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Tact: Design and Performance of an Open-Source, Affordable, Myoelectric Prosthetic Hand

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Abstract— **This paper presents the Tact hand—an anthropomorphic, open-source, myoelectric prosthetic hand that was designed for use by people with transradial amputations in developing countries. This hand matches or exceeds the performance of other state-of-the-art myoelectric prosthetic hands, but costs two orders of magnitude less ($250) and is easy to manufacture with a 3D printer and off-the-shelf parts. We describe our design process, evaluate the Tact hand with both qualitative and quantitative measures of performance, and show examples of using this hand to grasp household objects.**

I. INTRODUCTION

There are at least 30 million people with amputations living in low-income countries, 80% of whom cannot afford prosthetic care [1]–[3]. People with transradial amputations who live in economically disadvantaged communities need a prosthetic hand that is not only functional but also affordable, easy to manufacture, and simple to maintain [4].

Many open-source prosthesis projects exist with the goals of decreasing cost, increasing manufacturability, and encouraging widespread distribution [5]–[7]. A number of these, such as the Robohand [5], are purely mechanical prostheses, which are simple to build and less expensive than those that require electronics. However, these devices are limited in functionality, with most only being able to open and close, lacking important grasps used during most activities of daily living (ADLs). In fact, it has been shown that the power grip is used in 35% of ADLs, the precision grip in 30% of ADLs, the lateral grip in 20% of ADLs, hook; tripod, and finger point [8]. Several open-source myoelectric prosthetics exist [6], [7] with the ability to accomplish these grasps, but are hindered by poor performance, particularly in force production when compared to the commercial alternatives.

Recent research has focused on the development of advanced hands that are increasingly dexterous and biomimetic. There is a wealth of information on the desired design and performance characteristics of anthropomorphic prosthetic hands [8]–[11]. In addition, detailed studies of the problems prosthesis users experience offer information on improving the design of prosthetic hands [12], [13].

While these studies mainly discuss qualitative features of hand development and user difficulties, Belter et al. [14] focus on the quantitative abilities of leading commercial myoelectric prosthetic hands by presenting physical performance specifications as well as discussing design trade-offs in prosthetic terminal devices. Though advanced devices attempt to mimic a real hand in terms of performance, a trade-off must be made among the degrees of freedom (DOFs), power, durability, and cost of such devices. The current leading prosthetic hands are priced between $25,000-$100,000 [15], [16]. This price inhibits the use of these advanced devices in developing countries that have an unmet demand for prostheses.

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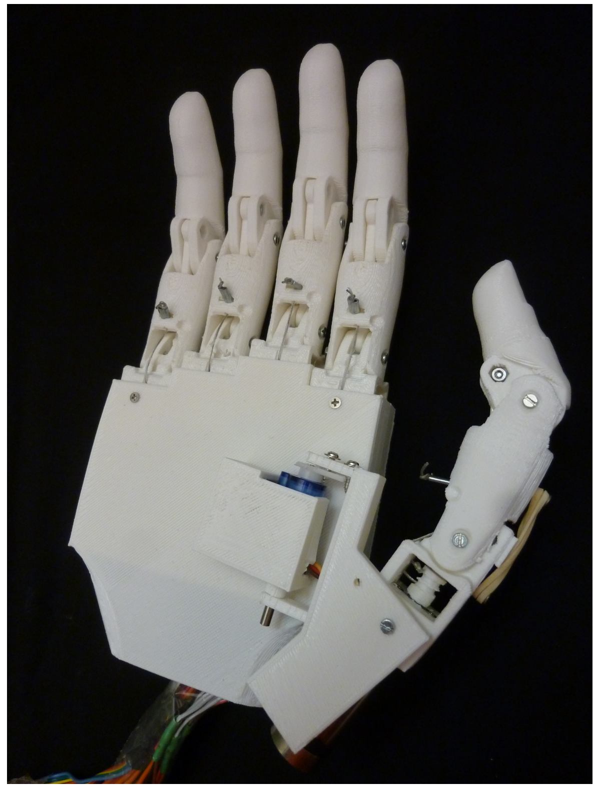


Fig. 1. Tact: the open-source, affordable, myoelectric prosthetic hand.

In this paper, we show that the Tact (Fig. 1), our open-source, anthropomorphic, myoelectric prosthetic hand, matches or exceeds the performance specifications of leading commercial hands while being two orders of magnitude less in cost ($250). The cost includes the materials for the hand, motors, and all electronic parts to allow use as a myoelectric prosthetic. By leveraging widespread 3D-printing rapid prototyping technology and off-the-shelf components, we make the device accessible to a wide audience through part files, parts lists, and assembly instructions available online.

(a) (b) (c)

Fig. 2. The Tact finger (a) unflexed and (b) demonstrating flexion compliance. A kinematic model of the finger joint coupling mechanism is shown in (c).

II. METHODS

In designing our prosthetic device in a methodical manner we evaluated the tradeoffs between cost, performance, durability, efficiency, and manufacturability. Since the goal for the design was to meet the needs of users in developing countries, the device needed to be affordable but still maintain performance equivalent to current commercial myoelectric prostheses. Manufacturability is important as lack of prosthetic care requires the device to be easily reproducible by any person. Since the design is easily made and repaired with common components, we did not consider the durability of the design to be as essential. Further tradeoffs in efficiency were made in designing the Tact in order to meet the needs of developing countries.

In order to maximize the affordability, performance, and manufacturability of the Tact, special consideration was given to the choice in motors, actuation method, assembly procedure, and joint coupling method. We compared motors in commercial myoelectric prostheses to lower-cost motors to determine if lower-cost motors could supply sufficient torque. Rather than using a completely tendon-driven design, as is common in open-source prosthetic hands, the joint actuation method was simplified to consist of a DC motor with a spool. The DC motor actuated a cable directly coupled to the finger for flexion and extension, minimizing the routing of the cable and number of components. All parts were designed to be put together in two piece assemblies. Only one part would need to be attached at a time during assembly. This avoided complex processes requiring two hands. A four-bar linkage was used as a finger joint coupling mechanism to produce consistent movement and greater force at the finger tip than a purely tendon-based design. These design choices were made at the expense of durability and efficiency due to the lack of nonbackdriveable gearing, higher-strength components, and precision parts.

To assess the physical performance specifications of the Tact, a comparison was made with five state-of-the-art hands: i-LIMB, i-LIMB Pulse, Bebionic, Bebionic v2, and Vincent [17]–[19]; as well as the open-source prosthetic hand, Dextrus [7]. The specifications for the commercial hands were extensively reported by Belter et al. [14] as well as through information published by their respective developers. These specifications include general physical characteristics, kinematic characteristics, motor specifications, and finger speed and force.

For general physical characteristics, we compared the mass, size, number of joints, number of DOFs, number of actuators, actuation method, and joint coupling method for each of the prostheses. The mass of each hand was recorded using a scale, and size dimensions were measured for the length, width, and thickness. The total number of joints in each device was assessed to determine similarities in underactuated structure. The number of DOFs and actuators were counted to assess device functionality. The actuation method was noted as it often indicates the cost of a hand, possibly requiring expensive custom gearing or a similar transmission method. The joint coupling method was included to illustrate the differences in methods of linking related finger joints in the hand, which can affect performance and consistency in grasping.

The kinematic characteristics of these hands were also compared. To quantify the dexterity of the hands, we measured the range of motion for the metacarpal phalange (MCP), proximal interphalange (PIP), and distal interphalange (DIP). Since the Tact and Dextrus incorporates a motor to give the thumb circumduction the range of motion for this was also recorded.

In order to decrease the cost of our hand, we had to make a methodical motor selection to maximize the torque produced at low cost while maintaining a reasonable size and mass. By

TABLE I
GENERAL CHARACTERISTICS

Hand	Developer	Mass (g)	Size (length x width x thickness, mm)	Number of Joints	DOF	Number of Actuators	Actuation Method	Joint Coupling Method
Tact	University of Illinois	350	200 x 98 x 27	11	6	6	DC Motor - Tendons	Linkage Spanning MCP to PIP
Dextrus (2013) [7]	Open Hand Project	428	205 x 88 x 45	15	6	6	DC Motor - Tendons	Tendon and free-spinning pulleys
i-LIMB (2009) [14], [17]	Touch Bionics	450-615	180-182 x 75-80 x 35-41	11	6	6	DC Motor - Worm Gear	Tendon linking MCP to PIP
i-LIMB Pulse (2010) [14], [17]	Touch Bionics	460-465	180-182 x 75-80 x 35-45	11	6	5	DC Motor - Worm Gear	Tendon linking MCP to PIP
Bebionic (2011) [14], [18]	RSL Steeper	495-539	198 x 90 x 50	11	6	5	DC Motor - Lead Screw	Linkage spanning MCP to PIP
Bebionic v2 (2011)[14], [18]	RSL Steeper	495-539	190-200 x 84-92 x 50	11	6	5	DC Motor - Lead Screw	Linkage spanning MCP to PIP
Vincent Hand (2010) [19]	Vincent Systems	-	-	11	6	6	DC Motor - Worm Gear	Linkage spanning MCP to PIP

looking at the motors from the compared hands we were able to find what amounted to appropriate torque, size, and mass statistics. By finding the nominal voltage and stall current of the motors we were able to compute the supplied power to the motor, which allowed us to see approximately how efficient each motor was when producing the stall torques. Due to the lack of published information, only the motors in the i-LIMB and i-LIMB Pulse [17] could be verified [14], [20] and accurately compared.

The motor torques and gearing are the main factors that correlate to the finger force and flexion/extension speeds. Grasp speeds have been omitted because the published information for commercial prosthetic hands do not follow a consistent method and grasping often depends on the size and shape of an object. To quantify the performance of the Tact in terms of force, we followed the methods of Belter et al. [14] and rigidly mounted a calibrated load cell and completely extended finger, orienting the finger until only the fingertip touched the load cell. The finger was actuated and the static force produced was recorded. The initial spike in the force was discarded until it maintained a constant level and this force was recorded. Two trials were recorded for both the Tact and Dextrus fingers. The optical encoder in the Tact and Dextrus motors were used to measure the time required to fully flex the finger from 0-90°. Since the range of motion for the joints was known, the speed in degrees per second for finger flexion and extension was computed.

Finally, to validate the ability of the hand in functional tasks, we tested whether the Tact could grasp a variety of household objects (a bottle cap, water bottle, cordless drill, and key), a number of which are suggested as practice objects by Klopsteg et al. [21]. In addition, we demonstrated the ability of the Tact to be used as a myoelectric prosthesis by using EMG pattern recognition to switch between a set of grasps.

III. RESULTS

Analyzing the general characteristics of the given hands (Table I), the mass of the Tact is 17-43% lighter than the others. The length and width of the Tact is within the same range as the other hands. However, the thickness of the Tact is only 27mm, substantially less than the 41-50mm range for the rest of the devices. The number of joints of all hands except the Dextrus are equivalent, with the excess joints in the Dextrus being due to the DIP joint being able to rotate. All hands have six DOFs, one for each finger plus thumb flexion and circumduction. All include one actuator for each finger with the Tact, Dextrus, i-LIMB, and Vincent including an additional actuator for thumb circumduction. The actuation methods of these hands varies with the Tact and Dextrus, using spools attached to the DC motors to manipulate tendons. The i-LIMB, i-LIMB Pulse, and Vincent all use a DC motor in conjunction with a worm gear and bevel gearing. The Bebionic and Bebionic v2 hands use a DC motor with a lead screw to make a custom linear actuator. The use of this custom gearing in the commercial hands increases the cost.

The Dextrus and Tact have a range of motion equivalent to the commercial hands for the MCP and PIP joints (Table II). The Dextrus is the only hand that does not have a fixed DIP joint, with the DIP joints of all others being designed at approximately a 20° angle. The Tact and Dextrus had a slightly increased range of motion for thumb flexion and circumduction. The thumb circumduction axis on all hands was parallel to the wrist axis. This simplifies the motion of the thumb during multi-fingered grips such as the three-jaw chuck, precision pinch, and key grasp, simplifying grasp execution by placing the thumb in a parallel plane to the other moving fingers. Each hand is able to achieve the power, precision, lateral, hook, and finger-point grasps, as defined in the taxonomy of grasps proposed by Cutkosky [23].

TABLE II

KINEMATIC CHARACTERISTICS

Hand	MCP Joints (Deg)	PIP Joints (Deg)	DIP Joints (Deg)	Thumb Flexion (Deg)	Thumb Circum-duction (Deg)
Tact	0-90	23-90	20	0-90	0-105
Dextrus (2013) [7]	0-90	0-90	0-90	0-90	0-120
i-LIMB (2009) [14], [17]	0-90	0-90	20	0-60	0-95
i-LIMB Pulse (2010) [14], [17]	0-90	0-90	20	0-60	0-95
Bebionic (2011) [14], [18]	0-90	10-90	20	-	0-68
Bebionic v2 (2011) [14], [18]	0-90	0-90	20	-	0-68
Vincent Hand (2010) [14], [19]	0-90	0-100	NA	-	-

Size constraints in an anthropomorphic myoelectric hand require small motors and gearing to produce sufficient force for ADLs. Comparing the motor and gearbox combination of the i-LIMB/i-LIMB Pulse to that of the Tact/Dextrus (Table III), we find similar torque outputs of 0.15Nm and 0.14Nm, respectively. By multiplying the nominal voltage and stall current drawn by the i-LIMB/i-LIMB Pulse and the Tact/Dextrus, we find similar power requirements of 3.6W and 4.1W, respectively. However, while performance and power requirements are similar between the motors used in the i-LIMB/i-LIMB Pulse and the Tact/Dextrus, the cost, size, and mass of the motors varies greatly. Unfortunately, due to the lack of information on the Bebionic, Bebionic v2, and Vincent, no comparisons could be made to those hands.

Finger flexion/extension speed for the Dextrus and Tact exceed the range of the commercial hands, with the Tact more than doubling the fastest commercial hand (Table IV). The force produced at the tip of the finger for the Tact lies within the range of forces produced by the commercial hands. The Dextrus hand could not produce comparable results, being substantially below the force range of compared hands.

The functional utility of the Tact was demonstrated by grasping a variety of household objects (Fig. 3). The Tact was easily able to grasp objects such as a bottle cap, water bottle, cordless drill, and key by using a three-jaw chuck, power grip, tool grip, and key grip, respectively. These actions required little or no assistance. The fine tasks of grasping a battery using precision pinch was complicated by the slick plastic surface on the tips of the fingers. This difficulty could be minimized by applying adhesives or liquid rubber to the fingertips. When using myoelectric control, users successfully performed these various grasps using pattern recognition.

IV. DISCUSSION

Comparing the physical properties of the prostheses gives a sense of the practicality of a prosthetic hand as a terminal device. A human hand has a mass of 400g on average [24]. Prosthetic devices around this mass are described by people who use them to be too heavy [25]. The perceived heaviness is due to the mass of the prosthesis being distributed over the softer tissues of the limb rather than directly to the skeletal system. This mass distribution is a contributor to pain and fatigue felt when operating prosthetic devices. The mass of the Tact is 350g, below both the 400g human hand mass and the 420-615g range for the compared hands. The main reason for the Tact's lightness is the use of 3D-printed materials. Using 3D-printing as the primary method of manufacturing allows the use of lighter and mostly hollow plastic bodies rather than solid, injection-molded plastics, metals, or composites. With a low mass, the Tact could potentially reduce the pain and fatigue caused by mass distribution over softer tissues.

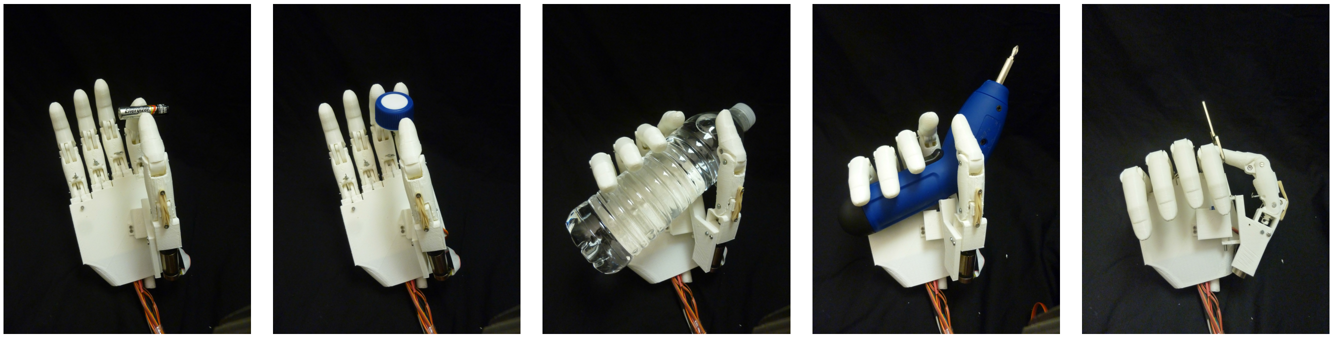
With respect to size, both the Tact and Dextrus fall within the range of lengths, widths, and thicknesses of the compared hands. The Tact is 34-46% thinner at 27mm than the thickness range of compared hands of 41-50mm, reducing mass and interference when grasping objects. Our hand, along with the Dextrus, i-LIMB, and Vincent Hand, includes an actuator to give the hand motorized thumb circumduction. This allows for a grasping advantage in being able to switch grasps with the thumb in different positions without having to manually change the position of the thumb [14]. This actuated thumb circumduction is essential when using multi-channel EMG pattern recognition to control a prosthesis, since a fixed thumb would severely limit the grasps the user could quickly swap between.

It is important to note that all the tested hands have an adaptive grip, but implement it through different means. It is incorporated in the Dextrus, i-LIMB, and i-LIMB Pulse hands via a spring and tendon system. The Vincent hand uses unique bends in the links that allow the finger to act as elastic

TABLE III

MOTOR SPECIFICATIONS

Hand	Motor Type	Gearbox Ratio	Nominal Voltage (V)	Stall Current (A)	Watts (J)	Motor Stall Torque (Nm)	Cost Per Motor (USD)	Size	Mass (grams)
Tact/Dextrus [22]	Escap 16G 214E MR 19	64:1	12	0.3	3.6	0.143	13.95	16mm diameter, 52mm length	38
i-LIMB/i-LIMB Pulse [14], [17]	Maxon RE 10 (Part Number 118394)	64:1	4.5	0.919	4.135	0.15	208.88	10mm diameter, 52.05mm length	18



(a) (b) (c) (d) (e)

Fig. 3. The Tact applying basic grasps to household objects. (a) precision pinch on a battery, (b) three-jaw chuck on a bottle cap, (c) power grip on a bottle, (d) tool grip on a cordless drill, and (e) key grip on a key.

TABLE IV
INDIVIDUAL FINGER SPEED AND HOLDING FORCE AT TIP

Finger	Avg. Speed (°/s)	Avg. Force (N)
Tact	249.8	4.21
Dextrus	175.4	1.71
i-LIMB Large (middle)	81.8	7.66
i-LIMB Med (index/ring)	95.3	5.39
i-LIMB Small (little)	95.4	5.17
i-LIMB Pulse Med (index)	60.5	4.15
i-LIMB Pulse Large (middle)	60.5	3.09
i-LIMB Pulse Med (ring)	74.3	6.43
i-LIMB Pulse Small (little)	82.2	4.09
Bebionic (index)	45.8	12.47
Bebionic (middle)	45.8	12.25
Bebionic (ring)	45.8	12.53
Bebionic Small (little)	37.8	16.11
Bebionic v2 Large (ring, middle, and index)	96.4	14.5
Vincent Large (ring, middle, and index)	103.3	4.82
Vincent Small (little)	87.9	3.00

elements in series [14]. In the Tact, Bebionic, and Bebionic v2 hands the adaptive grip is implemented mechanically with an elastic band. By using this method we require no excess parts or cost. An adaptive grip increases a hand's robustness, as excessive forces simply flex the finger rather than shearing gears or damaging linkages.

All compared hands except for the Dextrus have finger kinematics approximating the MCP and PIP joints. The DIP joint is fixed in all these hands to improve the transfer of torque from the motor to the finger. Fixing this joint also reduces both the cost and complexity of the finger mechanism. Contrarily, the Dextrus hand uses a design with a DIP joint that is free to rotate. This creates a small moment arm about the joint and decreases the force at the fingertip. As a result, the finger force of the Dextrus was below the commercial hand range. The free DIP joint and tendon-driven design of the Dextrus causes the phalangeal joints to flex sequentially, resulting in an unnatural grasping motion. In all other hands, the rotation of the PIP and MCP joints have a fixed relationship due to a four-bar linkage mechanism. Belter et al. [14] shows that the use of a four-bar linkage creates a change in the PIP joint approximately equal to the change in the MCP, closing the fingers in a consistent and natural manner.

To achieve motor performance comparable to the i-LIMB/i-LIMB Pulse at lower cost, we used a motor with a larger diameter (16mm versus 10mm) and almost double the mass (38g versus 18g). It should also be noted that the i-LIMB/i-LIMB Pulse uses a 1:1 bevel gear that drives a custom 25:1 worm gear that actuates the finger. The Tact design uses a 3D-printed, ABS plastic spool, costing cents in raw materials, that wraps and unwraps braided steel cable attached to the lower portion of the segment between the MCP and PIP joints to flex and extend the finger (Fig. 2c). The expense of additional and custom gearing is a main contributor to the cost difference between the i-LIMB/i-LIMB Pulse and the Tact. While this gearing leads to extra expense it also makes the i-LIMB/i-LIMB Pulse nonbackdriveable. All the commercial hands include this nonbackdriveability because it allows for the position of a finger to be loaded without drawing power. For the Tact and Dextrus, power must be drawn continuously for the fingers to hold its position while loaded. This poor efficiency decreases the operating time of the device, requiring more frequent battery changes. In the future we plan to address this inefficiency by using low-cost linear actuators, rather than just a DC motor with no gearing.

In a survey by Pylatiuk et al. [25], 100% of adult females, 76% of adult males, and 50% of children who used myoelectric hands described the speed of their prostheses as too slow. Speeds needed for most pick and place tasks require a finger flexion/extension speed between 172-200°/s [9], [26]. This led us to choose a motor with a higher speed and lower torque to achieve this desired range of speeds, but still maintain a force within the range of commercial hands. While a human hand can achieve speeds of 2290°/s, this is in great excess to the basic functionality desired by people with amputations. The flexion/extension speed of the state-of-the-art myoelectric devices range from 37.8-103.3°/s. These speeds highlight a disparity between desired and actual performance of myoelectric hands. The Tact hand with an average flexion/extension speed of 249.8°/s allows for speeds greater than the desired 172-200°/s range. However, this speed can be modulated electronically to provide desired speeds, giving the Tact a more natural grasping ability. The difference in the speeds of the i-LIMB/i-LIMB Pulse and the Tact is due to the additional worm gear in the i-LIMB/i-LIMB Pulse, which reduces speed to produce higher torque.

The raw cost in materials to build the Tact totals less than $100, with the motors comprising approximately $70 of this total. All other parts are off-the-shelf or 3D-printed. In order to control the Tact myoelectrically, electronics such as an EMG circuit, EMG electrodes, and microcontroller are needed. These circuits and components can be easily purchased and assembled for less than $150. These components read the EMG signals, classify the grip, and then drive the Tact to the appropriate grip. The use of off-the-shelf electronic and mechanical parts and 3D-printing technology decreases cost and increase manufacturability, since materials can be obtained easily. Open-sourcing the parts and assembly instructions enables anyone with access to these resources to produce the Tact at a low-cost through DIY instructions, which can be found at the following site.

`http://github.com/pslade2/TactHand` .

While open-source 3D-printed myoelectric hands such as Dextrus also offer affordable prostheses to developing countries, the design directions detailed in this paper can be used to reduce cost, increase manufacturability, and improve performance to the level of current commercial myoelectric hands. By simplifying the tendon design to only actuate a four-bar linkage, the Tact reduces the cost of parts, decreases manufacturing time, provides consistent movements, and produces greater finger force. The reduced number of parts decreased printing time from 16 to 10 hours and more than halved the assembly time from 5 to 2 hours. The design simplifications make it possible for the Tact to be assembled by one person, or even one hand with access to a vice.

V. CONCLUSION

We developed an anthropomorphic, open-source, myoelectric prosthetic device designed for people with transradial amputations in developing countries. We detailed the design process and showed that the Tact meets or exceeds performance in comparison to current commercial myoelectric prostheses and is easily manufacturable. By using 3D-printing and off-the-shelf components, the Tact can be produced for two orders of magnitude less ($250) than the compared commercial hands. By making available the parts and assembly instructions, the Tact can be easily manufactured by populations lacking access to affordable prosthetic care.

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