ExoSkin: On-Body Fabrication

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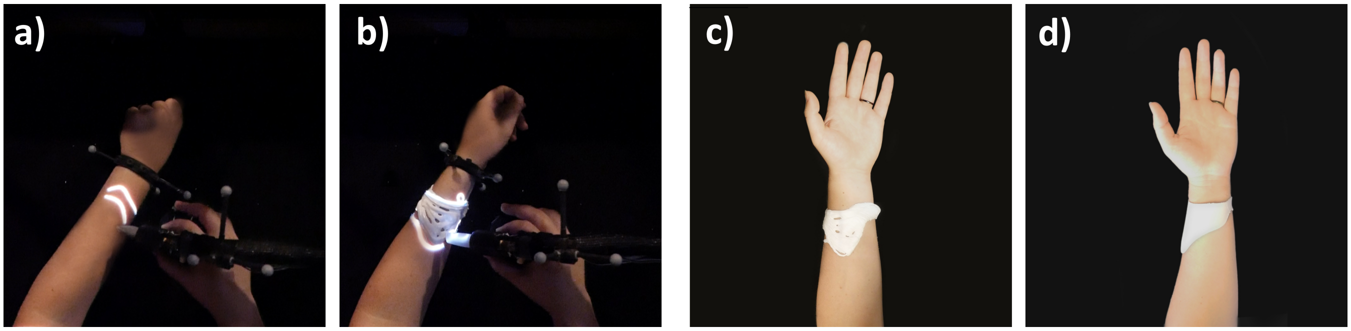

Figure 1. *ExoSkin* is a hybrid fabrication system for designing and printing digital artifacts directly on the body. a) A user sketches directly on the body using the tip of the extruder as a stylus. b) The user can then use a custom built handheld extruder to print directly on the body, tracing over the projected toolpaths. c) The printed material is adhesive and can be worn. d) The final geometry can also be exported and 3D printed using traditional 3D printers and materials.

ABSTRACT
There is a long tradition for crafting wearable objects directly on the body, such as garments, casts, and orthotics. However, these high-skill, analog practices have yet to be augmented by digital fabrication techniques. In this paper, we explore the use of hybrid fabrication workflows for on-body printing. We outline design considerations for creating on-body fabrication systems, and identify several human, machine, and material challenges unique to this endeavor. Based on our explorations, we present *ExoSkin*, a hybrid fabrication system for designing and printing digital artifacts directly on the body. ExoSkin utilizes a custom built fabrication machine designed specifically for on-body printing. We demonstrate the potential of on-body fabrication with a set of sample workflows, and share feedback from initial observation sessions.

INTRODUCTION
In art and design communities, there is a strong tradition for crafting directly on the body, or on proxies for the body. Fashion designers and tailors create bespoke garments on models or mannequins; special effects artists craft prosthetics and props on actors or lifecasts; tattoo artists inscribe their graphic designs onto their client's skin. In many of these domains, the techniques for on-body design and fabrication are purely *analog*. In each of these scenarios, the artifact is customized and hand-crafted on an individual's body by highly trained fabricators.

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More recently, engineering communities have been developing *digital* fabrication workflows, such as 3D modeling and 3D printing. Such processes make iterating between design and physical objects a more facile, flexible, and scalable operation [12]. Moreover, pragmatic functionalities like archiving, sharing, and reproducing a body-fabricated design are enabled. However, with such processes, the user, who may be an artist or designer, typically loses agency within the process, when creativity and control may be desired [8].

While today it may seem as a topic of science fiction[1,2], we foresee a future where these art and engineering spaces come together, and wearable artifacts, such as clothing, jewelry, and medical braces are fabricated in real-time directly on the body through a human-machine collaboration.

However, there are several human, machine, and material challenges unique to on-body fabrication that would make it difficult to realize this vision. With traditional Computer-Numeric Control (CNC) processes, material is added or removed on a flat, stabilized build platform. By contrast, when fabricating on the body, the build platform — the body — is a highly deformable, highly curved surface in constant motion. Moreover, materials for on-body fabrication, such as silicones, plasters, clays, or textiles, are dynamic, and are actively transformed by gravity, temperature, and the environment. Last, for safety reasons, traditional CNC processes are not designed for close-quarter human

[1] Iron Man [Suit Up]. https://youtu.be/Fcm7OjoOz4A
[2] Spray on Shoes. https://youtu.be/JpVtVUSYMRw

interaction. This requirement cannot be satisfied in on-body fabrication, where the human can be both the operator and the canvas for fabrication.

These challenges have impeded the development of digital workflows specific to on-body fabrication. For example, 3D printers *can* produce wearable objects, however this fabrication process is fairly inefficient: the form of objects that wrap the arms, legs, or shoulders tend to have high volumes of space, but low material densities [11]. This high volume-to-density ratio is particularly inefficient in material and time for 3D printing, where a form is sequentially built up layer by layer. By contrast, a printing process specifically designed for on-body fabrication could integrate the body as a three-dimensional support structure, which could reduce time and material wasted in fabrication. Moreover, printing on the body can provide a more direct and engaging user experience, which to date, has not been explored.

In this paper, we make several contributions towards enabling digital models to be fabricated directly on the body, synthesizing a diverse range of knowledge from Computer-Aided Design, computer vision, material science, and hardware design. Most notably, we outline a set of design considerations for digital on-body printing, including material choice, machine configurations, appropriate content, and hybrid workflows. We then present *ExoSkin*, a proof-of-concept system which demonstrates the feasibility of digitally designing and fabricating directly on the body (Figure 1). While ExoSkin does not yet produce product-ready artifacts, it shows how some of the challenges of on-body fabrication can be addressed. The core technology of ExoSkin is a custom hand-held extruder for digitally fabricating a single layer of material directly on the body. We discuss the range of workflows enabled by our system, and share feedback from an initial observation session.

Our work is positioned at the intersection of engineering and artistic practice. We build upon existing extrusion devices developed in the engineering communities, but make the necessary modifications to support on-body fabrication. Furthermore, we adapt the existing crafts of on-body design from the art and design communities to leverage the advantages of digital fabrication workflows while still supporting user agency throughout the process.

RELATED WORK

Our research builds upon existing *on-body design* and *hybrid fabrication* processes developed for artistic practices as well the engineering process of *free form 3D printing*. Furthermore, we leverage skin-based interfaces, as developed within the HCI community.

Crafting on the On Body

There are many existing fabrication methods for creating things on and around the body: including molding, extruding, weaving, wrapping, spraying, and draping.

These analog methods are often used to create wearable artifacts on proxies, and are then transferred onto the body of the wearer. For example, dressmakers and seamstresses will often use mannequins or dress forms as a canvas for patternmaking [35]. Fabric can be draped on the mannequin to better visualize the final shape and produce a better fit. On-body fabrication could adapt this practice to allow a better personalization of the final form.

Some crafts, such as lifecasting [1], involve working directly on the human body. Human models take on a desired stationary pose, and then the artist applies a mold material to the surface of the body. A casting material can then be used to create a duplicate of the molded body part. Prosthetic makeup artists may similarly use lifecasting techniques to create advanced cosmetic effects [2]. ExoSkin adapts these types of crafts to provide digital guidance and manipulation tools while designing and fabricating on the human body.

Hybrid Fabrication

Hybrid fabrication, or hybrid craft, is a method of integrating digital and analog fabrication techniques to augment traditional craft with digital workflows [38, 40]. Craft practices hybridized with digital techniques include drawing [25], carving [38], weaving [39], painting [32], sculpting [29], and fashion design [36]. Tools developed for hybrid fabrication are often hand-held devices that use mechanical or computational interventions to increase precision and accuracy [29, 31, 32, 38]. These tools have an awareness of the material they are manipulating and their location in space, and provide visual [24, 30, 32] or tangible [29] feedback. However, hybrid fabrication systems typically rely on static build volumes and canvases. Fabrication on the body — a constantly moving canvas with a high degree of freedom — is an added technical challenge.

The role of a hybrid fabrication machine during the production process can vary: from passive to neutral to active. With a *passive* approach, digital techniques may be used to print a static formwork that artisans can build upon [39]. A *neutral* approach could involve using digital techniques to guide the user, but not intervene if they deviate [32]. With an *active* approach, actuated tool-heads can be used to correct or constrain user actions to match a desired digital model [29, 31, 32, 38].

Recent research offers a more critical view of the role of the human in the hybrid fabrication processes. *The Hybrid Artisans* examines the value added and value lost to traditional craft practices [40]. *Being the Machine* reflects on the tradeoffs in agency and control between a user and hybrid fabrication machine [8].

While we take inspiration from these existing hybrid fabrication systems, we are unaware of existing hybrid fabrication systems that are designed to fabricate on complex, moving surfaces, such as the body.

Free Form 3D Printing

Free form 3D printing is a digital fabrication process in which Computer Numeric Control (CNC) machines three-dimensionally extrude material in free space. It differs from traditional 3D printing processes in that it does not build up geometry by printing horizontal layers and it does not fabricate its own support structure. As a result, artifacts fabricated through freeform printing can see a reduction in build time and material waste [28].

Freeform printers are often built using industrial robots, and use a variety of materials, such as thermoplastics [28], clays [4], metals [20], waxes [14], or photopolymers [19] to extrude geometry in free space. Many examples use external formworks such as machined foam [4], water [14], or inflatable shells [23] to receive the printing medium.

Closely related to freeform printing is the concept of printing directly onto existing objects, or *patching* [34]. This can be accomplished by placing the existing object on a 5 axis rotating platform [34] or on a custom 3D printed support [7]. These techniques still require traditional 3D printer devices, and thus do not directly adapt to fabrication on the body.

Finally, many hand-held devices for manually extruding materials exist (e.g., glue guns, UV curing pens, plastic extruding pens, motorized caulk guns). However none of these commercially available options provide a way to fabricate on the body without extensive modification.

To our knowledge the only such machines capable of operating on the body are experimental robotic tattoo printers [3]. Otherwise, these systems have yet to develop materials that are safe to print on the skin, nor have they used the body as a support structure for freeform printing.

Skin-based Interfaces

Skin-based interfaces appropriate the body as an always-available, spatio-tangible surface for sensing and displaying information. A number of techniques have been developed for sensing input on one's skin. This includes sensors worn on the body [5, 6, 15, 21, 27, 37], implanted under the skin [17], and embedded in the environment [13, 16].

To display information, projection-based systems can overlay traditional mobile interfaces, including buttons, menus, or games, directly onto the body [15, 16]. Projection-based skin interfaces have also been explored as a method to spatially guide the movement of a user [33], as well as a way of overlaying medical information directly on patients [26].

Most related to our work is our recent Tactum system, which explores the use of skin as an input platform for 3D modeling directly on the body [11]. While Tactum's design system is fabrication-aware, the resulting wearable models still must be printed on an external 3D printer and then subsequently attached to the body. This provides a disconnect in the overall workflow that could be remedied if the fabrication process also occurred directly on the body.

In summary, our review reveals that on-body fabrication has yet to be explored in the context of hybrid fabrication or freeform printing. Thus, combining skin interfaces with techniques in hybrid craft and freeform printing present a new thread of exploration in on-body fabrication.

DESIGN CONSIDERATIONS

In this section we present a number of considerations required for designing on-body fabrication systems.

Fabrication Methods

As described earlier, many crafts exist for manually creating on-body artifacts. With ExoSkin, we wish to adapt these practices by leveraging to benefits of digital tools, such as providing guidance and feedback, and supporting importing and exporting operations. Currently, we know of no CNC machines that are specifically designed to use these processes for fabricating directly on the body.

Each of the abovementioned fabrication methods insinuate the body to be in a specific location in relation to the fabrication machine. For example, a CNC loom that weaves directly onto a body would need that area to be positioned inside of it. Similarly, a CNC draping machine would need the body to be placed under, and a CNC spraying machine would need the body to be placed in front of it.

To use extrusion, the nozzle of the extrusion machine should remain perpendicular to its surface during printing. This spatial limitation prevents traditional 3-axis 3D printers to be used for on-body fabrication. The complex curvature of the body requires a minimum of 4 axes for the extruder to be normal to the printing surface. Machines with 5 or more degrees-of-freedom, such as hand-held extruders or robotic arms, have the ideal flexibility for printing on the body.

If hand-held devices are used, it may be hard to reach certain body regions, and there may be challenges in orienting the device to perform the fabrication. These constraints could be remedied if a third-party is performing the fabrication on a subject's body.

Safety

In every case where a fabrication machine comes in close contact with the human body, safety should be a primary concern. The risk of entanglement should be minimized by keeping moving machine parts fully enclosed and away from the body. Pinch points must be avoided by positioning the body in free space and not on a rigid platform. Most importantly, irritations and burns need to be prevented by using skin-safe materials.

Materials

Finding appropriate materials for on-body printing was one of the steeper challenges for this research. There are a number of constraints and limitations that impact the choice of materials for on-body fabrication. As described above, the material must be skin-safe, including its temperature at the time of extrusion. Second, it must be easy to remove and clean, unless the print is meant to be permanent. Third, the material must be resilient to movements and deformation on the body. Lastly, it must be a workable medium for a given fabrication process (*e.g.* extrudable).

The safety requirements immediately rule out materials that change states using heat. For example, polymers that liquefy with heat, such as the thermosoftening plastics used in Fused

Deposition Modeling (FDM) 3D printers, or materials that cure with heat, such as the thermosetting plastics, concrete, resins, clays, and plaster often used in freeform printing, are not appropriate for on-body printing. Photopolymers may be applicable, however they were avoided in this research due to concerns of prolonged UV exposure to the skin.

The second consideration for skin-safe material is that it can be removed from the body. Latex and silicones are commonly used to make prosthetics, masks, and molds for the body, however they often require adhesives to remain stuck to the skin and must be peeled off the body when done. Water-soluble clays and pastes, by contrast, will stick to skin during fabrication, and can be simply washed off after use. Excessive body sweat or humidity, however, may impede drying and can deteriorate the printed material over time.

Other considerations are the specific material properties in relation to a chosen fabrication process. In extrusion, for example, the viscosity of a material plays a critical role. If the material is not viscous enough, it will take a long time to set, and consequently slide off the body during printing. But if the material is too viscous, it will be extremely difficult and slow to extrude. Moreover, attributes like drying rate, drying time, and layer adhesion all influence the performance of the material during extrusion, as well as the finish quality of the fully cured material.

Hybrid Fabrication Workflows

Integrating analog and digital craft into a hybrid fabrication workflow can be strategically challenging. As discussed in our related work section, there is a spectrum of possible influence in which the digital tools can control the process, from *active* to *neutral* to *passive*. If the workflow becomes too digitally oriented (*active*), the benefit of the human agency is minimized. Likewise, if the advantages of digital fabrication processes are not leveraged (*passive)*, the existing analog methods may be limited. In designing hybrid workflows for on-body fabrication it is important to consider where in this spectrum the system should fall.

Design

One important aspect of any fabrication workflow is the design phase. Existing research has developed techniques for designing digital models on and around the body [11, 36]. Developing additional digital input modes based on tools currently used in on-body fabrication may be a more contextual approach to hybridizing these analog crafts. For example, a tailor could digitally design a garment directly on a customer's body, rather than manually measuring the body dimensions and subsequently producing the design.

Adapting body-based input as a digital process also enables us to augment several existing analog design methods. For example, positioning, scaling, copying, or reorienting a 2D pattern on the body can be a time consuming analog process. However, these geometric transformations are trivial in digital design. Moreover, in many analog on-body processes, such as creating garments or prosthetics, the design and fabrication stages happen simultaneously. The ability to visualize a digital design on the body prior to fabricating can enhance the design-to-production workflow, and enable more rapid design iteration before committing to fabrication.

A final benefit of utilizing digital design is that it could enable a design fabricated on the body to be more easily replicated, shared with others, archived, fabricated remotely, or adapted to different bodies. This increases the potential impact of a design beyond a single individual's body.

Fabrication

In terms of the actual fabrication process, a fully digital fabrication process could be preferred to ensure the highest level of precision in the final fabricated model. However, there are certain practices that may be best suited as an analog technique within hybrid workflows.

For example, the person who will wear the artifact may desire more agency and control over the final outcome. In this case, keeping human input integrated into the design process may increase overall satisfaction, since people have complex sensitivities and preferences to what gets put on their bodies.

Additionally, in certain scenarios, a fully digitized fabrication process may not be appropriate for hybrid workflows. For example, fabricating near sensitive or injured areas of the body require a level of delicate and dexterous control that goes far beyond the sensing and actuation capabilities of current fabrication machines. In these scenarios, integrating a hand-held or assistive fabrication device into the hybrid workflow may be most effective.

EXOSKIN

To initiate the exploration and investigation of these design considerations, we developed ExoSkin, a proof-of-concept system for printing digital designs directly on the body. Similar to existing on-body crafts which we reviewed, a user can design and fabricate directly on a human body. However, we adapt these analog arts with digital tools, to provide guidance, feedback, and to support additional operations such as importing and exporting designs.

The general workflow of ExoSkin allows users to first use a handheld fabrication machine as a stylus, to provide design input directly on the body. The resulting geometry is projected in real time directly on the body. Once satisfied with a design the user can switch to an output mode and fabricate the design by extruding a single layer of material. This fabrication process is facilitated by a projection guidance system which visualize the required tool paths.

ExoSkin uses a *neutral* hybrid fabrication process, where digital guidance is provided to the user, but there is no actuation or force feedback to control or constrain the geometry as it is fabricated.

For our system development, we focus on a single body part: the arm. We chose the arm as a representative body part, as it is highly mobile, has a complex curved form, and tires quickly when unsupported. However, we believe the techniques and ideas explored through the arm are largely applicable to other parts of the body.

The designs which can be generated by ExoSkin are simple and abstract. Our emphasis is less on generating product-ready models, and more on demonstrating the feasibility of on-body fabrication. Domain-specific applications and potential use cases are discussed later.

Fabrication Material

Guided by the constraints identified in our design considerations section, we explored three types of clays as a possible printing medium: an oil-based polymer clay, a water-based polymer clay, and a natural stoneware clay. We controlled the viscosity of each substance by adding a thinner to the first oil-based polymer clay, and water to the second polymer clay and stoneware clay. Each material was extrudable, however the oil-based polymer clay would not harden at room temperature. The stoneware clay would harden too quickly, and was prone to cracking and chipping.

In the end, we chose the water-based polymer clay (Jumping Clay) as our printing medium (Figure 2). It has a few unique affordances that make it an ideal candidate for on-body printing. First, it is an air-dry clay, so it cures from liquid to solid at room temperature. Second, when cured it is a lightweight, semi-flexible foam (Figure 3). This flexibility is an ideal material property for printing on the body, as the surface finish is resistant to cracking as the skin deforms. Lastly, the clay is reusable. Even when fully cured, this clay can be harvested and returned to its paste-like state by submerging it in water. This last material attribute is particularly compelling, as the majority of materials currently used in 3D printing are either one-time use only, or have a complex recycling process.

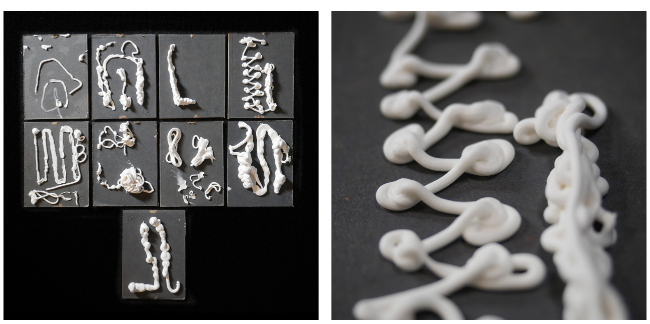

Figure 2. ExoSkin uses a water-based polymer clay as the printing medium.

Figure 3. ExoSkin prints with an air-dry polymer clay (0 minutes, 2 minutes, and 6 minutes after extrusion). The clay dries with a smooth surface finish and a foam-like flexibility.

Fabrication Hardware

The main hardware component of ExoSkin is the custom fabrication machine designed specifically for on-body printing. The system uses extrusion as its hybrid fabrication method. We choose to develop a hand-held extruder instead of adapting an industrial robot for on-body printing over concerns of safety and user engagement. Developing the additional safety measures needed for a robotic arm to safely touch a human body were beyond the scope of this research. Although a hand-held extruder will be less precise than a robotic arm, users can gain an increased sense of control and agency throughout the design and fabrication process [8].

Our on-body fabrication machine consists of three parts: a motorized clay extruder, a hose, and a hand-held extrusion nozzle (Figure 4). The clay extruder is a Potterbot linear RAM extruder, which has a 2-liter material reservoir. We add an 18” high-pressure polyester reinforced PVC tubing to transfer material from the extruder reservoir to the hand-held effector. The hand-held portion of the extruder consists of a hose adaptor, motorized ball valve, a set of interchangeable nozzle tips, two input/output buttons, and motion capture markers (Figure 5). The hose adaptor and nozzle tip screw into the motorized ball valve.

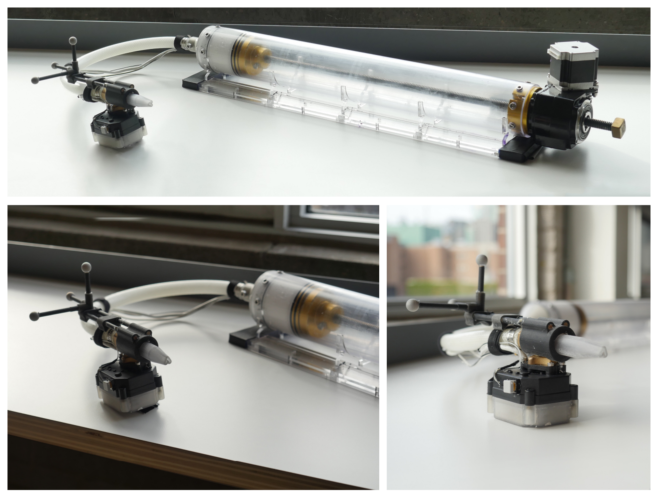

Figure 4. Our custom fabrication machine designed for on-body printing. The machine consists of a motorized clay extruder, a hose, and a hand-held extrusion nozzle.

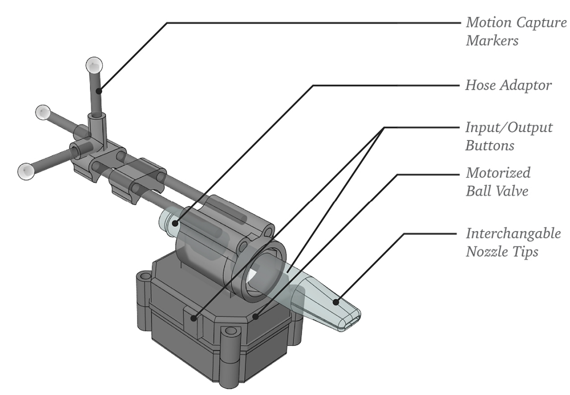

Figure 5. Diagram of the hand held extrusion nozzle.

The motorized ball valve has a slow 3-second phase cycle, which means it takes 3 seconds to fully open or close. However, it can operate with high viscosity material, unlike quicker, but weaker solenoid valves. Prior to fabricating, we pre-pressurize the extruder to push our clay paste from the material reservoir, through the hose, and to the hand-held effector. An output button under the thumb triggers the ball valve to open or close for extruding material. An input button, positioned on the ball valve under the index finger, switches to an input mode which is described later.

The profile of the extruded material can be changed throughout a fabrication session by exchanging nozzles tips on the extruder (Figure 6). Swapping a small diameter for a large diameter nozzle will help rapidly increase the volume of material extruded. Swapping a low perimeter tip for a high perimeter tip will improve drying times for our air-dry clay, since increasing the surface area-to-volume ratio exposes the extruded section to more air.

Many factors contribute to the flow rate of the material from the extruder nozzle: the viscosity of the material, the shape of the nozzle profile, the length of tube between the material reservoir and the hand-held effector. In our system, the flow rate would vary from approximately one to four inches per second, mostly depending on the viscosity of the material and the size of the nozzle being used.

Figure 6. The nozzle tips on the extruder can be exchanged.

Fabrication Guidance System

ExoSkin uses a fabrication guidance system for tracking and visualizing toolpaths data directly on the body. The guidance system is comprised of a motion capture tracking system, projection-mapped visual feedback, and user input.

Motion Tracking

We use a six camera OptiTrack motion capture system mounted above a 3'x 4'x 3' tracking area. Motion capture cameras are mounted from above and below in order to track the full rotation of the arm. Passive markers attached to the wrist of the user track the position and orientation for the arm in world space. Markers attached to the end of the extruder track the position and orientation of the nozzle tip.

Motion capture is handled by OptiTrack's Arena (version 1.7.3). It tracks two pre-defined rigid bodies: the wrist worn marker set and the marker set on the extrusion tool. The position and orientation of these markers are streamed over Open Sound Control (OSC) to our software that controls body-based input, output, and projection mapping.

Visual Feedback

Generic toolpaths used by traditional CNC machines are sometimes visualized in software as simple lines that map how a tool head will move across a volume of space. However, the body is a more complex canvas for fabrication, and brings a number of complications for the generic toolpath. To begin, the user is printing with a hand-held extruder, which is inherently less accurate than a CNC controlled extruder. Moreover, the extruder must move relative to the arm not a volume of space. As a result, this highly curved, constantly shifting surface will have parts of toolpaths that go around the body, and can't be seen by the user. Our system projects custom toolpath visualizations directly on the body to mitigate these challenges unique to on-body fabrication.

A DLP projector is mounted above the tracking area to provide on-body visual feedback. To accurately project onto the body, we first calibrate the projector to the motion capture system using a simple one-time routine that correlates projected 2D points with tracked 3D world points.

User Input

In addition to fabricating, the hand-held extruder serves as a digital input device. The user enters an input mode by pressing the input button on the extruder. In this input mode, the user can draw digital content on their physical arm by using the tip of the extruder as an on-body stylus.

A CAD backend records the world coordinates of the extrusion nozzle's tip. These user-recorded points are down sampled and smoothed from the initial motion capture data. The motion capture system streams coordinates at 100 fps at sub-millimeter precision. The filtered coordinates are then attached to the virtual representation of the arm. This lets the user freely move and rotate their physical arm, while keeping the user input geometry fixed to its original location relative to the reoriented arm.

CAD Backend

The underlying software of our system is a backend CAD program not seen by the user. It holds the pre-scanned mesh of the body part intended for on-body fabrication, a mesh of the extrusion tool, and the 3D model of the current design. The meshes are dynamically rigged to the rigid body data streaming from the Arena software. The CAD backend aligns the arm's mesh to the incoming tracking data by translating the mesh from a known offset to the incoming marker coordinate, and then reorients the medial axis of the mesh to the normal of the wrist-marker plane. Similarly, the mesh and tip of the extrusion tool is transformed from a known offset to the position and orientation streaming from the tool-marker set. Synchronizing a virtual representation of the arm and extrusion tool with the physical arm and extrusion tool enables the CAD backend to record user input in coordinates that are relative to the moving body.

Software Implementation

ExoSkin was implemented using the Java programming language at 60 FPS. It uses the following open-source libraries: processing for graphics, OpenCV for projection mapping, toxiclibs for computational geometry, and oscP5 for streaming data over Open Sound Control (OSC). Rhinoceros 3D and Grasshopper 3D are used to illustrate how our system can send and receive geometry from external CAD software.

User Interaction and Workflow

ExoSkin strategically implements a hybrid fabrication workflow that enables digital designs to be printed directly on the body. In designing our hybrid workflow, we build upon analog techniques in on-body fabrication. The analog design process for on-body fabrication happens *in-situ* — within the local context of the body. This enables a fabricator to dynamically adapt a design in response to the surface, the person, or other conditions that would otherwise impact the final outcome. ExoSkin adapts this dynamic, in-situ design process as a digital workflow. The designs which are created are meant to demonstrate the capabilities of the system, and do not necessarily represent product-ready models.

Design

A user begins by digitally drawing on the skin by pressing and holding the input button on the extruder. As they move the extruder over the arm in world space, the sketched lines are projected as toolpaths directly onto the body (Figure 7). Together, the tracking system and projection mapping keeps a persistent rendering of the artwork relative to the moving arm. This means that when the user moves or rotates their arm, only the correct, visible portions of the design are rendered.

To smooth user input, the system down samples motion capture data to have a minimum distance of 3mm between points. Additionally, ExoSkin automatically snaps user input points to the closest points on the virtual surface. These filtered surface points are then interpolated into a smooth 3-degree spline.

Figure 7. The user can directly sketch virtual strokes onto their body.

Fabricate

Once a sketch is complete the user can transition to the output mode of the extruder. To begin extruding, the user holds down the output button on the nozzle, which opens the ball valve to begin extruding material. The user can then slowly trace the rendered design on their body (Figure 8). During fabrication, ExoSkin displays Toolpaths that are designed to provide multiple layers of information to assist the user during the fabrication process.

Figure 8. The user holds down the output button and extrudes over the rendered design.

To help improve accuracy for fabricating with a hand-held device, our system provides continuous visual feedback relating the nozzle location in relation to the toolpath. As the user brings the extruder near a toolpath, a halo around the tip of the extruder and the closest point on the toolpath is projected (Figure 9a). The halo illustrates the disparity between locations and visually prompts the user to adapt their tool position.

Next, to indicate the continuation of a toolpath towards a non-visible part of the body, we dynamically animate the line thickness and color gradient of the toolpath. Toolpaths grow thicker and brighter directly under the extruder. However, as the user moves the extruder tip from one side of the body to the other, the thickness and color of the toolpath thins and dims, as if it is wrapping around to the backside of the surface (Figure 9b). This serves as guidance for the extruder paths.

Users can also physically manipulate the material once it is extruded, if they do not get a desired result. A minor error can be corrected by nudging the material to better match a desired toolpath. A larger error can be corrected by removing portions of the fabricated path and re-printing it.

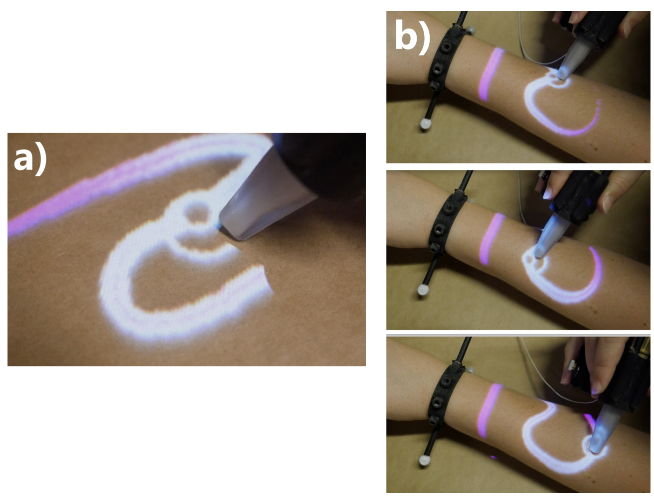

Figure 9. Visual feedback during fabrication. a) A halo around the extruder directs the user to the closest point on the toolpath. b) A dynamic toolpath indicates the path that the extruder should follow.

Sketch Beautification

Our system implements simple sketch beautification [18] to transform imprecise user input into precise geometric objects. In Figure 10, the user quickly sketches a circular shape onto their body using the input mode of the extruder. The system then recognizes the sketch as a circle, creates the idealized geometry on the virtual arm, and then projects the 3D dimensional perfect circle as a toolpath, and the user can press the output button to extrude material while tracing the toolpath. Likewise, a triangle is sketched on the body, processed into an idealized polygon, and then projected back as a precise shape. Again, the user presses the output button on the extruder and traces the toolpath to fabricate the shape.

Figure 10. Precise sketching demo.

Importing Geometry

As an alternative workflow, ExoSkin can connect to conventional 3D modeling software for importing geometry. This lets a user create precise digital designs for the body, which are then sent to our system for on-body projection and fabrication. In Figure 11, a user designs an organic 2D pattern in Rhinoceros3D, a commercially available CAD software (Figure 11a). We developed a script running in the CAD program to map the 2D pattern to the 3D mesh stored in our system, and then send the 3D geometry to ExoSkin via OSC. ExoSkin stores the geometry as toolpaths attached to the virtual arm. This keeps the CAD-generated geometry attached to the user's arm as they move and rotate around the workstation. These CAD-generated geometries are projected onto the body, and are ready for printing (Figure 11b). ExoSkin's pipeline to existing 3D modeling software enables users to quickly test out a design directly on the body. Users can easily translate, rotate, copy, or scale a design in the CAD program, which then updates the geometry projected onto the body in real-time. The floral pattern armlet in Figure 11b demonstrates ExoSkin's capability of fabricating highly intricate toolpaths.

Exporting Geometry

ExoSkin's connection to external CAD software brings an additional benefit to the hybrid fabrication process: the ability to export an artifact designed or fabricated on the body as a ready-to-print 3D model (Figure 1). In Figure 1a, the extruder is used as an input device to draw the design of a bracelet directly on the arm. ExoSkin stores the user input as a set of toolpaths, which it also sends to a connected CAD program. The user then prints the bracelet on the body by tracing the projected toolpaths, then infilling the defined region (Figure 1b). Simultaneously, a script running in the CAD program generates a thickened surface from the user's input geometry, and exports a valid mesh for conventional 3D printing (Figure 1d). This allows users to obtain a quick physical prototype printed directly on the body, and then print a more robust model on an external 3D printer with rigid 3D printing materials.

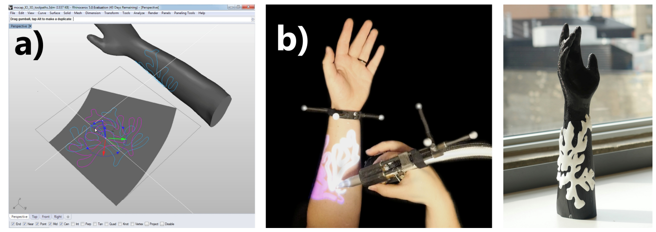

Figure 11. a) Design can be generated in commercial CAD software. b) The CAD geometries are projected onto the body.

A Framework of On-Body Fabrication

Figure 12 contrasts the input and output workflow paradigms facilitated with ExoSkin, to existing workflows for the design and fabrication of wearable objects. Our system provides several new design and fabrication workflows that sit in between fully analog and full digital methods for on-body fabrication. We believe the flexibility to mix input and output methods offer a number of opportunities for future exploration.

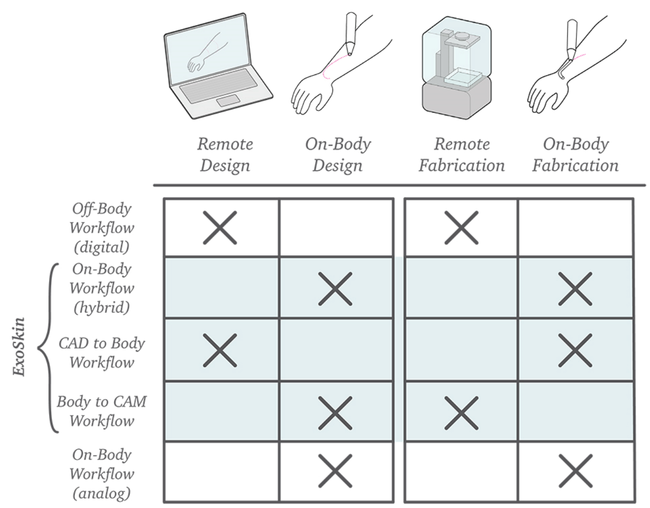

Figure 12. Input and output paradigms for the design and fabrication of wearable objects. ExoSkin provides several new design and fabrication workflows (highlighted blue) that sit in between a fully analog on-body workflow and a traditional fully digital off-body workflow.

INITIAL USER OBSERVATION SESSION

ExoSkin is an exploratory system designed to investigate the concept of on-body fabrication. As such, it was not our goal to evaluate the system or conduct formal caparisons to other fabrication techniques. However, we still felt it would be useful to get initial user feedback on the system and the concepts which it represents.

We invited four users to participate in a single workshop session — two male and two female, aged 20–30. Participants were internal to our organization but were not members of our research group and had no prior knowledge or exposure to the ExoSkin system.

All four participants had engineering or computer science backgrounds, but had very little previous experience with digital design and fabrication methods. One participant had basic knowledge of 3D modeling and only one participant had ever used a 3D printer.

Procedure

During the workshop session, we first explained the system configuration, providing an overview of the fabrication, sensing, and projection technology. The fabrication workflows were then demonstrated to participants, highlighting the main features of the system. Each of the four participants were then given an opportunity to use the system, and were prompted to design and fabricate a simple model directly on their arm. The entire session took approximately 45 minutes. Below we discuss the main observations and feedback which were collected.

Participant Feedback

In general, participants reflected positively on our system and were enthusiastic about on-body fabrication. When initially extruding onto the skin, each participant made a comment on the printing material's texture. They were surprised by its stickiness and cool temperature, with one participant exclaiming *"It tickles!" (p2)*.

Participants did see the value in printing with a washable, reusable material, however there was also a desire to preserve a print so that it can be worn multiple times:

"I would like to be able to take it off my body without destroying my beautiful design." (p1)

When prompted for their thoughts on the extrusion tool, three participants noted a potential preference for a robotic instead of hand-held tool. They felt a robotic system would increase the speed and accuracy of the fabrication process and would take less effort on their part. There was also a sense that a machine would do a better job than they themselves could:

"I don't trust myself to make it right… I'd rather trust a machine." (p3)

P4 enjoyed the hand-held device, and also noted the desire to use it on others, in addition to using it on his own body:

"I'd use it to give someone a tattoo!" (p4)

Participants were also asked if they would entrust a machine to fabricate on sensitive areas of their body, such as the face or back. Three participants gave a definitive *'No'*, however one participant said they would feel comfortable as long as there was a human overseer:

"I wouldn't mind a machine printing on my face … as long as a person would come check up on me every once in while. You know … to check if I'm still alive." (p2)

At the end of the workshop, participants were asked to think about the kinds of thing they would print on their bodies. Clothing and accessories were immediately mentioned, and one participant wanted to print custom electronics:

"I'd print a game controller right on my arm!" (p3)

DISCUSSION

We believe there are many analog craft processes that can be adapted for hybrid workflows in on-body fabrication. We are optimistic that further exploration into on-body fabrication will prompt additional innovative interaction techniques that circumvent the unique challenge of crafting digital designs directly on the body.

Domain Specific Applications

Our research was focused on the interaction implications and hardware configurations for printing on the body. We have provided some abstract examples of the artifacts which could be generated with such a system. Further work could investigate specific applications for fabricating functional objects on the body.

Body-centric design industries that rely on one-off, handcrafted designs are currently limited in their ability to rapidly create, iterate, and share a given design. Augmenting these high-skill analog craft practices with digital techniques brings an opportunity to streamline design-to-production workflows for on-body fabrication. In particular, we see four primary domains that would benefit from on-body digital fabrication: skin-centric industries (such as cosmetics), fashion and wearables industries, film and special effects industries, and the medical device industry. Such domains may specifically benefit from on-body design, on-body fabrication, or both.

In applications that modify the skin, such as cosmetics, digital drawing or brushing instructions that are projected onto the body can help non-experts learn expert techniques. In the movie and special effects industries, body-worn props or prosthetics can be precisely designed in a CAD environment, then digitally fabricated directly onto an actor. For fashion and wearable devices, on-body design could give both the artist and the model agency in a customized design process, while direct-to-body fabrication enables bespoke designs to be customized to many bodies, and inherently ensures the design will fit the wearer. Lastly, for medical applications, the design of prosthetic sockets or silicone dressings, for example, can be created by an expert then sent to remote locations for technicians to fabricate directly on a patient.

Body Parts

Our discussion of possible content domains indicates that many areas of the body may be appropriate for on-body fabrication. However, each specific location brings unique challenges and considerations that impact the choice of machine configuration. This can relate to *physically sensitive* areas of the body — such as the face, head, neck, and spine — *socially sensitive* areas — such as the chest and nether regions — or *highly mobile* areas — such as the arms, hands, legs, and feet.

Printing on physically sensitive areas require continuous, nuanced feedback on how the fabrication device is touching the body. In these scenarios, hand-held devices may be most reliable and appropriate as fabrication devices. Socially sensitive parts of the body, may be less desirable for direct on-body fabrication or may be preferred to be operated by the person being printed on instead of a third party. For highly mobile areas of the body, the fabrication system cannot assume that the body part will remain still for long periods of time. Therefore, the configuration of the system must be designed to adapt to continuous changes in position and orientation of the fabrication surface.

LIMITATIONS AND FUTURE WORK

We chose to develop a hand-held extruder as the fabrication device for our on-body fabrication system. Our decision was guided by the relatively quick development time for a hand-held device, as well as the low risk of injury for the end user. However, what we gained in agile deployment and increased safety, we lost in precision and accuracy when compared to existing multi-axis CNC machines. Future work could focus on developing compliant, multi-axis systems that strike a more even balance between precision, accuracy, and safety for on-body fabrication. For example, worker-friendly robotic arms, such as Universal Robots, would be particularly interesting to explore.

Our implementation uses a motion capture system as a low-latency, high accuracy, and highly flexible solution to track bodies in space. However there are other spatial tracking technologies that could be used in on-body fabrication systems. In particular, markerless tracking would be desirable for any sort of deployment. We experimented with both Kinect and Leap motion tracking, but found the accuracy was not yet reliable for the purpose of our project.

We use a single projector to visualize fabrication instructions on the body. Although the throw of the projector adequately covered the volume of our work area, shadows cast by the extrusion tool could hide portions of projected toolpaths from the user's view. Future fabrication systems could mitigate this problem by using alternative visualization configurations; for example, switching multiple projectors or using augmented reality devices, such as translucent screens or head-mounted displays would eliminate the shadows cast by physical objects in the workstation.

With regards to our implementation, we examine the implications of direct on-body printing using a single, skin-safe material. However, there are many more materials to be developed and explored. We are particular excited for composites that layer skin-safe and non-skin-safe materials together. For example, a skin-safe paste could be printed as an insulating layer against other heat-transferring materials, like thermosoftening or thermosetting plastics. Moreover, edible materials such as frostings, pastes, or foams may also be applicable for on-body fabrication.

One notable limitation of our implementation is that it supports extrusion of only a single layer of material. While ExoSkin supports complex toolpaths that are curved and three-dimensional geometry, it does not provide traditional multi-layer three-dimensional fabrication. To support this, the set time of the material would need to be accounted for. Furthermore, or toolpath generation algorithm would need to be advanced to support multi-later digitization.

Our work could also be extended to support printing on areas of the body under high amounts of deformation or stress, such as joints, hands, and feet. Moreover, fabricating electronics directly on the body could be explored by combining skin-safe materials and conductive pastes or inks.

The machine processes for on-body fabrication also warrant further investigation. In our implementation, we create a custom material to use in an extrusion device. However, existing everyday materials could prove useful if the appropriate fabrication process were developed. For example, threads and textiles could be used in fabrication machines that weave or drape directly on the body, and medical tapes or gauzes could be used in machines that wrap bandages, braces, casts, or splints around patients.

Fabricating with a custom-made material also limits quality control from batch to batch. Despite our best efforts the water content of each hand-mixed batch of polymer clay would vary slightly. As a result, the behavior of the material, its viscosity and drying time, would differ each time the material reservoir was reloaded. Future implementations could integrate an air-assist onto the extrusion tool to actively dry the clay when too wet.

Finally, we would like to conduct more thorough and formal evaluations of on-body fabrication. Our preliminary observation session provided some interesting insights. For example, the issue of reusability came up – how can models printed directly on the body be preserved and re-worn? Furthermore, the topic of human agency revealed subjectivity and trade-offs – while some identified the manual extrusion tool as potentially imprecise, others valued the ability it gave them to control the fabrication process. Follow-up studies could explore these and other related topics.

CONCLUSION

We have shown how existing crafts of on-body design can be adapted with hybrid fabrication workflows to enable digital designs to be crafted directly on the body. Our initial observation session indicates that this new paradigm for interactive 3D modeling involves curiosity and intrigue, motivating further explorations and implementations. Moreover, we have outlined design considerations for future on-body fabrication systems, and have identified the unique human, machine, and material challenges that these systems will need to solve. We acknowledge that digital on-body fabrication is a challenging domain. However, we believe the potential impact of digitizing this previous analog craft to be an important area for future explorations.

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