were rigid, made out of injection-molded plastics, they would break. Hopefully, it's covered by warranty, but you have to go through the whole process. You might not get it back for another three months and, until then, you don't have a hand. So, it's just a huge ordeal and we didn't know this until we talked to the real people. We were 3D printing our hands in rigid plastic at that time as it is inexpensive. But the problem is if these injection-molded hands are breaking, then our 3D-printed hand is going to break in days. We had to come up with a way that we could still build something low-cost, but much more resilient and robust to impact. That's when we came up with the idea that instead of 3D printing the fingers themselves, we would 3D print the molds, and then use low-cost silicone and rubber to inject into those molds. Now our current model is flexible and will survive a huge lateral impact.

Q: What are the specific challenges involved in developing prostheses?

The challenge, especially when compared to like traditional robotics, is that you're interfacing this directly with a human. It's not just operating a device with a remote control or a joystick. It's not completely automated either. It's driven by users directly attached to them. This human-machine combination presents its own set of challenges. You have a limited set of inputs from residual muscles that might not have dexterous control over the fingers. Several other challenges are specific to prostheses. Prostheses are mobile devices and we cannot power them from a wall socket or heavy batteries. Because of that, you have to be very conscious of how much energy you're drawing, and you have to make design choices that allow the user to be able to wear a device for the entire length of the day. You have to pick the actuators and all your microcontrollers properly, so they don't drain your energy quickly; at the same time they need to be able to control the fingers as best as they can.

Q: What kinds of sensor input do you need to control the finger movements in your bionic hand?

We build the hand with the motor-controlled fingers and the socket parts separately. The socket contains the battery and the charging system. The hand itself is agnostic to the control system. We do not care if this is an I2C communication or an analog 5 volts signal. We can make it work with any of these and can control the hand to move. That way, the clinician can determine what is the best control system for their patient. Some people might work best with two-channel muscle sensors while others might work better with eight channels. Some other people may have a shoulder harness with a mechanical switch that opens and closes the hand. So, in that regard, we don't necessarily care what the control system is.

What's nice about that, as well, is that we are starting to collaborate with universities, like the University of Pittsburgh, where they're doing implanted electrodes on the spinal cord and in the brain. With this interface, you can interpret your motor cortex signal and control movements in the hand. Also, ours is the first bionic hand on the market to give sensory feedback to users. We've got pressure sensors on the index finger, or the pinky and the thumb, as those come into contact the most with objects. Right now, we just have a simple vibration motor in the socket. Whenever you touch something, you'll feel the vibration in the socket, that lets the user know when they've contacted an object and how hard they've been pushing. But with the implanted electrodes, our collaborators can stimulate your nerves directly inside your body, or that run inside your brain to make it feel like it's coming from the hand that you don't have anymore. Like I said, because we're agnostic to those control systems, we can implement our model with any system. We can just plug and play this into a brain implant or surface electrodes that we are using.

Q: I know you are a passionate proponent of the makers community and DIY enthusiasts. How do you think these makerspaces and DIY projects are helping in technology development?

When we started building these hands, we started by using open-source designs that were built by other people. We eventually created a completely new design of our own, based on the issues we saw with those open-source designs in particular. Now we have an open-source version of our hand that people can use. We have provided instructions on how to build the entire thing from scratch – including how to print and mold all the parts. I think this cycle is really important, especially for the research community.

WITH A BIT OF CREATIVE THINKING AND BY USING RESOURCES IN DIFFERENT WAYS, YOU CAN CREATE NEW THINGS THAT MIGHT UPEND AN ENTIRE INDUSTRY

Q: What more can academia do to nurture this culture of making?

Part of the reason why we went down this route was that a lot of my work during my PhD wasn't well-funded. I didn't have a lot of research funding to do this kind of stuff. Although, in our case, it worked well, it forced us to think differently. Instead of throwing money at it, we developed a low-cost procedure to manufacture our models. This now opens the doors to commercialization and mass manufacturing.

Q: Is there something that industries can do better for this community?

We made an earlier version of our models open-source; this serves as an example. Also, there was the research version that we had been developing at UIUC. By sharing some resources like that we can help each other. Tesla did a similar thing with a lot of their patents, so that the entire community can shift towards electric vehicles. I think that is a good example of how the industry can foster the maker community.

Q: What would be your message or words of wisdom to budding makers and entrepreneurs?

I would say not to limit yourself in the approaches that you might take to solving a problem. Just with a little bit of creative thinking and utilizing resources around you in different ways that you might not expect, you can create completely new things that might upend an entire industry. ■