CHAPTER

THE MODULAR PROSTHETIC LIMB

21

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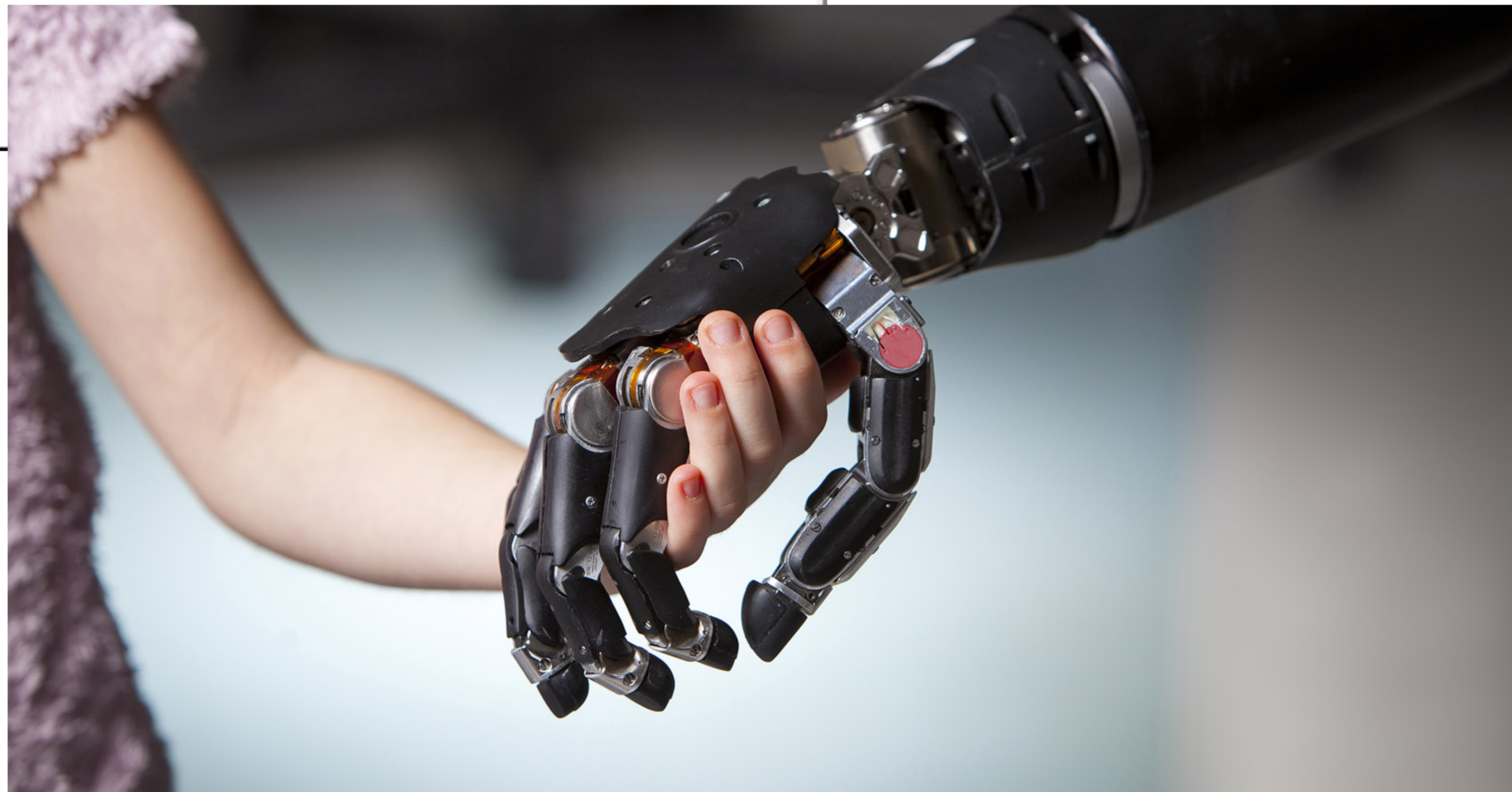

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In **2005** the Defense Advanced Research Projects Agency (**DARPA**) selected the Johns Hopkins University Applied Physics Laboratory (**JHU/APL**) as one of two primary participants to execute the **Revolutionizing Prosthetics program**. [1]The other institution was Deka Integrated Solutions Corp. which developed the Luke Arm.

Mission: replicate the functionality of the human arm and hand through a neurally integrated prosthetic system

- utilize implantable cortical or peripheral nerve electrodes
- match dexterity, size, weight, strength, speed, and sensory capabilities of the natural arm and hand

Table 21.1 Select Challenging High-Level Requirements Influencing the MPL Design

Performance and Function	Environmental, Sustainability, and Reliability
Weigh less than 3.9 kg (8.6 lbs.)	Survive rain up to 4 in. per hour
Match human limb inertial properties	Survive blowing dust and sand per MIL-810
Provide 81.3 Nm of torque at elbow	Survive 3 ft. drop
Provide 13.6 Nm of torque at wrist flex/extend	Function after patient fall on prosthetic
Hand cylindrical grasp strength of 311 N	24 h of operation on a single charge
Unloaded joint speeds of 120 degrees per second	Wearable up to 18 h with no ill effects
Full hand and arm articulation capabilities	Production cost of $50,000
All actuated joint torque sensing	Maintenance cost of $500 per year or less
All revolute joint position/velocity sensing	Shoulder, elbow, and wrist quick releases
Fingertip force sensing of 0–5 N, 0.1 N resolution	MTBF of 3000 h
Fingertip spatial touch discrimination of 2 mm	MTBM of 1500 h
Accommodate all amputation levels from shoulder to wrist disarticulation	MTTR of 2 h
Natural swing kinematics during running	Chronically implantable neural interface components

APL assumed the role of lead institution and developer, seeking experts in the fields of

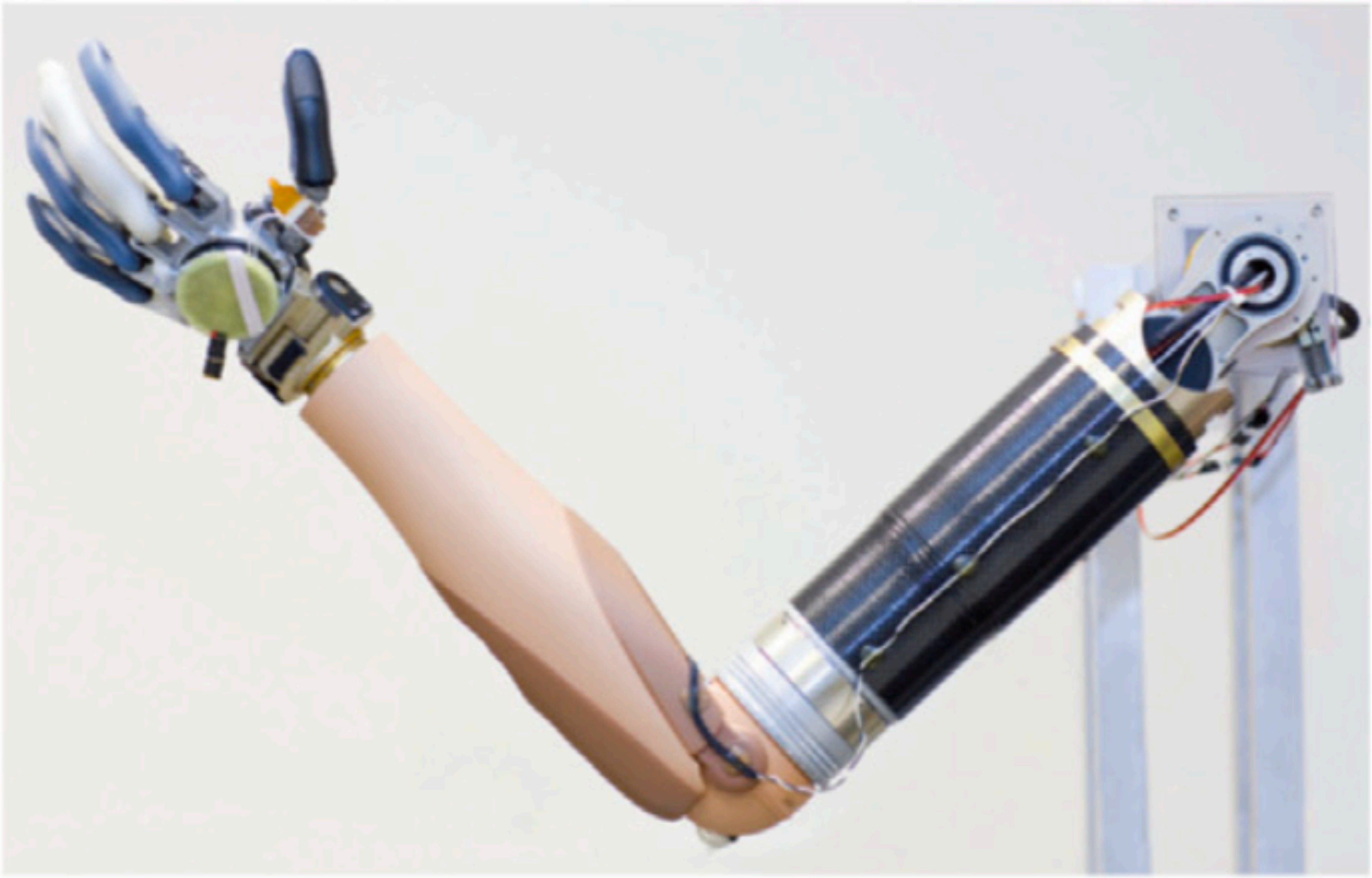
- clinical prosthetics,
- prosthetic device manufacturing,
- electromechanical system design,
- implantable neural device manufacturing,
- implantable electrode manufacturing,
- sensors,
- actuators,
- materials science,
- neurosurgery, and
- neuroscience

to round out technical proficiencies and fill development gaps.

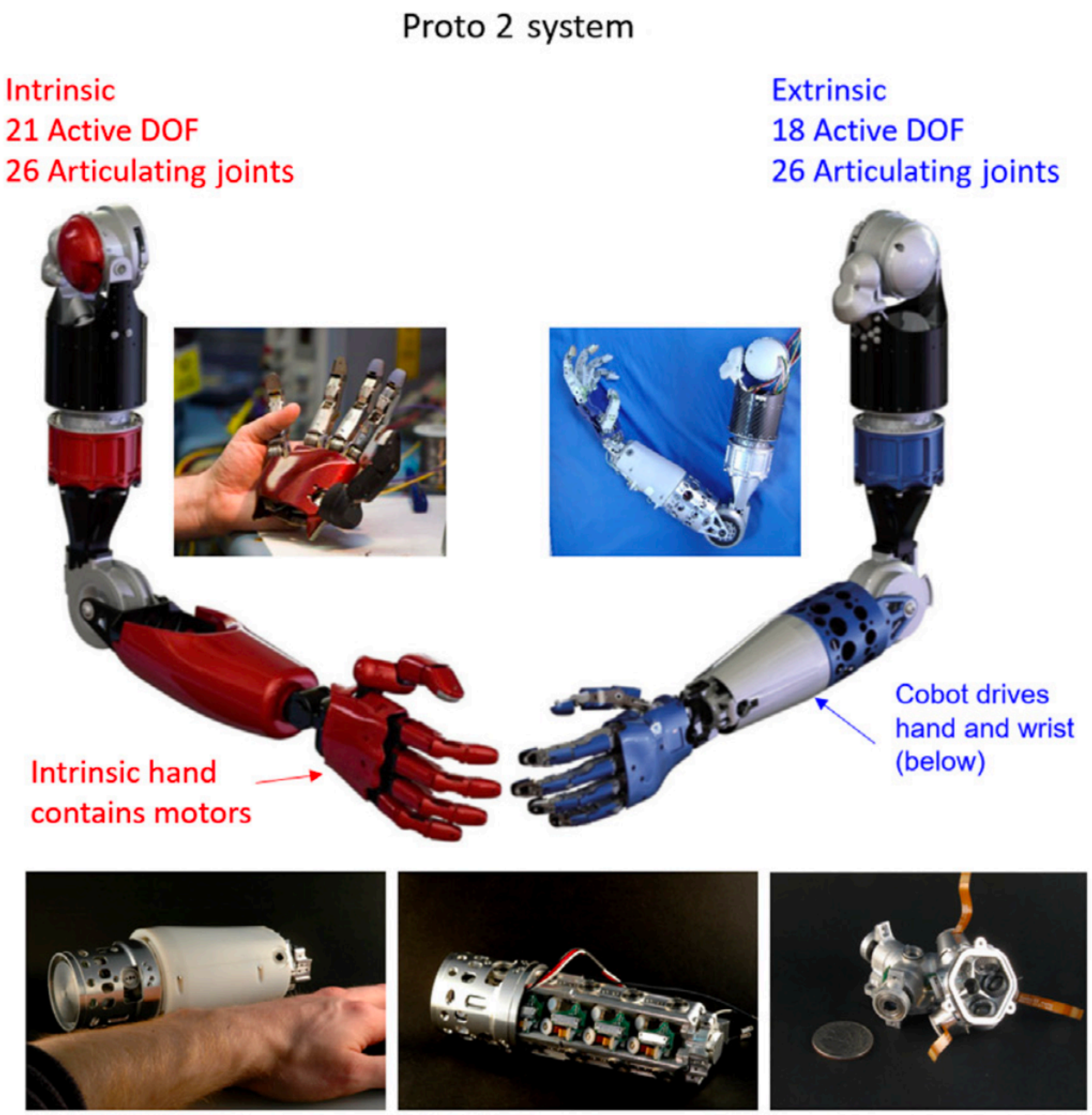
Table 21.2 APL's Collaborating Institutions in the Revolutionizing Prosthetics Program

The Alfred E. Mann Foundation	Arizona State University
BioStar Group	Blackrock Microsystems
Booz Allen Hamilton	Chicago Physical Therapists LLC
The California Institute of Technology	The Defense Advanced Research Projects Agency
Duke University	Flexsys Incorporated
Fraunhofer Society	HDT Global
Illinois Institute of Technology	The Johns Hopkins University
The Johns Hopkins Medical Institute	Harvey Mudd College
IDEO	Kinea Design
National Institute of Aerospace	Martin Bionics
The National Aeronautics and Space Administration	The National Rehabilitation Hospital
New World Associates	Northwestern University
Oak Ridge National Laboratories	Orthocare Innovations
Otto Bock	Punch Communications
Ripple LLC	Rockwell Scientific
The Rehabilitation Institute of Chicago	Rutgers University
Science and Technology Associates	Scott Sabolich Prosthetics and Research
Scuola Superiore Sant'Anna	Space and Naval Warfare Systems Command
Stanford University	Sigenics Incorporated
Umea University	The University of California Irvine
The University of Chicago	The University of Michigan
The University of New Brunswick	The University of Pittsburgh
The University of Rochester	The University of Southern California
The University of Texas Health Science Center	The University of Utah
Vanderbilt University	Van Doren Designs LLC
Walter Reed National Military Medical Center	

Proto 1 system



- Seven active DoF prosthetic system
- December 2006
- clinically tested using surface electromyography on a patient who had undergone targeted muscle reinnervation
- active wrist rotation, elbow flexion/extension (F/E), and humeral rotation found in the AxonArm (Ottobock)
- passive shoulder abduction/adduction (A/A) joint, which was a variant of the Liberating Technologies Inc. Locking Shoulder Joint
- custom-designed active shoulder and wrist F/E drives
- early prototype version of the Michelangelo hand under development by Ottobock, which could realize two grasps patterns (lateral and power) with actuators in the palm and thumb.



The two separate prototype limb systems, one intrinsically actuated (motors within the hand) and the other extrinsically actuated (a CVT in the forearm driving tendons to the wrist and fingers).

The systems shared a common upper arm design with active three-DoF shoulder and elbow.

Both systems had different active three-DoF wrist designs.

The intrinsically actuated system had

- an active three-DoF thumb,
- four active two-DoF (one-DoF underactuated) fingers,
- active index, ring, and little finger A/A,
- passive middle A/A.

The extrinsically actuated system had

- an active four-DoF thumb,
- four active one-DoF (two-DoF underactuated) fingers,
- active index, ring, and little finger A/A.

The phase 2 effort spanned primarily from January 2008 to December 2009.

At the outset of phase 2, a major architectural decision was necessary from an actuation standpoint

- intrinsic vs. extrinsic actuation?

The primary driving factors in choosing all **intrinsically actuated design** for the Modular Prosthetic Limb system was

- patient accommodation
- transradial and longer residual limb lengths
- large portion of the amputee population — from 62% to 85% in studies with larger patient populations (N>200).

A key feature of the MPL system as a result of this decision was modularity, which allowed for accommodating amputees from shoulder to wrist disarticulations.

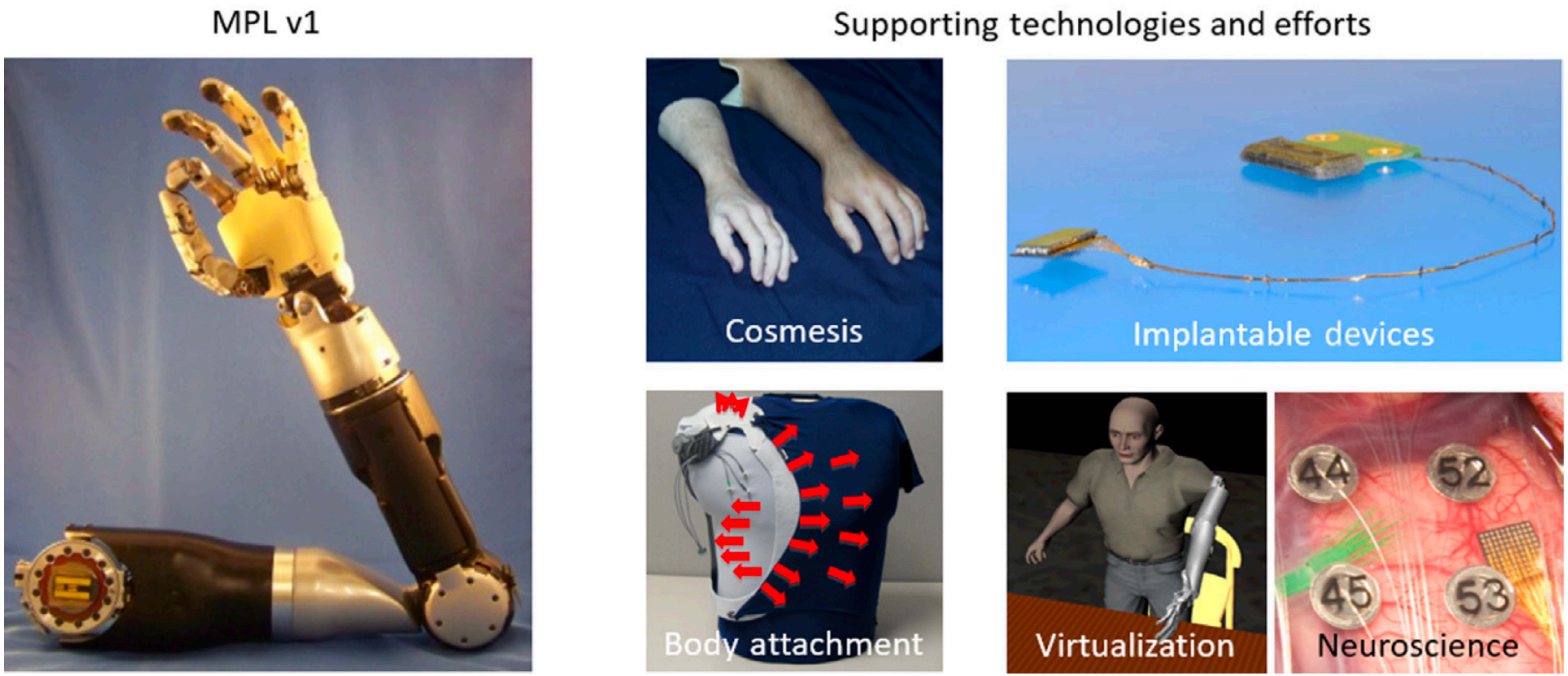


FIGURE 21.2

The MPL v1 System (left) was the first fully built system within the program based upon the final selected architecture characteristics, actuation technologies, and form factor. Numerous supporting technologies were also part of the phase 2 effort (right).

FIGURE 21.3

MPL systems developed in the scope of the phase 3 effort. MPL v2.0 (left) and MPL v3.0 (right).

Phase 3, beginning in 2010 began with revisions of the MPL system to prepare for clinical testing

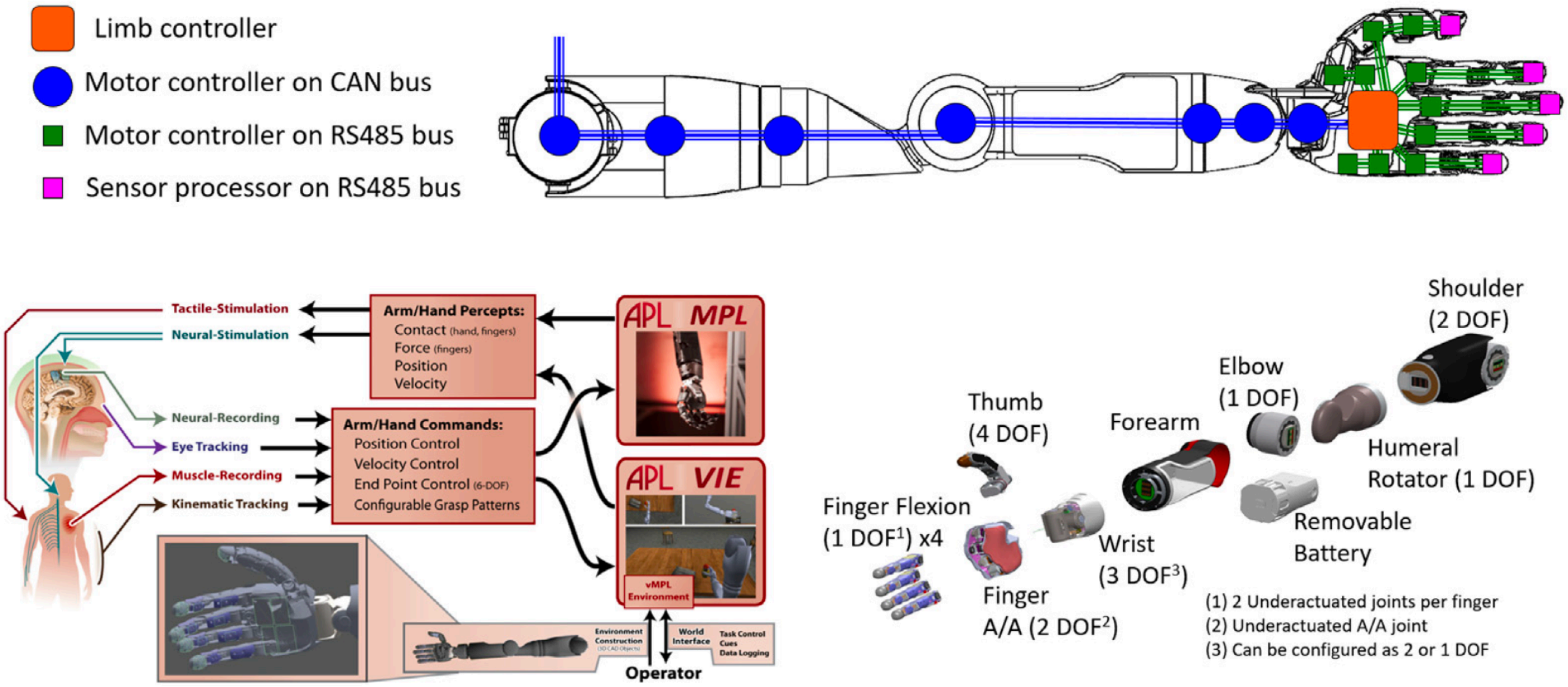


FIGURE 21.4

MPL architecture overview highlighting the communications bus, central processing and low-level controller locations, active and passive degrees of freedom, modularity, and data flow between a user and virtual and physical systems.

The MPL system as a whole has 17 controllable actuators that drive 26 articulated joints.

The MPL has one primary processor, the limb controller (LC) located in the palm

input sources can include:

- user intent
- wearable sensors
- implanted sensors
- commands from preprogrammed or automated trajectories

feedback information includes:

- position,
- velocity,
- discrete contact,
- interaction force

feedback can be sent to

- stimulating electrodes or implants,
- surface tactile elements, or
- higher level control systems for autonomous trajectory planning and control.

Table 21.3 Select MPL v3 Performance Specifications

Select MPL Specifications		
Parameter	**Value**	**Units**
Articulated joints	26	
Motors (DoF)	17	
Onboard motor controllers	17	
Mass of hand and wrist	2.9	lbs
Mass of upper arm with battery	7.4	lbs
Payload capacity (wrist active)	15	lbs
Cylindrical grasp force	70	lbf
Two-jaw pinch force	15	lbf
Three-jaw chuck pinch force	25	lbf
Lateral key pinch force	25	lbf
Upper arm and wrist joint speed	120	deg/s
Finger joint speed	>360	deg/s
Hand open or close time	300	ms
Communications	CAN (MPL direct), UDP (VulcanX)	

JHU/APL and HDT.

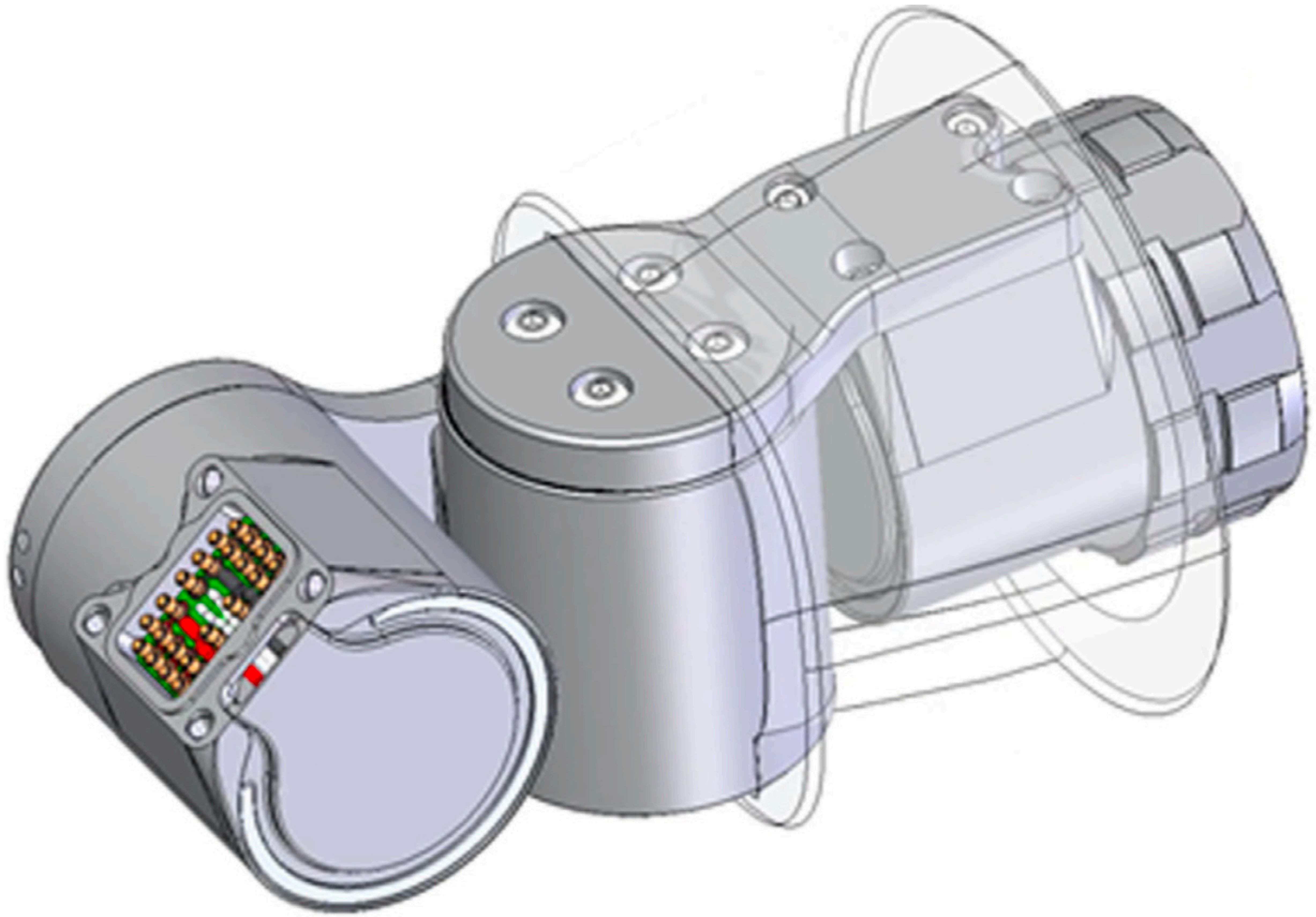


FIGURE 21.13

The wrist consists of three identical drives for flexion, deviation and rotation, or any combination thereof via a use of configuration-specific brackets. A polyurethane shell fits around the rotator and deviator, and the flexor fits mostly within the volume of the palm. At the proximal end an adapter accommodates the quick-release mechanism at the end of the forearm.

The baseline requirements for minimum useful active flexion torque migrated from 4 Nm to near 8 Nm during the program, some of this dedicated to lifting the hand (which is heavier than anthropomorphic) and some due to having to operate through a cosmetic glove.

In addition, it was a requirement that the joint lock at up to 13.6 Nm while consuming no power.

Since program practice was to use a factor of safety (FS) of 3.0 on a routine load and an FS of 1.5 on quantifiable shock loads (catching a patient's fall, or an impact of the arm at full speed with an object), 13.6 Nm became a 41 Nm on-axis and off-axis durability requirement for all three wrist joints (since they were to be the same for economic reasons).

The scenario of a patient catching a fall with outstretched arms drove a requirement for a 1500 N heel-of-palm strike up the wrist and forearm.

It was also desirable for the wrist rotator to have infinite rotation, so all (identical) wrist joints have a slip ring group for power and data.

The wrist joint consisted of a 4:1 planetary followed by a 76:1 cycloidal reduction, for a total reduction of 304:1.

The torque-speed curve was carefully sloped to provide a balance between stall torque and high speed.

The motor's rotor inertia was carefully specified to match that of the hand interacting with a 23 lbs (0.91.4 kg) object in order to assure stable load lowering and admittance control despite backlash.

The wrist incorporated a tuned "drag" seal (i.e., tuned friction) on an early stage in the reduction in order to provide zero-power load-holding, this approach avoided having to integrate a roller-clutch mechanism. Although this approach increased power consumption when moving it kept the system from back-driving at up to the 13.6 Nm load hold, without getting in the way of admittance control.

The construction of the wrist involves exotic/specialty materials and very complex machining operations.

Strain gage-based torque sensing is integrated into each joint output.

The hand of the MPL system consists of 10 actuated drives and 19 articulating joints.

There is one actuator in each finger controlling an additional two underactuated degrees of freedom for three total revolute joints per finger.

In the palm tucked behind the LC are two finger A/A drives:

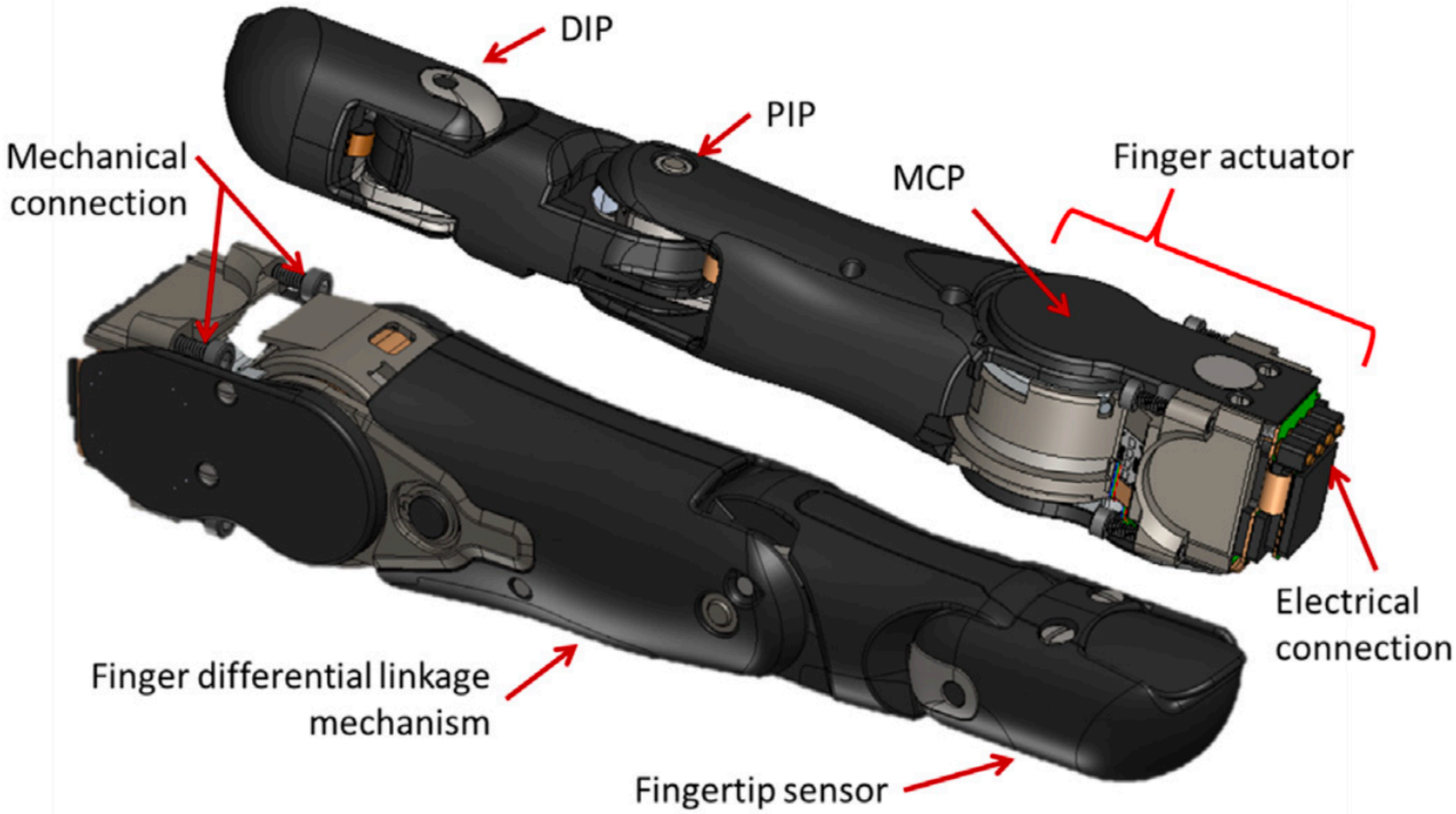
- one for the index finger
- one for the ring/little fingers connected via a linkage for an additional underactuated DoF.

Finally, there is an actuated four-DoF thumb that allows the MPL to assume a plurality of grasps and provide for an anthropomorphic movement quality.

The driving requirements for the fingers were to have the strength of a 95th percentile male, but a form factor suited for a 50th percentile female palm.

The strength of a 95% male means resisting a 67 N (15 lbf) tip-pinch force generated by the thumb. We designed for a safety-factor of 3, which means the finger is robust to a fingertip force of 200 N (45 lbf), even though the finger actuator can only actively generate a 32 N (7 lbf) force [i.e., from 2.7 Nm (21 lb-in) drive torque at the MCP joint].

In addition to the fingertip pinch force cases, the finger was also designed for a 600 N (134 lbf) stub/poke scenario, as well as a 67 N (14 lbf) lateral pinch case (i.e., thumb pinching against the side of the index finger).



DIP
PIP
Mechanical connection
MCP
Finger actuator
Electrical connection
Finger differential linkage mechanism
Fingertip sensor

The dexterity requirement coupled with a desire to minimize weight and complexity drove the development of a one-motor finger (1MF) with behaviors similar to a finger with two independently controllable degrees of freedom.

This was done by the invention of a novel differential linkage mechanism.

The difficulty in controlling three finger joints with a single motor is that there is usually a tradeoff between tip-pinch behavior and grasping behavior.

It is possible to couple all three joints with a kinematic linkage that appears to behave similarly to a human finger—except that the finger will not curl well around an object to make a secure grip.

It is also possible to couple all three joints differentially. This is common with cable mechanisms. That kind of finger curls well around objects, but often cannot hold a stable tip pinch.

The 1MF linkages invented and developed for the MPL hand are able to do both things well.

- Contact with the fingertip—or anywhere distal to a location called the "focal point"—does not produce curling. The joint positions stay stable for good fingertip manipulation.
- Contact anywhere proximal to that, such as on the medial or proximal phalange, produces curling behavior that brings objects into a stable grasp.

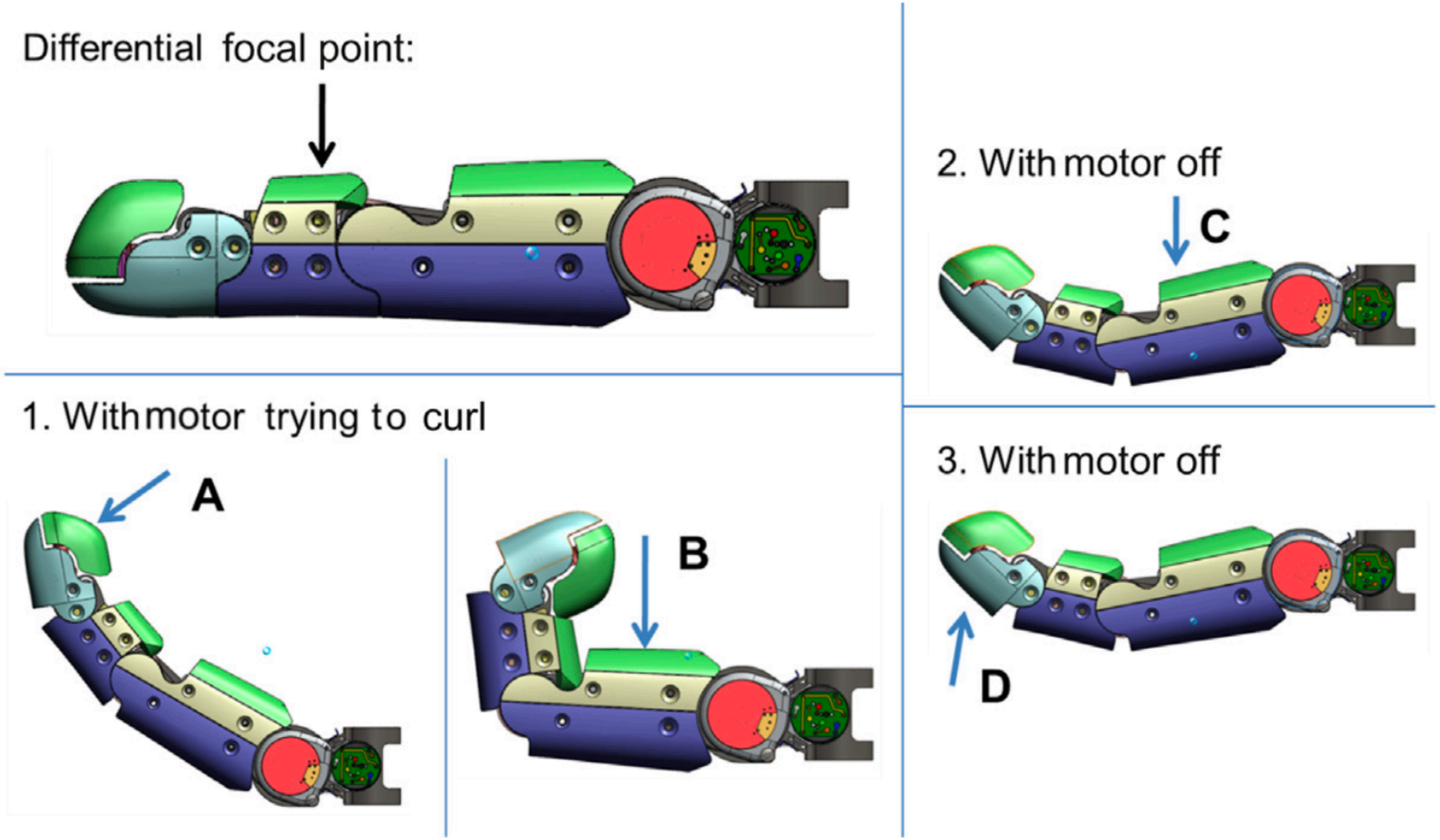


FIGURE 21.21

Description of novel hybrid fixed-linkage/differential that allows the one-motor finger to exhibit both pinching and conformal grasping behaviors, previously only achievable with a two-motor or cable (tendon)-based finger.