Tactum: A Skin-Centric Approach to Digital Design and Fabrication

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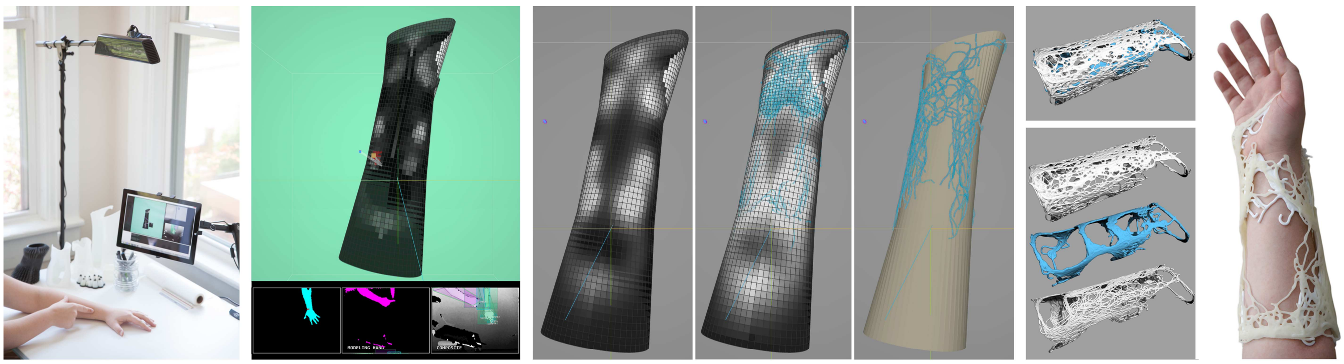

(a) (b) (c) (d)

Figure 1. Our fabrication-aware design system captures a user's skin-centric gestures for 3D modeling directly on the body. (a) the system captures skin input on a user's forearm and (b) translates it to a digital 3D modeling environment model. (c) skin-centric gestures enable the user to create a 3D printable design, (d) which inherently fits the complex geometry of their forearm.

ABSTRACT

Skin-based input has become an increasingly viable interaction model for user interfaces, however it has yet to be explored outside the domain of mobile computing. In this paper, we examine *skin* as an interactive input surface for gestural 3D modeling-to-fabrication systems. When used as both the input surface and base canvas for digital design, skin-input can enable non-experts users to intuitively create precise forms around highly complex physical contexts: our own bodies. In this paper, we outline design considerations when creating interfaces for such systems. We then discuss interaction techniques for three different modes of skin-centric modeling: *direct*, *parametric*, and *generative*. We also present *Tactum*, a new fabrication-aware design system that captures a user's skin-centric gestures for 3D modeling directly on the body. Lastly, we show sample artifacts generated with our system, and share a set of observations from design professionals.

INTRODUCTION

Skin-based input has become an increasingly viable interaction model for user interfaces. This large, always-available surface enables intuitive, tactile interactions [30, 43] and can even be reliably accessed without visual feedback [30, 23, 43]. However, skin-based input has yet to be explored outside the domain of mobile computing. In this paper, we examine *skin* as an interactive input surface for gestural 3D modeling-to-fabrication systems.

Gesture-based interfaces for 3D modeling offer a number of unique affordances that can empower non-expert users to participate in digital design. They facilitate the expressive creation of digital geometry, while requiring little prerequisite skill for most interactions [8, 36]. However, their intuitive use comes at a cost: it is difficult for these systems to enable both high precision control *and* expressive form generation. As a result, the digital geometry generated is often limited to abstract or sculptural forms [20, 25, 34, 35, 49]. *Skin*, as both the input surface and base canvas for digital design, can enable non-experts users to intuitively create precise forms around highly complex physical contexts: our own bodies.

Further, as new forms of 3D printing and digital fabrication are reaching wider, non-technical audiences, there is a potential for users to design and fabricate personalized products [7]. In some cases, such personalization may relate to a user's own body – such as jewelry, braces, and other wearable devices. As such, we explore both design *and* fabrication workflows that utilize skin as an input platform.

In this paper, we make four contributions along these lines. First, we outline design considerations when creating interfaces that use skin-based input for gestural 3D modeling-to-fabrication. Second, we discuss interaction techniques for three different modes of skin-centric

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modeling: *direct*, *parametric*, and *generative*. Third, we present *Tactum*, a new fabrication-aware design system that captures a user's skin-centric gestures for 3D modeling directly on the body (Figure 1). Last, we show sample artifacts generated with our system, and share a set of observations from design professionals.

RELATED WORK

Our research builds upon existing work in digital garment design, gestural 3D modeling, skin-based mobile computing, and fabrication-aware design.

Digital Garment Design

Computer-Aided Design (CAD) for the body brings unique challenges in simulation, interaction, and manufacturing [24]. Research for screen-based garment CAD systems has focused extensively on simulating the drape or movement of cloth [38], generalizing models of human anatomy [40], interactive 3D modeling [37], and deconstructing 3D designs for 2D fabrication [26]. Tangible interfaces for garment design and fabrication have attempted to augment traditional tailoring tools with computer vision [44] or embedded intelligence [47].

However, none of these systems attempt to use skin as an interactive input surface for a gestural 3D modeling-to-fabrication system. In addition, these systems only focus on cloth-based garment design, and do not incorporate CAD for rigid or semi-rigid 3D printed materials.

Gesture-Based Modeling

Interfaces for gesture-based 3D modeling primarily capture input as mid-air interactions [8, 9, 34, 41, 49] or through tangible props [25, 35, 36]. One problem with both means of capture is the lack of precision and control, when compared to more conventional, mouse-based 3D modeling software. In addition, arm fatigue is prevalent in gestural interfaces using mid-air interactions [14]. Content creation in these gesture based modeling systems is often limited to sculptural or abstract modeling [8, 25, 34, 35, 49] or simple 3D navigation [20, 41]. One approach to bypass these limitations is by capturing mid-air gestures to search databases of pre-existing, detailed 3D models [17]. This, however, does not enable users to create new geometry.

More recently, researchers have begun incorporating physical contexts into the digital modeling environment [5, 6, 21, 22]. Bridging analog and virtual contexts helps novices of fabrication-based 3D modeling understand a sense of scale in what would otherwise be a scale-less virtual environment. *MixFab,* for example, incorporates physical props with gesture-based geometry creation for 3D printing [42]. This system is limited to basic 3D Euclidean modeling operations, which aren't sufficient when digitally designing for geometrically complex physical contexts, such as the human body.

Skin-Based Mobile Computing

The unique affordances of skin—its tactility, availability, and elasticity—have enabled a vast array of interaction scenarios to push beyond traditional, screen-based input surfaces. Solutions for sensing interactions with one's skin have been explored in devices worn on the body [2, 3, 13, 19, 23, 28, 30, 48], embedded in body [16], and embedded in the environment [10, 11, 29]. Combining these sensors with projectors enables skin to act as both an input and display surface [10, 12, 29].

Visual feedback is not entirely necessary to effectively interact with skin-based interfaces [12, 17, 31]. The body can act as a persistent anchor for the spatial and tactile memory of users, which is important for spatial input [15]. Recently, the social, physical, and psychological implications of skin-input have emerged as important design criteria for skin-based mobile interfaces [12, 31, 43, 44]. However, this prior research has not explored skin as an input surface for gestural 3D modeling.

Fabrication Aware Design

Fabrication-aware design embeds the technical expertise of an experienced fabricator into the workflow of a digital design environment. This method is traditionally used for large-scale engineering projects, where multiple material assemblies must join together to create complex geometries [32]. However, the rise of affordable CNC machines (*e.g.*, 3D printers, laser cutters, routers), has made fabrication-aware design an invaluable technique for opening advanced modeling and fabrication to non-expert users. Researchers are looking for new interfaces that engage this wider, non-technical audience. *Sketch-to-fabrication* systems, for example, link sketch-based 2D geometry to additive or subtractive processes in fabrication [4, 18, 26, 33]. Alternatively, *Interactive fabrication* systems enable a user to digitally design and fabricate directly on a material using intelligent hardware [27, 45, 50]. These systems, however, use neither skin nor the body as the design interface for a fabrication process.

In summary, our literature review reveals significant work in both skin input and gesture-based design. However, these two areas have yet to be explored in combination. They are particularly compatible because skin has the potential to provide persistent spatial and tactile references for gesture based design tools. Thus, the intersection of skin input and gesture-based design tools is an area ripe for exploration.

DESIGN CONSIDERATIONS

In this section we present a number of design considerations for the appropriate *content*, *configuration*, and *input and output* of skin-centric gestural modeling-to-fabrication systems.

Possible Content

Skin is an appropriate input surface for design tools intended for on-body artifacts. The non-Euclidean nature of our anatomy can make the design of wearable objects unintuitive in conventional CAD environments. However, appropriating skin as a starting canvas could help embed ergonomic principles into the foundations of a design. We therefore see three domain spaces that could specifically benefit from skin-centric interfaces for digital design.

First, fashion items, like garments, shoes, accessories, and jewelry can be adapted to skin-based input and 3D printing. Second, wearable computing devices, such as watches, smart eyewear, and fitness trackers, can also be customized or personalized using skin-centric design and fabrication tools. Third, medical devices – such as braces, splints, or casts – can be designed, customized, personalized, and fabricated through these systems for at-home rehabilitation.

Possible System Configurations

Three important aspects of a skin-centric design tool's system configuration are the user's point-of-view, the location of the canvas area, and the number of users interacting with the system.

Point-of-View

Figure 2 illustrates three possible point-of-view configurations. In *first-person* systems, the point-of-view of the modeler is directed at their own body [13]. This method is appropriate when there is a clean line of sight between the user and the canvas area. The forearms, hands, and upper thighs are likely locations for this system (Figure 2a). *Second-person* systems have parts of the desired canvas area occluded from the user's line of sight. As a result, these systems should provide representations of the body through an auxiliary display [49]. The face, neck, bust, back, or full body are likely locations for second-person systems (Figure 2b). *Third-person* systems have the canvas area located on a person other than the modeler [29]. This method is appropriate when multiple users collaborate on a single design (Figure 2c).

Single versus Multi-User Systems

Recent research has surveyed the propriety of touch for different locations of body-based interfaces [11, 30, 43]. While the social acceptance of touch may not be applicable to first- or second-person systems, it becomes an important factor when designing multi-user interfaces. Skin is useful as a collaborative modeling platform in scenarios where professionals work with non-experts. This scenario could occur with a doctor working directly on a patient [29], a fashion designer working directly on a model, or an engineer working with a consumer. It is important to give each party agency in the design process, although one user may have more influence over the final design than another. Moreover, additional instrumentation, such as touching with a stylus instead of the hand, can be introduced in locations where touch is necessary, but socially inappropriate or awkward.

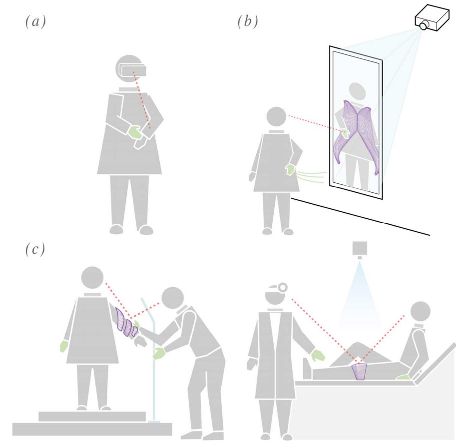

Figure 2. The point-of-view of the user or users determine the physical configuration of a skin-centric design tool. (a) first-person systems have a direct line of sight to the user's canvas area, (b) second-person systems have partially occluded canvas areas, and (c) third-person systems enable multiple users to participate in design.

Input

Hardware options for detecting touch input on the body have increased in recent years, however not all techniques are applicable skin-centric 3D modeling interfaces. Skin-based input for gestural 3D modeling must be able to detect both tactile input from *on-body* interactions and spatial input from *near-body* interactions. Moreover, sensor readings must be translatable to local and global Cartesian coordinate systems. Therefore many of the hardware solutions that infer touch based solely on disruptions in electric or acoustic signal may provide insufficient information for 3D modeling purposes [*e.g.,* 2, 3, 13, 23, 28]. However, pairing these devices with optical sensors, such as RGB, IR, or depth cameras, can provide robust information for 3D modeling with skin-based gestures.

Output

Visual output for skin-centric design tools can exist both *on* and *off* the user's body. As mentioned previously, one valuable affordance of skin as an input surface is that it facilitates the user's tactile and spatial memory of the body. Therefore, conventional off-body displays can effectively aid a user's bodily interactions. However, there are also a number of output devices that can provide direct visual overlays. Mobile or embedded projectors (Figure 2c) can provide robust visual feedback, especially when mapping two-dimensional forms onto parts of the body [10, 12]. For depth-rich three-dimensional designs, augmented reality devices, such as translucent screens (Figure 2c) or head-mounted displays (Figure 2a), may be better suited to overlay 3D visuals on the body. However, these devices are still limited by the canvas areas a user can directly see.

Spatial Landmarks

In addition to touch input, individual variations of skin, such as freckles, veins, and tattoos, can provide spatial landmarks to anchor a user's spatial and tactile memory [10]. If integrated into the modeling workflow, these landmarks can provide a persistent reference to skin-based interactions as the designer works at 1:1 scale with their body.

TACTUM

To explore these design considerations, we developed *Tactum*, a new fabrication-aware design system that captures single and multiple user gestures for 3D modeling directly on the forearm. Digital designs generated through the system can be immediately 3D printed and worn.

We focus specifically on the forearm, for a number of reasons. First, research has shown that the forearm is one of the most acceptable locations for single and multi-person touch [12, 31, 39, 44]. Second, a wide range of applicable artifacts, from jewelry to medical devices, can be designed for the forearm. Third, fatigue is a major challenge for gesture-based interfaces [14]. Limiting interactions to the forearm allows both the modeling hand and canvas arm to use a tabletop surface for continuous support.

Our system uses four core design principles to link meaning between skin-centric gesture and purposeful 3D modeling: (1) favor natural over symbolic gesture, (2) make digital geometry dynamically react to user input, (3) balance high precision control with expressive gesture, and (4) embed fabrication constraints into the design of a digital model.

Implementation

Hardware Configuration

The workstation is comprised of a first generation Kinect mounted ~800mm above the work area and a Microsoft Surface Pro 3 mounted on a desk. The desk is also used as a base surface to place the arms (Figure 3). The effective tracking region is 90cm x 65cm, with an approximate 3-5mm working resolution. The system was implemented using the Java programming language at 12-15 FPS, and uses following the open-source libraries: processing for graphics, opencv image processing, and toxiclibs for physics simulation.

Arm Tracking

The depth camera detects a user's forearm as they sit at the workstation. The contours of the arm are then processed to define anatomical regions (e.g., the elbow, wrist, hand, fingers). With these regions defined, we simplify the forearm's point cloud into two 3D planes. These 3D planes dynamically segment the depth image into a *modeling hand* and *canvas arm* mask. Everything above these planes becomes a part of the modeling hand mask, and everything between the planes and a given maximum distance becomes the canvas arm mask (Figure 4a).

Touch and Gesture Detection

To reliably detect skin-centric interactions between the modeling hand and canvas arm, we adapt the image processing techniques in [46] to the three-dimensional geometry of the forearm: the dynamic 3D planes used to segment the *modeling hand* and *canvas arm* masks are offset by a minimal distance (~20mm in our implementation). When a finger of the modeling hand enters the space between the offset and original planes, we know a touch has occurred (Figure 4b). This enables skin-centric gestures that will be described later.

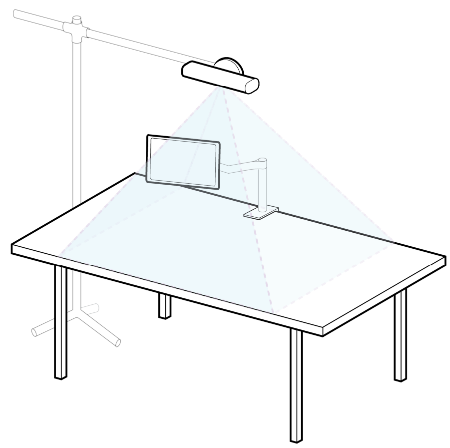

Figure 3. The workstation is comprised of a Microsoft Kinect mounted above the work area for input, and a Microsoft Surface tablet mounted within the work area for output.

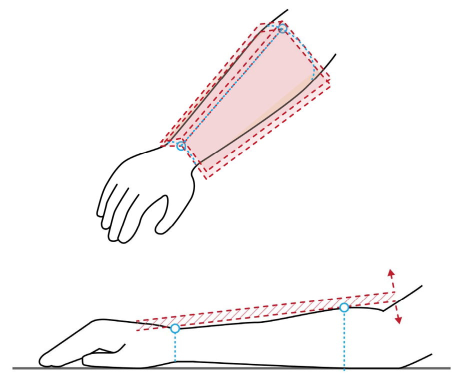

Figure 4. Image segmentation and touch detection are generated from the anatomy of the forearm. (a) The axes from elbow to wrist and from middle-of-arm to side-of arm create the 3D plane for segmentation. (b) an offset from the 3D plane defines the 3D touch region of the forearm.

Real-Time Display

The flat panel display above the work area is used to provide users with real-time visual output of the arm and finger tracking, within the context of a 3D modeling environment (Figure 5).

Once the canvas arm is detect and processed, the 3D modeling environment is generated on the auxiliary display. While the system's depth camera can continuously 3D scan the user's forearm, this data was found to be too noisy and incomplete to provide a useful virtual reference in the modeling environment. Instead, we built an accurate representation of the forearm using a simulated spring system in the modeling environment. Live scan data from the depth camera then updates select particles in the spring system with a small number of 3D points from the elbow, wrist, and hand (Figure 6a). The spring system both dampens depth noise from the streaming points and facilitates smooth motion for the virtual forearm.

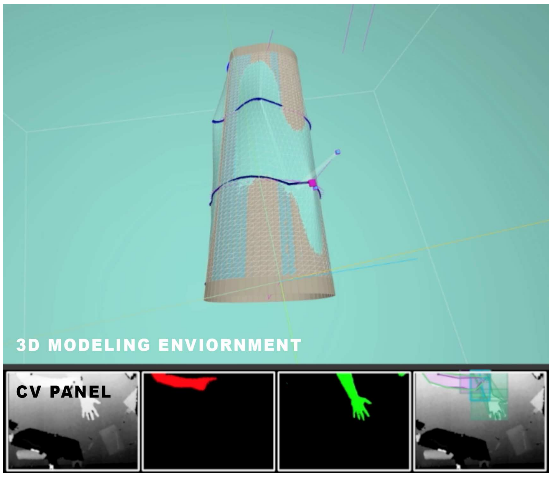

Figure 5. Real-time visual output shows the 3D modeling environment, and a computer vision panel with the raw depth image, modeling hand segmentation, canvas arm segmentation, and hand and gesture tracking.

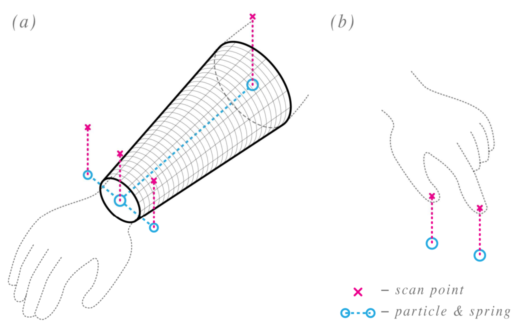

Figure 6. Virtual geometry is updated by live scan data from the depth camera. (a) elbow, wrist, and wrist axis points update the canvas arm, and (b) index and thumb points update the modeling hand.

A similar strategy is used to visualize the modeling hand in the virtual environment: a 3D scan point from each finger is rigged to a heavier particle with a spring (Figure 6b). This dampened particle is visualized as the user's virtual finger.

Skin-Centric Gestures for Design

Our system implements both natural and symbolic gestures based on the tracking of the modeling hand and canvas arm. Figure 7 summarizes the gesture set of our system. Gestures performed with one or two fingers of the modeling hand are used for design operations. These include *touch*, *poke*, *grab*, *rub*, *drag*, and *pinch*. Additional gestures performed with canvas arm are used for 3D navigation. These include *flip, orientation of arm*, and *rotation of wrist*.

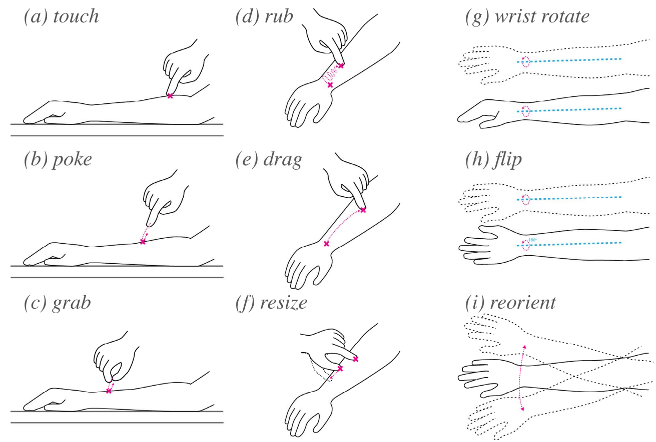

Figure 7. Natural gesture set. (a) touch; (b) poke: a single tap on forearm; (c) grab: pinch thumb and index, and touch forearm; (d) rub: touch and drag repeatedly; (e) drag: touch and move; (f) resize: touch and move thumb and index; (g) wrist rotate: rotating hand about the wrist; (h) flip: flipping the forearm; (i) reorient: moving the forearm.

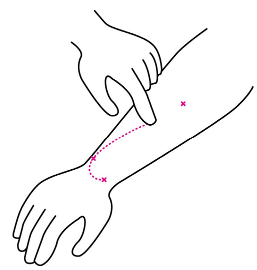

Figure 8. Skin-centric gestures incorporating landmarks are generated through an initial calibration step: a user selects landmarks by touching desired points on the forearm, then records a gesture by drawing a path to each point.

The system also includes skin-centric symbolic gestures by incorporating landmarks on a user's forearm. For example, a user can touch their middle knuckle to export a design for fabrication, or they can touch a set of freckles in a particular order to run an application-specific command. An initial calibration step generates landmark gestures: the user first selects landmarks by touching the desired points of their forearm, then records a gesture by dragging their finger to each landmark (Figure 8).

Modeling Modes and Workflow

Tactum illustrates how skin-centric input can be used as a gestural 3D modeling-to-fabrication system through three distinct modeling modes—*direct*, *parametric*, and *generative*. These modes are adapted from the primary 3D modeling techniques of conventional CAD environments. Although bodily interactions and geometric manipulations may vary, the goal of each mode is the same: balance high precision control with expressive gestures, and to ensure fabricated digital designs have an ergonomic fit to the geometry of the forearm.

Direct Manipulation

With *direct manipulation* mode, the interactions between modeling hand and canvas arm directly transform the base geometry built from the canvas arm. Gestures such as *grab, drag, wrist rotate, flip,* and *reorient* are used to modify an underlying mesh structure.

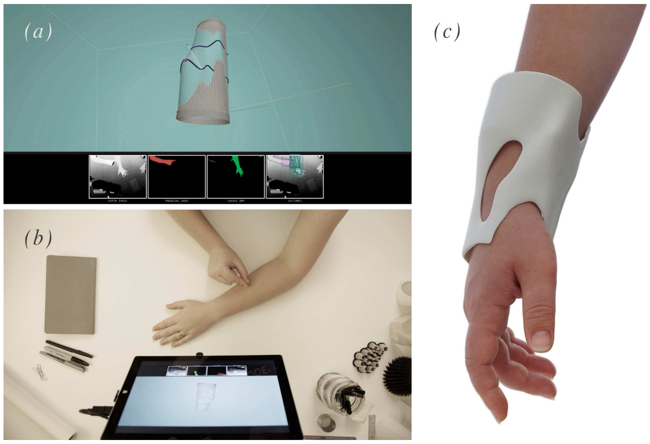

Figure 9. An armlet is designed using the parametric manipulation mode. (a) skin input updates the arm's base geometry, and simulated rubber bands can be pulled and deformed by the user; (b) the model can be customized to the user; (c) the resulting physical artifact on the user.

In our prototype, we use direct manipulation to design and fabricate an armlet for the forearm (Figure 9). When the user's forearm is detected, the system generates a malleable digital surface from four control edges built from the virtual forearm (Figure 9a). These control edges are digitally simulated rubber bands that are manipulated by the user's touch (Figure 9b). Using a *grab* gesture, the user touches a corresponding spot on their physical arm and pulls the virtual point off of their body. An elasticity threshold built into the control edge releases the deformed edge once breached, thereby updating the underlying surface.

This lower level manipulation of geometry is most similar to conventional gestural modeling systems, and it therefore brings similar limitations: while it allows high formal variation, it is difficult for users to have precise control over the final form. To compensate for this lack of control, we ensure the digital design will have an ergonomic fit to the body by subtracting the volume of the virtual forearm from the final manipulated surface. The geometry can then be exported for fabrication, and the 3D printed artifact can be placed back on the body of the user (Figure 9c).

Parametric Manipulation

Within *parametric* mode, the user's gestures interact with open parameters of a pre-designed digital form. This mode allows a base design generated by an expert to be manipulated by a non-expert. Gestures such as *touch, poke, resize, flip,* and *reorient* are used to manipulate and stimulate an interactive parametric model.

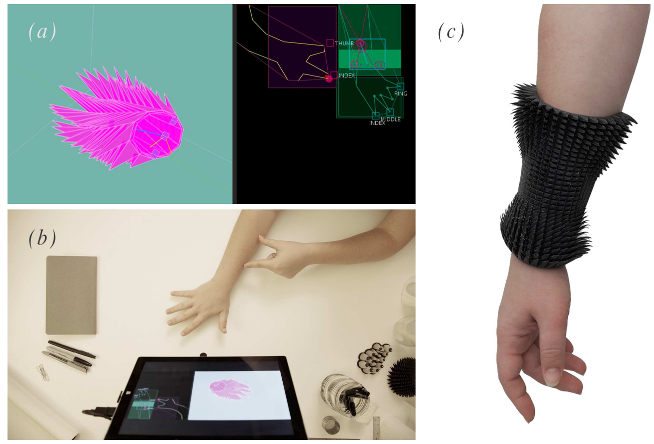

Figure 10. A piece of jewelry is designed using the parametric manipulation mode. (a) skin-centric gestures manipulate a pre-designed 3D model, and the animated digital geometry responds to the users movements; (b) the model is customized by the user; (c) the resulting physical artifact on the user.

In our prototype, we use parametric manipulation to customize the design of a piece of 3D printed jewelry (Figure 10). When the user's forearm is detected, the system generates a base 3D surface between the wrist and the elbow, and then subdivides it into planes. Next, a pre-designed, interactive module is placed on each plane of the subdivided surface. In our implementation, each surface module was programmed as a pyramid, with springs along each edge and a repelling particle at the top. The springs enable the module to sway as it is manipulated in the virtual environment, and the repelling particle prevents each module from intersecting with its neighbors (Figure 10a). Each surface model is connected to its neighbor at its base, thereby creating a closed, ready-to-fabricate mesh.

Once the parametric model is generated, the user can interact with the virtual environment using skin-centric gestures, like *touch*, *rub*, and *poke*. The spring-based surface modules of the parametric model definition enable the digital geometry to dynamically react to the user's gestural input. In our model definition, for example, the *touch* gesture the forearm attracts each module to the user's finger, the *rub* gesture repels each module from the finger, and *poke* gesture agitates the modules. Moreover, the user can shake their forearm to disrupt the entire field of animate modules (Figure 10b) or close their fist to *freeze* the physics simulation. A *resize* gesture is also used to allow the user to scale and position the design along the forearm. The final design was printed from a rubber-like material, and a magnet closure was added (Figure 10c).

While designs generated through parametric manipulation may have limited variation in form, they facilitate both expressive gesture from the user and a high level of quality control through the pre-designed module. In the current implementation this module must be pre-programmed, however future development could create an interface for user-defined parametric modules. This mode may be particularly useful for personalizing consumer products where high tolerance precision is required.

Generative Manipulation

With *generative manipulation*, a user's gestures manipulate the underlying abstractions that guide the behavioral properties of an expert defined design. Gestures such as *touch, rub,* and *drag* are used so a user can guide how a design is regenerated on the forearm.

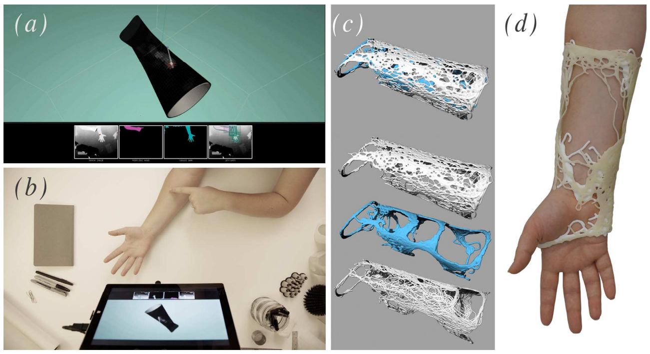

Figure 11. An arm brace designed using the generative manipulation mode. (a) skin input updates a touch heatmap of the user's forearm; (b) a design is generated using virtual agents; (c) resulting geometry is processed for fabrication; (d) the resulting physical artifact on the user.

Our prototype enables a user to personalize the structure and support of an arm brace (Figure 11). When the user's forearm is detected, the system generates a touch heatmap around the forearm, wrist, and hand of the user. Areas where the user *rubs* become brighter to indicate repetitive touch along the heatmap (Figure 11a). Once the user achieves a desired pattern for the heatmap, they use a landmark gesture to generate a digital design, and the system then deploys a pre-designed generative algorithm that processes the touch heatmap. In our implementation we programmed hundreds of Braitenberg vehicles [1] to seek out bright areas and avoid dark areas of the user-defined heatmap. As they move across the three-dimensional surface, the trails left behind each vehicle are used as the digital geometry. So in effect, areas where the user touches more add extra support for the arm brace, and areas where the user touches less receive less support. Once the simulation has finished, the geometry is exported and post-processed for 3D printing (Figure 11c).

For this example, we have also implemented a multi-user mode, where a *client* and *professional* user design a brace together. In this scenario, touch interactions from the *client* are given less weight than the *professional*: *client* touches appear in red, whereas *professional* touches appear in white on the touch heatmap (Figure 12). The *client* can therefore indicate where they would like brace supports to be generated, but the *professional* controls the actual location and density of the generated design.

Generative manipulation strikes a balance between the formal variation of *direct manipulation* and the precision and control of *parametric manipulation.* It enables the user to directly influence highly complex geometry, but can also ensure quality control over design and fabrication parameters. This mode may be particularly useful in scenarios where a high amount of user agency is desired in the design process of a complex artifact, such as in personalized medical devices or prosthetics.

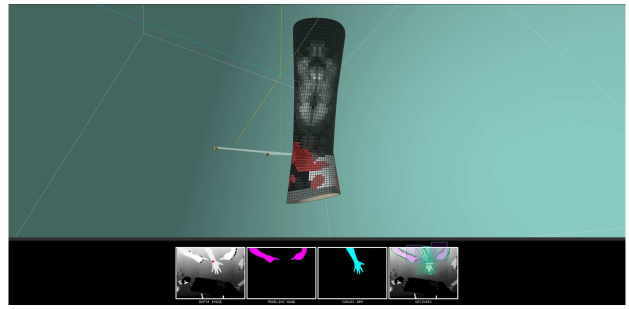

Figure 12. In multi-user mode, users can have a different level of impact over the design. Here, one user adds suggestions (red), and the other user implement the design (white).

Fabrication-Aware Design

To 3D print a 3D model, digital geometry must satisfy three conditions: it must have a minimum thickness, it must be made of closed-meshes, and these meshes cannot have self-intersecting faces. Rather than fix invalid geometry to meet these conditions, our strategy is to only allow properly formatted geometry to be created. In the *direct* and *parametric* manipulation examples, we achieve this by basing the user-manipulated geometry on spring-mass models simulated in a virtual physics environment. Digital geometry is first initialized as a closed mesh with a minimum thickness. This minimum thickness is maintained, and self-intersecting faces are prevented, by inflating the spring-mass model with repelling particles. In the *generative* manipulation example, we build these conditions into the geometry processing: the trails of the virtual vehicles are first converted from lines to closed-mesh pipes, and then exported as one closed-mesh. Building expert knowledge directly into the modeling environment lessens technical overhead for users, thereby enabling them to focus on their interactions while designing with *Tactum*.

The fidelity of printed geometry created through *Tactum* was tested by printing artifacts on 3 kinds of 3D printers, using a variety of materials: artifacts from the *direct manipulation* example were printed with ABS and PLA plastic on a Fuse-Deposition Modeling (FDM) printer; the *parametric manipulation* example was printed from resin on a SLA printer; and the *generative manipulation* example was printed with nylon and rubber on an SLS printer.

INITIAL USER OBSERVATIONS AND DISCUSSION

Although our system is still in the research prototype stage, it is important to get early feedback from potential users. Since the system is intended for both expert and non-expert users, we invited 10 participants to participate in an observation and feedback session. Participants had varied backgrounds and experience levels in 3D modeling and 3D printing. Three participants were design professionals, two were professional artists, two were design students with engineering backgrounds, and three were design students with architecture backgrounds. The 3D modeling and fabrication experience of each participant varied from complete novice to seasoned expert.

Procedure

In each session we first explained the setup and sensing of our system, and went through the different skin-centric interactions for gestural 3D modeling. We then demonstrated each of the three modeling modes, and highlighted the differences between each mode. After each demonstration, participants were able to try the system, and were guided them through the gestural modeling process. We also allowed participants to try on sample artifacts made through our system. Below we summarize the key observations and comments collected from these sessions.

Participant Feedback

In general, participants gave positive feedback about our system. They were all able to create or manipulate digital models with the three modeling modes, although most participants took longer to create a satisfactory design with *direct* modeling than with *parametric* or *generative.* When prompted for their thoughts on skin as an input surface for 3D modeling participants were enthusiastic about integrating touch and tactility into the digital design processes. One participant made a comparison to a haptic mouse:

"I've used a Phantom [haptic mouse] before for 3D modeling, and it's kind of cool, but it still feels like poking something with a stick instead of actually touching it." (p5)

They also appreciated how a digital design would inherently be scaled to fit. One novice to 3D modeling noted:

"It makes sense that if you're designing something to wear on your body, you should be able to literally design it on your body." (p1)

However, we received mixed reactions on the usefulness of landmark gestures. Most participants liked the novelty of it, but didn't see a significant improvement over clicking or pressing a button with a mouse or keyboard:

"I guess it's really only useful when you have to keep both arms highly engaged in modeling." (p4)

"It's neat, but I could also just press a key to export my file." (p2)

In general, participants with little experience in 3D modeling appreciated the *direct* and *parametric* modeling modes most, and found them "engaging" and "empowering". Those with experience in 3D modeling and printing tended to favor the *parametric* and *generative* modes. When discussing the generative mode, one experienced modeler noted:

"I have no idea how I would recreate that in the 3D modeling software I'm used to." (p3)

However, the experienced modelers showed concern with *how* the model definitions would be created. One participant suggested:

"I don't really want to have to learn another parametric modeling software [...] it would be great if you could just import the parameters from Grasshopper or Maya or something." (p9)

All the participants with some experience in 3D printing liked that they didn't have to think about formatting the digital geometry for fabrication. One beginner noted,

"It's great that it takes care of that for you [...] I always get nervous about it right before I go to print something I modeled." (p6)

Overall our observation sessions show that both expert and non-expert users were able to design wearable artifacts using skin-centric gestures. They were also eager for additional forms to manipulate in *parametric* mode, and offered suggestions for other algorithms to incorporate into *generative* mode.

DISCUSSION AND FUTURE WORK

We are encouraged by initial results and observations of our system. Despite the preliminary nature of these evaluations, our observational study provides insights into the feasibility of skin input for fabrication-aware design. However, our work only begins to explore what could be a wide design space around skin-centric input for design. As our system develops further, more thorough evaluations will be necessary to fully understand issues around ease-of-use and ergonomic fit for printed designs. This section reflects on lessons gathered from our implementations and observation sessions, in addition to topics for future work.

Both expert and non-expert participants showed enthusiasm for what can be produced through our system, however experts were concerned with how parametric and generative content could be created. For our research prototype to engage design professionals, back-end content creation would need a friendlier, non-programing interface. This back-end interface could be designed as a stand-alone, modular design system, or it could integrate workflow pipelines from existing design-to-fabrication software.

In our implementation, we wanted to push the envelope by relying solely on skin-based input for all interactions. However, as noted by some participants, traditional desktop input devices could also be used in combination with the skin-based gestures we developed. Integrating voice commands could be an effective means for hands-free communication with the gestural modeling system.

With regards to our implementation, we relied on a single depth camera to sense skin-input on the forearm. While this one sensor did allow for many gestures to be recognized, issues of image resolution and occlusion were inherent limitations that we had to negotiate. To reconcile the low-resolution and noisy data of the kinect with the high resolution and fidelity of the user-manipulated 3D geometry, we chose to visualize the forearm and hands in the modeling environment as simplified representations. However, directly visualizing the skin and hand in the virtual modeling environment may help strengthen the connection between a user's on-body interactions and the manipulation of digital geometry. Using additional cameras or sensors to capture and map a user's actual skin texture and hand details onto user-manipulated geometry could help bridge bodily interactions and geometry manipulation.

Relying a single sensor also limited the fidelity of our arm tracking. While our system allowed a user's free arm movement to manipulate digital geometry, only canvas arm gestures (*e.g., flip, rotate, reorient*) directly manipulate geometry through free movement. In two-handed interactions, our tracking and recognition strategy requires the canvas arm be stationary to adequately detect gestures from the modeling hand. Integrating additional modes of sensing into skin-centric gestural modeling system could allow for more dynamic interaction between both arms. It could also enable better detection of skin-specific gestures.

There are several output modalities that are appropriate for skin-centric design systems. In our implementation we elected to use an auxiliary display, as it provides consistent visual representation without suffering any possible occlusions. However, direct visual overlay onto the user's forearm (through head-mounted displays, projection mapping, or see-through displays) could also provide a strong connection between bodily interactions and geometry manipulation. Projection in particular could be a useful means of visual overlay. Future work could investigate how projection could also display three-dimensional volumetric geometry that comes off the forearm, such as the geometry created in our direct and parametric manipulation examples.

Although our system implements basic multi-user interactions, there are more ways for skin to be a collaborative input surface for design. For example, we show how two users can collaborate on one forearm. But an alternative scenario would be for two users to remotely work on one design on their own forearms. This scenario can increase in complication when design teams work on a single design.

Finally, our system focuses only on gestural modeling on the forearm. However there are other parts of the body that are appropriate for skin-centric design tools: the face and head can become an interactive canvas for designing eye-wear, masks, or apparel; the shoulders and neck can be used to design jewelry or medical braces; full body systems can be used to design costumes or garments; legs and feet can be used for shoes, medical braces, or casts. Moreover, skin-centric tools for deformable body parts, such as the joints of the neck, back, elbow, knee, or ankle, could combine complex mechanical design with intuitive customization.

CONCLUSION

We have shown how skin as an input surface for gestural 3D modeling-to-fabrication systems can enable non-expert users to create highly complex and expressive designs for the body. Moreover, our observation session with design professionals and students indicates a potential for skin-centric gestural modeling to be a collaborative platform for experts and non-experts. We have also outlined design considerations for future skin-centric systems, and discussed three separate manipulation techniques for balancing geometric precision and expressive control in such systems. While advances in hardware have increased *accessibility* to 3D printing, software interfaces have yet to provide increased *agency* in who can use this technology. We believe that *skin* can act as the interface that bridges digital and physical contexts, and can better enable experts and non-experts alike to participate with this technology.

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