

THE HUMAN HAND

remember the first time I touched my wife's hand. It was truly electric, as it still is today. Her skin was warm and smooth. I don't know how I could sense it, but through her touch I could feel her radiance, warmth, confidence and sense of humor. That first touch instantaneously triggered every one of my brain cells and immediately created a unique haptic signature that still persists 31 years later. Similarly, I remember how my grandfather's hand felt 24 years ago, when he was 92, as I sat on the couch next to him holding his hand. He was tall with thick, calloused hands from the manual labor of a farmer pushing on the end of a shovel, picking apples or working on his Farmall A tractor. While his hands were large and strong, his touch was gentle. I also will never forget how my memory of his hands changed in an instant when I reached out and held them as he lay in his casket.

By Bryce G. Rutter, PhD, IDSA

The human thumb affords opposition and has allowed

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What is truly amazing to me is how indelibly etched these tactile experiences are in my heart and mind decades later. These are great examples that underlie the power of touch and the permanence of haptic memory. Both magnify the need and opportunity to sweat each and every detail in the design of everyday objects-because every detail matters.

What Is a Human Hand?

Next to the brain, the hand is the most fascinating and complex human organ we have. It is used for more natural actions that interface with our artificial world than any other anatomical unit, and as such its role in helping humans to effectively work and play is significant. Given the central role hands play in our existence, it is surprising just how little we understand about how we elicit such utility from these funny-looking, five-pronged, multihinged instruments of prehension dangling from our shoulders.

The oldest definition of

the human hand is provided by Sir Charles Bell in his 1834 Bridgewater Treaties, Volume IV: The Hand, Its Mechanism and Vital Endowments as Evincing Design: "We ought to define the hand as being exclusively to man-corresponding in sensibility and motion in that ingenuity which converts the being who is the

weakest in natural defense, to the ruler over animate and inanimate nature." Without a doubt this is the most fascinating book written to date on the evolution, phylogeny and ontogeny of the human hand. Bell's definition, by virtue of its generality, is specific and offers clearly defined boundaries for the word. Human is implicit in the word "hand."

What is clear and defining about the human hand is that we possess an opposable thumb to the other four fingers. This hand function alone separates man from primates, who also possess five digits but without opposition do not have the advance functioning capability that we as humans possess as toolmakers. So next time you look at your hand, pay a little more respect to the role of your thumb!





Think about how we use our hands throughout a typical day. You wake to your alarm using your fingers to turn it off, trudge off to the kitchen to load your coffee maker, grab

and position your cup

under the spout, grasp the fridge door handle with one hand and with the other reach in and grab the cream that you then pour into your coffee. Using a wide variety of grips and dexterous motions, you use knives, forks, spoons and other kitchen appliances to make a quick breakfast. Now off to work. You jump in your car, and using a wide variety of hand controls, you navigate the streets while selecting your source of entertainment and adjusting the climate. At work you sit in front of your workstation using your mobile device,

> keyboard and mouse to navigate another digital day. Two hours in and the amount of time and the number of different ways in which you have used your hands to navigate a typical life is nothing less than amazing and ubiquitous. There is no other organ we use as continuously and with as much variety as we do with our hands.

> Our current understanding of the human hand is limited to physio-

logical and anatomic characteristics and, to a lesser degree, by mechanical properties of what the hand is capable of doing. To date, there is no agreed to model on how the hand is controlled or coordinated by the brain-referred to as motor control. The prevailing majority opinion is that as we mature we build a library of motor programs that are stored in our brain that we draw on for each and every action. For example, this camp believes that when you reach for your cup of coffee in the morning that there is a homunculus in your mind that selects the "grasp my coffee cup" motor program off the shelf that drives your grasping behavior. Regardless of the prominence of this opinion, it's impossible for me and other leading experts to accept this



theory when you think of the trillions of motor programs that would need to be stored in your brain for even the simplest day—not to mention the need to marshal them in picoseconds or less to execute a successful outcome without any delays. This camp also has great difficulty explaining how we can successfully execute new and novel behaviors when there is no previous motor program to pull off the shelf.

In 1967, J.J. Gibson pioneered the field of ecological psychology, which prescribes that our movements and behavior are driven by what we see and that objects around us provide information meaningful to the control and coordination of action—*affordances*—and when integrated with intentionality cause us to react with the most effective action patterns. For example, when you look at the handle of your coffee cup, you immediately and automatically know what grip to use based on the relative size of your hand to the size of the handle and whether the cup is full or empty.

Understanding affordances and how they drive our grasping behavior is important because through the articulation of a product's shape, size, color, textures, mass, etc., designers are in fact constructing affordances that tell users how to most effectively interact with the product. For example, if design constraints dictate that a product requires a specific amount of force or range of motion, the designer can embed visual, tactile and auditory cues into its design that will afford and elicit the most effective user behavior, biomechanically, functionally and emotionally.

All of us at some point in time have tried to use a product only to be frustrated to learn that how we think is in fact incorrect. This lack of intuitiveness is directly linked to a product's affordances being wrong. Explicit and seamless communication of a product's functionality means that the content of its affordance provides all the necessary cues relative to action, size and form for the user to automatically determine the optimal behavioral interface. A final point: I do not want to confuse product semantics with affordances where the former speaks to a product's imagery, contrasted to the latter, which is the scientific and calculated articulation of a product's form, scale, texture, color and physical properties by the designer to communicate all necessary visual, physical, functional and sensory-based cues to drive the most efficient human response. As we grow and as adults when learning new and novel tasks we acquire coordination and control in the arm by first "locking" out the elbow, wrist and hand joints, then after mastering shoulder control we successively unlock and master the remaining joints—proximal to distal motor skill develop.

How Hands Get Smart

We've all witnessed infants taking their first Frankenstein-like steps, then over time learning to walk fluidly like an adult. Similarly, when you are learning how to play a racquet sport you have the same initial awkward robotic motion, and as you begin to master the skill, your finesse, coordination and control increase. In both cases, the same phenomena is in play. Mastery of coordination, control and skill in the hand develops proximally to distally. As we begin to learn a new task, our brain by necessity limits the degrees of freedom it needs to control the biokinematic chain. When learning any new, hand-related task, first we lock out the shoulder joint, then our elbow, wrist and fingers so that our brain has fewer things to control. Then as we develop mastery over our shoulder joint, our brain engages control of the elbow and subsequently the wrist and then the fingers.

This is important when designing handheld products that require any degree of novelty or learning. To the extent that you can design a product that leverages legacy motions that do not need to be learned, there will be a benefit. However, when not possible and you are designing products that require novel control characteristics, it is imperative to think about how novice users will migrate to expert users and how you can articulate the scale, form, textures, control interface and configuration of the product to mitigate control conflicts and to optimize the acquisition of dexterity. This is accomplished by designing in physical attributes that allow the novice user to be successful as they migrate through to mastery.

Grip Architectures & Grasping Strategies

While the variety of things we do with our hands on a daily basis are broad and diverse, common threads cut across the way in which we use our hands. Broadly speaking, we use three general categories of grip architectures: static grips, dynamic grips and gravity-dependent grips. The most common type of static grip we design for is a power grip when brute force is needed, for example, when swinging a hammer or holding a small bone saw steady when cutting the skullcap. The most common type of gravity-dependent grip we use daily when carrying things is the hook grip. Precision grips—which include bilateral, trilateral and multilateral grip architectures—are used when accuracy is needed, and typically are dynamic grips that we use to execute dexterous control over an object.



Static and gravity-dependent grips differ from precision grips in that the former relies primarily on the larger and more powerful extrinsic muscles of the hand in the forearm, whereas precision tasks utilize small muscles within the compass of the hand. Small muscles within our hands provide highly dexterous and accurate movement and control; however, they quickly become fatigued. Conversely, when using static and gravity-dependent grips that recruit larger muscles in the forearm and upper arm, these muscles have more endurance, but the trade-off is that they also provide less accuracy. The challenge in the design of hand-intensive products is determining the balance between endurance, strength, precision and dexterity, then developing a design strategy that elicits the most effective balance between these factors.

Scaling Products to Fit 5th to 95th Percentile Hands

One of the biggest challenges in designing handheld products is accommodating hand size variances. Intrinsic variability in hand size also equates to variability in strength (remember smaller fingers have smaller muscles and strength is correlated to the cross-sectional area of the muscle), and directly impacts the functional reach envelopes of the digits themselves. These factors directly impact the design and layout of controls for tools, instruments and, more generally, any handproduct interface. Variability between a small female hand and a large male hand can be up to 1.5 inches in length and 1 inch in breadth across the metacarpal ridge. (shown right)

An effective design strategy for addressing accommodation is to overlay the optimal hand-product interfaces for 5th, 50th and 95th percentile hands, both male and female, and use this compound mapping to help derive surface topology and switchology locations that will accommodate the full range of users. When working through this balance with small hands, be cautious about including too much fill in the palmer region, which effectively pushes the hand away from the product and directly impacts fingertip reach and the ability to exert fingertip control. With large hands, reach and force are typically not an issue. However, because of the scale of the digits themselves, spacing of switchology becomes much more critical in preventing accidental actuations. Also important with large hands is to ensure that there is sufficient bulk on the product to engage the ring and pinky fingers to ensure a good, secure grip, while the index, middle and thumb are busy performing highly dexterous control operations.

It's not uncommon for designers to be challenged with developing a sizing program to accommodate 5th to 95th percentile hands. We see examples of this every day with small-, medium- and large-size categorizations. The classic mistake when implementing a sizing program is the assumption that the product can be linearly scaled. Scaling products to accommodate for size variability is a nonlinear exercise.

Without getting into all the details, consider the basic physics of body scaling. As length is doubled, mass increases as a cube function.

Strength, on the other hand, is proportional to the crosssectional area of muscle, which has also been doubled while the mass of the hand has been cubed. As a result, the dynamics within the larger hand are entirely different than the smaller hand. This kinematic difference alone needs to be reflected in the design of the product.

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While we all share the same anatomic structure, all of us have a unique fingerprint.

Touch Sensitivity

Our ability to sense infinitesimal differences in dimensions, temperature, surface textures, surface topology and materials is nothing short of astonishing. Within our 10 fingertips alone we have no less than 20,000 specialized neuroreceptors that independently sense and report back to the brain heat, cold, proprioception, pressure, itch, chemical pain, thermal pain and joint stretch. Equally stunning is that all the more than 7 billion people on this planet have a unique fingerprint.

Our hands afford the ability to sense a bump on a sheet of glass as small as 3 microns high—to put that in perspective, hair ranges from 80 to 120 microns in diameter. I've conducted research on computer input devices in which 0.009 inches in the height of a mouse can be sensed by the palm of the hand, causing users to score the design as being a poor fit. I've seen in the design of a pen's input stylus that as little as 0.001 inches transforms it from feeling perfect to feeling like a fence rail in your fingertips.

This potency of touch can easily be witnessed by placing laptops from different manufacturers in front of you, then closing your eyes and running your fingertips slowly across the surface of the lids. Some feel masculine, and some feel feminine. Some feel tough, and some feel durable. And some simply feel cheap and awful. Because our fingertips are populated with these highly specialized and unbelievably accurate sensors, minute changes in something as simple as texture define how consumers experience your product and how your brand imprints its signature in their mind.

The power of tactile sensitivity and the accuracy of our fingertips are showcased by those who have lost their sight. Those who are blind feel the world through surfaces, textures and temperature, and communicate through the subtle and sophisticated three-dimensional language of Braille. Through minute changes in dot reliefs, Braille readers sense patterns to discern individual characters, and with the stroke of their hand across a line of what appears to be random dots, they integrate and translate patterns into words and sentences. The sense of touch provides what the loss of vision has taken.

The Future of Handheld Product Design

Many argue that in the future, we will not hold products but rather will control functionality through nontactile holographic interfaces or interfaces that provide synthetic haptics. Once we cut the cord and migrate into synthetic interfaces, a myriad of design opportunities and challenges will be introduced.

Let's consider what is going on in the robotic surgical system space. Because everything is controlled by wire, as opposed to traditional mechanical connections, we can design every system response to produce what we think is the optimal man-machine interface design. But how do we define this optimal interface? How closely should we be mimicking our human system? And do we now have the technical capability to amplify hand function?

We know through research that when you reach to grasp something, there are two distinct phases in this movement action. First is the transport phase where your hand form is frozen and transported close to the proximity of the object with which you want to interact. During this phase, your arm accelerates and then decelerates as you approach a point in travel when the hand unlocks and the manipulation phase begins; when the hand and fingers begin to form into the grip architecture needed to be successful. Similarly, during the manipulation

phase, your hand accelerates, and then as it approaches the object of desire it decelerates until contact is made. There has been significant research conducted in the kinematics of this motion, and we understand it clearly. So a key question in the design of any robotic interface is whether or not you replicate the exact kinematics of the human system or amplify or alter certain kinematic features of this natural action to improve hand performance.

A related design factor is gain. For example, when a surgeon who is interfacing with the controller moves the hand's position by 2 inches, at what amplitude should the tool tip be? Research is inconclusive on this topic. Based on research and the few systems in place today, there seems to be gravitation toward a sweet spot somewhere in the order of a 2:1 to 5:1 gain. More generally when considering gain, the type of robotic system we are dealing with drives the significance of the gain parameter.

How we design in gain depends on the type of robotic system being developed. If it is a surgical robotic system operating within the heart where fractions of a millimeter matter, then what we may need to do is dial in gain that decreases the potential risk of crashing into sensitive anatomic structures, thereby actually enhancing surgical performance. Alternatively, when operating heavy equipment, such as controlling a bucket on a backhoe, we have a lot more latitude in terms of speed and accuracy, and as a result, the amount to gain we introduce into the system can be dramatically different. Furthermore, we need to look beyond fixed gain and evaluate the benefit of dynamic gain and conIs there a better hand design?

sider how we apply it across both the transport and manipulation phase of grasping to enhance hand-function performance.

Another interesting factor in robotic interface design relates to who the user is. Younger millennial users who have grown up with virtual reality and have advanced dexterous control experiences from years of gaming present an entirely different set of legacy experiences and skills when compared to baby boomers. Robotic surgical systems are far less daunting to millennials than they are to baby boomers, who sometimes struggle to adopt new techniques with different degrees of freedom. What is fascinating is that research suggests that traditional laparoscopic surgeons need no more than five or six surgical procedures to be at parity when using a robotic surgical system. It's unclear as to

whether or not this is entirely due to the elimination of reflected motion or is a combination of the kinematics and true motion. What is clear from the research is that regardless of age, the most difficult surgical skill, suturing, is improved when using a robotic surgical system as compared to using traditional laparoscopic hand instruments.

Synthetic haptics offer the ability to amplify feedback to the user. For example, surgeons routinely use the tip of their instrument to gently tease and push against the tissue in an effort to feel the tissue's compliance and characteristics. It's not at all unrealistic to think that we can amplify this feedback in a way that provides surgeons with a degree of touch they have never experienced before, thereby enhancing their surgical performance.

Another area of advanced research is in gestural and holographic interface design. We've now gone beyond a physical connection between the user and the system and are now driving control through dynamic gestural hand forms. This is the edge today. Thought leaders are exploring ways in which we can accelerate control, minimize the stress and fatigue on the human hand, and amplify the sense of touch.

For me, I find the concept of touch versus synthetic haptics to be a conundrum. While the latter may increase my ability to perform in virtual space, I wonder whether it disconnects me from the hand-mind emotional experience that I get every time I touch my wife's hand or when I grasp the perforated leather steering wheel of my sports car. Or maybe we need to consider surgical techniques to alter the hand's design in order to improve performance!