

## On the design of robotic hands for brain–machine interface

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U Brain–machine interface (BMI) is the latest solution to a lack of control for paralyzed or prosthetic limbs. In this paper the authors focus on the design of anatomical robotic hands that use BMI as a critical intervention in restorative neurosurgery and they justify the requirement for lower-level neuromusculoskeletal details (relating to biomechanics, muscles, peripheral nerves, and some aspects of the spinal cord) in both mechanical and control systems. A person uses his or her hands for intimate contact and dexterous interactions with objects that require the user to control not only the finger endpoint locations but also the forces and the stiffness of the fingers. To recreate all of these human properties in a robotic hand, the most direct and perhaps the optimal approach is to duplicate the anatomical musculoskeletal structure. When a prosthetic hand is anatomically correct, the input to the device can come from the same neural signals that used to arrive at the muscles in the original hand. The more similar the mechanical structure of a prosthetic hand is to a human hand, the less learning time is required for the user to recreate dexterous behavior. In addition, removing some of the nonlinearity from the relationship between the cortical signals and the finger movements into the peripheral controls and hardware vastly simplifies the needed BMI algorithms. (Nonlinearity refers to a system of equations in which effects are not proportional to their causes. Such a system could be difficult or impossible to model.) Finally, if a prosthetic hand can be built so that it is anatomically correct, subcomponents could be integrated back into remaining portions of the user's hand at any transitional locations. In the near future, anatomically correct prosthetic hands could be used in restorative neurosurgery to satisfy the user's needs for both aesthetics and ease of control while also providing the highest possible degree of dexterity.

**KEY WORDS** • brain–machine interface • robotic hand

**I**N just the past decade, neuroprostheses and BMIs have evolved from science fiction to clinical science. Neuroprosthetic devices have been approved by the US Food and Drug Administration and are commercially available. In addition, the first clinical trials of BMIs for humans are underway. Simultaneous development in both of these areas is providing hope to victims of trauma and stroke as a way to overcome handicaps resulting from paralysis or amputation.

Current BMI algorithms allow patients to use their thoughts to communicate directly through a computer. For example, current clinical trials of BMIs for use by humans focus on asking patients who have little or no motor function to use the BMI to move a cursor on a computer screen or a keyboard as a way to communicate with others.<sup>23,42</sup> This type of BMI uses a neuroprosthetic implant in the brain to extract spatial degrees of freedom (for example, up/down, left/right) from a number of neurons.

A next step is to use similar techniques to control paralyzed or prosthetic limbs. Uncovering the relationship between neural signals and limb position and movement would enable the development of natural BMIs (which use the neural signals in the same way they already are used in the nervous system) and neurally controlled pros-

theses. This merger of BMIs and robotics could return motor function to paralyzed patients or individuals with amputations by routing neural commands to individual actuators.<sup>20–22,68,71,74,76</sup> Alternatively, remotely operated devices controlled by neural commands could be used to provide precise human manipulation in distant or hazardous environments. Both of these applications rely on the assumptions that neural activity could be translated into intended naturalistic movements and that these movements could then be used to command the movement of a prosthetic device or paralyzed muscles. Animal studies are underway to correlate neural signals with the endpoint trajectory of the arm of an animal in two or three spatial dimensions.<sup>16,28,33,59,60,83</sup> Numerous statistical techniques have been explored to better model the highly nonlinear relationship between neuronal signals and limb movements.<sup>8,69</sup>

In this paper, we study the question of how to design a prosthetic hand that would use BMI. The complexity of our hand mechanisms is one aspect that separates humans from other species, and it is not surprising that a disproportionately large part of the human brain is used to control hand movements. Even if motor functions can be restored to legs and arms following traumas or strokes, victims of such events can only interact with the world in limited ways if they do not have a functional hand. The more than 4 million people in the US who are unable to use their own hands due to paralysis, deformity, or orthopedic impairment could benefit from a complete BMI sys-

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*Abbreviations used in this paper:* ACT = Anatomically Correct Testbed; BMI = brain–machine interface; EMG = electromyography; MCP = metacarpophalangeal.

tem for hand movements (according to the Vital Health and Statistics National Health Interview Survey, National Center for Health Statistics, 1996 [http://www.cdc.gov/nchs/data/series/sr\_]). This is why the development of a robotic hand that is designed specifically for a neural interface is critical in restorative neurosurgery.

A robotic hand that would be part of a complete BMI system must be more anatomically accurate than a corresponding robotic arm. Hands are involved in intimate contacts and dexterous interactions with objects that require the user to control not only the finger endpoint locations (as do current BMIs that control robotic arms) but also the joint angles, forces, and perhaps most importantly, finger stiffness. To duplicate all of these human properties in a robotic hand, the most direct and perhaps the optimal approach would be to duplicate the anatomical musculoskeletal structure of the human hand. In this paper we focus on the critical issues involved in building robotic hands for BMI and the justifications for requiring lower-level neuromusculoskeletal details in designing both mechanical and control systems. In the section directly following this one, we describe three key criteria in designing a prosthetic hand. After that, we review the currently available robotic hands, including a new device that targets the neural interface. In the final section we discuss the lower-level control structure necessary for high-fidelity, dexterous control with BMI.

### Three Key Criteria for BMI Robotic Hands

When researchers consider a robotic hand as a prosthetic device, the focus is on dexterity. The number of fingers and joints is key for clinicians and engineers. However, what the users consider to be crucial is not necessarily aligned with what engineers or clinicians think. In this section we review popular prosthetic devices and outline three key criteria that need to be addressed in designing a robotic hand that a person with an amputation would actually wear.

#### *Conforming to the Societal Norm*

There is a societal expectation to look “normal.” When disabled people walk on the street, they might be noticed because they look or move differently from this norm. Leg prostheses can be covered up with pants and shoes, and they frequently are not noticed. However, hand prostheses are not as easy to hide. They cannot simply be concealed with a glove unless the shape, size, and posture of the device resemble a regular hand. A hook or two-fingered hand cannot be concealed. For this reason, even though there are numerous controllable prosthetic hands available on the market, the most popular ones are nonarticulated but aesthetically pleasing systems such as the LivingSkin hand (Aesthetic Concerns Prosthetics, Inc., Middletown, NY) and the Dermatos hand (Alatheia Prosthetics Rehabilitation Center, Brandon, MS). These devices allow users to interact with some objects, and silicone filling can allow some vibratory tactile stimulation to be transmitted to the residual fingers or hand. Furthermore, if the prosthetic hand looks like a real hand but doesn’t move like one, people easily notice it as unusual. Just as people can pick up slight limps, if prosthetic fingers move with unusual or mechanical trajectories, people will identify this

to be abnormal. Ideally, a BMI robotic hand should both look and move like a real hand.

#### *Comfort of Prosthetic Devices*

If a prosthetic device is not comfortable, the user will not wear it frequently enough to learn how to use it effectively or benefit from it fully. The comfort of a prosthetic device is affected by its size, weight, the ease of putting it on and taking it off, and its interface with the stump and the neural signal source. For example, the lack of hard edges may allow a device to be worn while sleeping. Joints and movable parts must be shielded so nothing can get pinched and no food crumbs can get inside. No parts should heat up, even under extreme usage. All of these issues are challenges in designing a robotic hand. Matching the weight of the prosthetic hand with that of the original limb while also matching the degrees of freedom is extremely challenging when using current materials. As discussed later, most robotic hands built to date cannot be classified as either comfortable or convenient.

#### *Ease of Control*

If the BMI algorithm for control of a prosthetic hand does not preserve the relationship between the cortical signals and the original hand movements, it could be difficult for the user to learn to control the prosthetic device. If this happens, or if it takes too much time to train the device to adapt to the user’s neural signals, he or she probably will abandon the prosthetic device.

To control a BMI device that is currently in clinical trials, the user is instructed, for example, to imagine a balloon floating upward, which moves the cursor on the computer screen upward. As the user thinks about the balloon moving, the neural signals are recorded and distinguished from neural signals that are transmitted when the user is not thinking of the balloon. Freehand and other similar neuroprosthetic systems provide pinching and grasping behaviors that are commanded by electrical stimulation of the devices through the actions of functional muscles or joint movements (for example, contralateral shrugging motion of shoulders) that are unrelated to the hand area.<sup>30,32,45,63,70</sup> These examples work well for their applications if the number of degrees of freedom that they control is kept relatively low. However, a greater number of control strategies would be required to provide easy control of a highly articulated prosthetic hand and to train the hand to adapt to the user’s neural signals.

One way to express human hand movements, although it allows for fewer degrees of freedom, is to use a principal set of hand postures, known as primitives or synergies.<sup>54,66,67</sup> It has been shown that most of the grasp motions can be achieved with a combination of only a few primitive postures. It has also been shown that stimulating a specific set of motor neurons in the primary motor cortex results in a set of postures used for grasping.<sup>24,25,34</sup> These primitive postures can be important in allowing simple movements such as holding a coffee mug or a pen, but they can not be used for dexterous interactions with objects that involve force and stiffness control.

To provide a person who has had a limb amputated with a fully dexterous prosthetic device that is easy to control, it may be best to use the cortical control structure that

interacted with the original hand. The brain is probably plastic enough to learn some modifications to the original mapping from cortical signals to finger movements. However as more of this highly nonlinear relationship is captured within the BMI system, it will be easier for the user to learn to control the prosthesis. The incorporation of this highly nonlinear relationship into the design of a prosthesis requires not only advanced statistical methods but also modeling of the anatomical nonlinearity in the device itself.

### Currently Available Robotic Hands

In this section we review the currently available anthropomorphic robotic hands, address the reasons for needing an anatomical robotic hand for BMI, and describe the design of the ACT Hand.

There have been numerous anthropomorphic robotic hands made for various reasons, including those constructed to perform various assembly tasks (BarrettHand; Barrett Technology, Inc., Cambridge, MA), for the investigation of human-like manipulation abilities,<sup>4,38,55,65</sup> and as a part of a humanoid robot<sup>48,55</sup> (Fig. 1). Some of these hands achieved dexterity in performing specific tasks matching that of human hands; however, none of these hands is completely anatomically equivalent to a human hand, for one of the following three reasons. First, in designing the device, it was never important to mimic the biology of the hand. As long as the specific tasks the creators wanted to achieve could be accomplished in somewhat human-like ways, a design that was not strictly anatomical was acceptable. Second, making the hand anatomically equivalent was too complex or otherwise too difficult, or the space involved was too limited to fit everything needed. As a result, the creators, understandably, simplified the actual anatomical structure when making their design. A typical example of this is to limit the degrees of freedom within each finger. The Cog hand and the Belgrade/USC hand have a single degree of freedom per finger.<sup>4,55,56</sup> The Robonaut hand has 12 total degrees of freedom for five fingers,<sup>48</sup> and the JPL/Stanford hand has three degrees of freedom per finger.<sup>65</sup> Third, the goal was to construct a hand that mimicked a human hand's degrees of freedom and its joint movements but not its biological control mechanisms. Each finger of the Utah/MIT hand has four degrees of freedom, the same as a human finger,<sup>38</sup> but each joint is actuated by two dedicated cables, unlike a human joint, in which a complex web of tendons actuates the joints. In addition, the lateral degree of freedom at the MCP joints is not anatomically accurate in its kinematics.

Lee and Shimoyama<sup>46</sup> built a prosthesis that mimicked the extrinsic muscles of a human hand but did not include the intrinsic muscles due to their complexity. The ShadowHand (Shadow Robot Co., London, United Kingdom) and the Gifu Hand<sup>41</sup> (Dainichi Co., Ltd., Kani, Japan) have four joints per finger and fairly accurate ranges of motion for each joint. Of the ones currently available, these two prostheses are perhaps the closest to human hands. However, because the goal in their design was not for use in a BMI, their joint movements are not kinematically accurate to the human counterparts, human force/stiffness modulation cannot be mimicked, and the neural inputs to the muscles cannot be used to move the fingers. In a consortium project in the European Union, investigators are working

on a device called the CyberHand that is designed to recreate the natural link that exists between neural signals and the hand.<sup>17,18</sup> This prosthetic hand will interface with the peripheral neural signals that used to arrive at muscles of the original hand. Because this hand does not mimic the human musculoskeletal structure, the neural signals will be interpreted to correlate with the joint movements. Furthermore, although this hand has passive compliance, it is not the same compliance as in the human hand.

As a way to understand the routing structure of human tendons and to find the optimal routing method for robotic cable, the force capabilities of human fingers have been studied and compared with those of two robotic hand systems.<sup>3</sup> Typical robotic hands have symmetrical flexion/extension force capabilities, whereas human fingers have flexion-dominant force production capabilities. It has been shown that for a robotic finger with four degrees of freedom, expressed as  $N$ , particular arrangements of control cables to create either two times  $N$  or  $N$  plus one degrees of freedom will yield a finger that achieves the same range of forces as a human digit.<sup>62</sup> Valero-Cuevas<sup>78</sup> used the principles of robotic manipulation to analyze human digits as serial manipulators and was able to predict muscle activity levels for specific force production. Biggs and Horch<sup>6</sup> built a three-dimensional kinematic model of the index finger and the muscles that actuate it.

Numerous studies have been conducted on the anatomy and function of the human finger extensor mechanism, also known as the dorsal aponeurosis.<sup>7,26,27,31,39,44,58,73</sup> Garcia-Elias, et al.,<sup>26,27</sup> measured seven human extensor mechanism specimens to determine the average stiffness values for different branches of the structure. They also measured the changes in geometry of the weblike structure of the same specimens for different finger postures and determined that although changes in length along individual segments were relatively small, the spatial orientations of the segments varied considerably.<sup>26</sup>

When put together, these investigations are helping engineers in the design and construction of a robotic hand for a BMI that it is anatomically accurate compared with the human counterpart, and in which the force/stiffness modulation is mimicked and the neural inputs to the muscles can be used to move the fingers.

### *Advantages of Anatomical Structure for BMI*

Although the majority of robotic hands do not mimic anatomical structures accurately, there are several reasons why it is crucial to do so for BMIs.

*Original Control Strategies are Usable.* When the prosthetic hand is anatomically correct, the input to this hand can use the same neural signals that arrived at the muscles in the original hand. Neurons that encode muscle-level commands can be used along with the neurons that encode other, higher-level commands. The user's own spinal reflex can be used appropriately. Also, the more similar the mechanical structure is to a human hand, the less learning time is required for the user to simulate dexterous behavior.

*Peripheral Nonlinearity is Modeled in Hardware.* The relationship between the cortical signals and the finger joint movements is not only a high-dimension relationship, but it is also highly nonlinear. Removing some of this nonlinearity by using hardware that mimics the biomechanics of

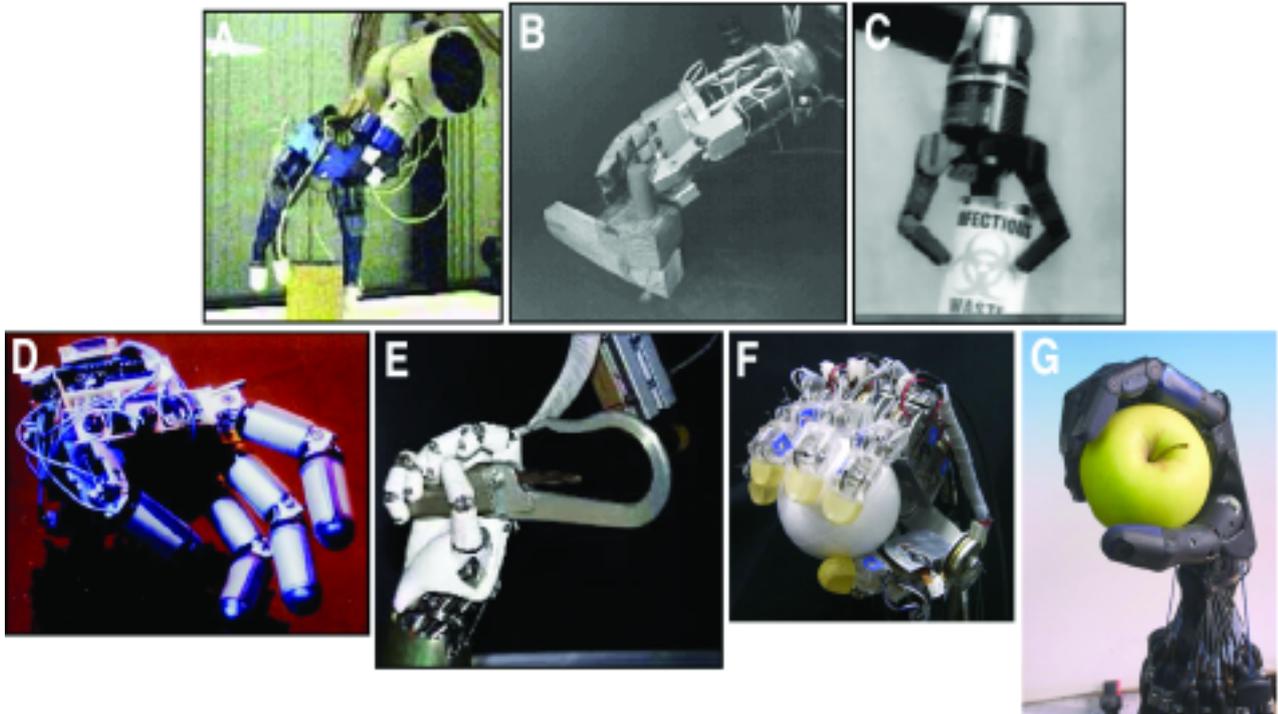


FIG. 1. Photographs of sample anthropomorphic robotic hands. A: The JPL/Stanford Hand (reproduced with permission from Professor Salisbury). B: The Belgrade/USC hand (reproduced with permission from George Bekey). C: The BarrettHand (reproduced with permission from Barrett Technology, Inc. [<http://www.barretttechnology.com/robot/products/hand/handfram>]). D: Cog Hand. E: The Robonaut hand (reproduced with permission from the National Aeronautics and Space Administration). F: The Keio Hand (reproduced with permission from Professor Maeno). G: The ShadowHand (reproduced with permission from the Shadow Robot Co., (c) 2006).

the hand vastly simplifies the BMI algorithms needed. Furthermore, dexterous behavior with stiffness and force controls can be simulated with fewer actuators if the anatomical structure is mimicked. Natural passive degrees of freedom are incorporated automatically.

*Partial Prosthetic Device is Possible.* If the partial prosthetic hand is built so that it is anatomically correct, sub-components could be integrated back into the user's hand at any transitional locations. For example, a patient who is missing a few segments of a finger can get a functional digit by having the existing musculoskeletal system stitched to an anatomically correct prosthetic finger. The patient could then use exactly the same neural control techniques that had been used to control the original finger. This anatomical approach allows as much of each patient's residual structure as possible to be preserved and available for incorporation in a complete BMI system. If the prosthetic device is not anatomically correct, then the entire original hand might have to be amputated to be connected to the whole prosthetic hand system.

#### *Design of the ACT Hand*

For the advantages listed earlier to become manifest, it is clear that the development of an anatomically correct prosthetic hand with musculoskeletal accuracy is critical for BMI. The mechanical model presented in this section is called the ACT Hand (The Robotics Institute, Pittsburgh, PA).<sup>19,29,81,82</sup>

Figure 2 shows an ACT Hand integrated into a robotic arm (WAM Arm; Barrett Technology, Inc.). This hand replicates a human hand's degrees of freedom, kinematics, number of bones and muscles, and muscle strengths as well as its musculotendon origin and bone insertion points, so that forces can be applied by the muscles at the same locations and along the same vectors as they are in the human hand. In addition, this hand has replicated the human hand's passive musculotendon properties, overall size, and tendon routing structure. Musculotendon passive properties are known to be spring-like and allow compliance to the fingers. To replicate the tendon routing structure, the structure of the extensor mechanism was investigated and mimicked.<sup>5,82</sup> Modeling of the extensor hood onto a mechanical finger revealed that the extensor mechanism provides independent control of the MCP joint and acts not only as an extensor but also as a flexor, abductor, adductor, or rotator, depending on the finger's posture.

To provide correct dynamics in the extensor mechanism, the shape of the bone surface was replicated. Three-dimensional data obtained in human bones was used in our computer-assisted device system to model the subtle bumps, dips, and curves and to integrate our mechanical joints directly into our design.<sup>81</sup> Furthermore, the bone mass was matched with its human counterpart by assigning to our models a density equal to that of human bone ( $1.9 \text{ g/cm}^3$ ) and removing extra materials from inside the bone structure.<sup>14</sup> Small cylindrical volumes were added to represent the estimated synovial fluid at the proximal end

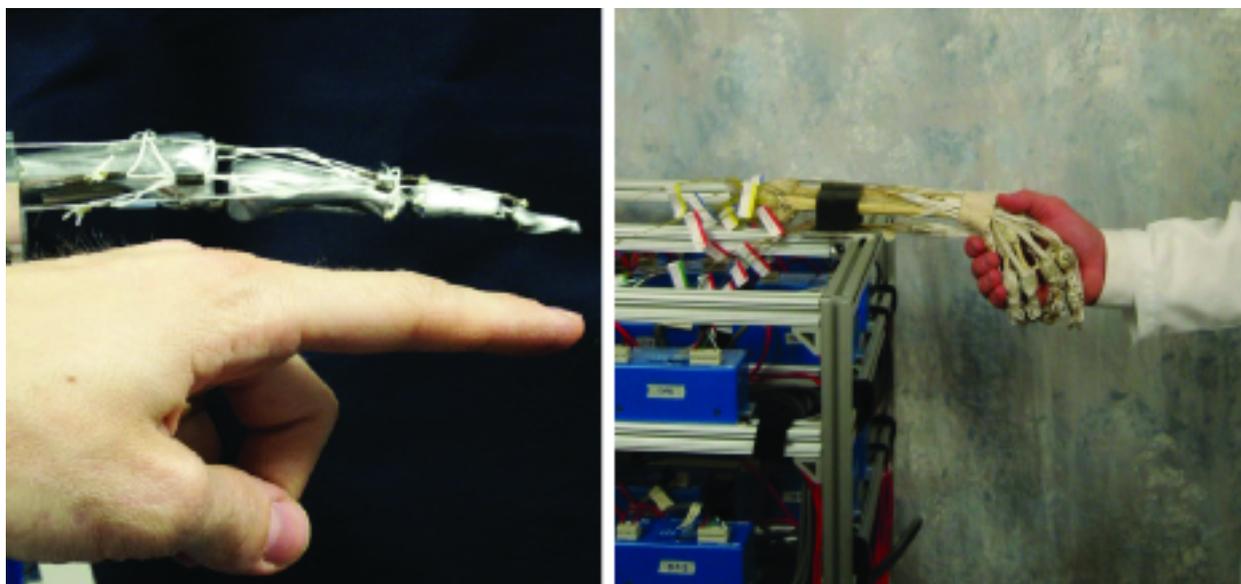


FIG. 2. Photographs showing the ACT Hand used for BMI.

to mimic the joint mass properties. These volumes were assigned a density equal to that of water ( $1.0 \text{ g/cm}^3$ ).

To mimic actions of human joints, three critical properties were matched at each one. First, the geometry of each joint was matched to have the same degrees of freedom, range of motion, and relationships between the axes as its human counterpart. Second, the internal friction of each joint was also mimicked. Third, the elastic properties of each joint were matched to ensure the consistent dynamic performance of each joint by itself and in relation to the others. Most importantly, these critical properties were designed so that their use would not affect the other components of the system.

The joint axes were placed in the correct anatomical position for accurate finger dynamics. For example, the ACT thumb recreated five anatomical axes of a human hand to represent hand biomechanics accurately.<sup>19</sup> Computer simulation of a thumb model with intersecting and orthogonal axes at the MCP and carpal metacarpal universal joints predicted that forces would be generated at the thumb tip that would not match what humans would produce.<sup>80</sup> In addition, Hollister, et al.,<sup>35,36</sup> reported that modeling the robotic thumb with nonperpendicular and offset rotational axes provided the kinematic basis for other important anatomical characteristics, such as muscle moment arms about a given rotational axis. Using the more complex model of nonorthogonal and nonintersecting joints more accurately preserved the workspace of the thumb. For the ACT Hand, this could be achieved without added actuation complexity because the motors are connected indirectly to the bones through the tendons instead of being mounted directly within the joint, as is done in other robotic hands.

An effective moment arm created by the muscles is critical to the biomechanical mapping between the muscle activation level and the kinematic configuration. The design decision to use the exact three-dimensional bone geometry and add a tendon routing structure was specifi-

cally aimed at preserving the relationship between the muscles and the moment arm at all joint angles and for all degrees of freedom. In particular, the moment arm is not constant with the joint angle.<sup>2,72</sup> Sample data for the moment arm from the ACT thumb are shown in Fig. 3A. The majority of the data for the ACT finger fell within one standard deviation of cadaveric measurements.<sup>19</sup>

The choice of which actuators to use for the ACT Hand was difficult because none of the ones currently available matched the combination of size, weight, and strength in the muscles involved in controlling a human hand. Many actuators have been developed to simulate muscles. Some of these devices are made with shape memory alloys,<sup>61</sup> hydrogel polymers,<sup>75</sup> and pneumatics.<sup>13</sup> The most popular muscle-like actuators used in practice are McKibben-style pneumatic devices because they are small and compliant.<sup>15,77</sup> In addition, they respond quickly, unlike those made with hydrogel polymers, and have a reasonable travel length compared with those made with shape memory alloys. On closer inspection of natural muscle properties, however, it becomes evident that the compliance of a McKibben muscle simulation is significantly different from that of human muscles. On the other hand, a system that uses servomotors could more precisely mimic the properties of human muscle by using external springs and control. Servomotors are more efficient sources of power than other actuators, so they are more effective in terms of size and weight than alternatives such as batteries, controllers, valves, pumps, and other components. Nonlinear, custom-made springs were added in parallel to simulate the passive compliance of the muscles.<sup>29</sup> This parallel structure provides faster response, the necessary compliance to achieve stable force control,<sup>37,64</sup> and the ability to use a simpler control algorithm for the motor drive.

The ACT Hand has a sensory feedback structure equivalent to that of muscle spindles and Golgi tendon organs in a human hand. (In a human hand, the muscle spindles detect the length, and the Golgi tendon organs detect the

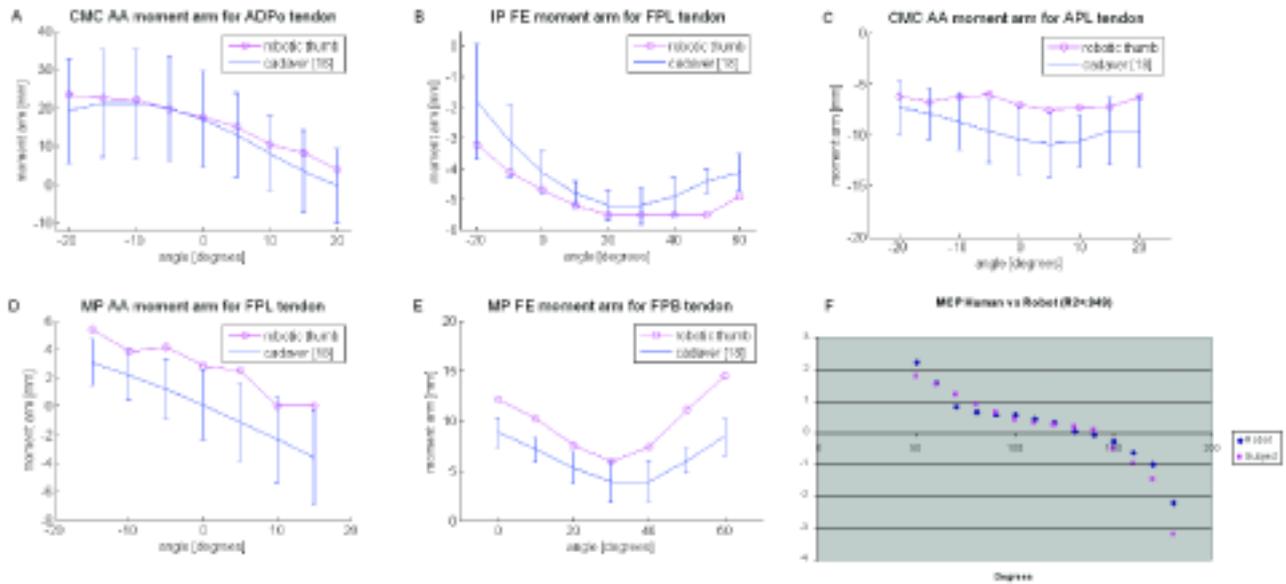


FIG. 3. A–E: Graphs of comparisons of moment arms in data obtained in cadavers and an ACT thumb, showing most ACT moment arms within one standard deviation of values obtained in cadavers. F: Graph of results of system identification experiments conducted in an MCP system, showing validation of the mechanical design compared with human data ( $R^2 > 0.9$ ). AA = abduction/adduction; ADPo = adductor pollicis; APL = abductor pollicis longus; CMC = carpal metacarpal; FE = flexion/extension; FPB = flexor pollicis brevis; FPL = flexor pollicis longus; IP = interphalangeal; MP = metacarpal phalangeal.

tension of each muscle.) With this anatomical sensory feedback structure, the proprioceptive information that is fed back to the cortex can be used for the BMI. The ACT Hand does not provide joint angle sensing, but through kinematic calculations (and even some tactile feedback), users should be able to infer the joint angles. High-density, compliant skin is under development.<sup>43</sup> With this skin, a rough estimate of the joint angles could be provided by monitoring the stretching of the skin near the joints. The tactile feedback provided by the skin is also critical for a BMI.

Finally, system identification experiments were conducted on the assembled fingers to ensure that when the individual components of the robotic hand such as tendons, bones, joints, and muscles were put together, the whole system had properties similar to those of its human counterpart. The data from the joints were correlated and shown, using static system identification, to have an  $R^2$  of more than 0.9 (Fig. 3F).

The ACT Hand is a robotic hand that is built to enable the use of BMI applications. It also has been used as a test bed to study the biomechanics and neuromuscular control of human hand movement so that the BMI system can be further improved. With this level of anatomical accuracy, it should be possible to satisfy the design criteria of conforming to the societal norm and providing adequate ease of control. The comfort criterion should improve as the weight of the device drops with advances in material science.

### Lower-Level Hand Controller for BMI

To take full advantage of the anatomically correct structure of the hardware, it is crucial to preserve the lower-level neuromusculoskeletal control structure that is part of the hierarchical BMI control. Recreating dexterous behav-

ior requires not only moving the prosthetic endpoint to the desired position in space but also producing the desired limb force and stiffness. In this section, we describe the lower-level details that are necessary to simulate human-level dexterity as a part of a BMI controller.

It has been shown that neural signals predict dynamic movements of hands better when the lower-level musculoskeletal parameters are explicitly provided.<sup>49,57</sup> Afshar and Matsuoka<sup>1</sup> noted that the dynamic index finger con-

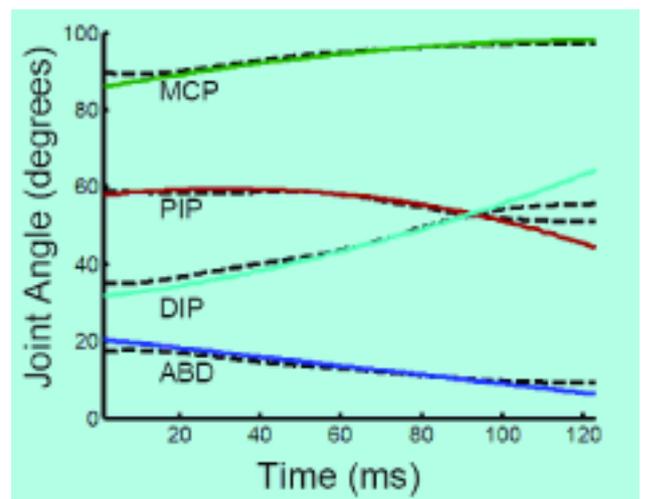


FIG. 4. Graph showing joint angle predictions of a neural network with an EMG-based torque estimate as input. *Solid lines* are measured joint angles, *dotted lines* are predicted by the network. ABD = metacarpophalangeal joint abduction; DIP = distal interphalangeal joint; MCP = MCP joint flexion; PIP = proximal interphalangeal joint.



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Manuscript received March 30, 2006.

Accepted in final form April 28, 2006.

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