

VR Gestural Modeling to Recapture the Human Body in Design

SARA CODARIN

Lawrence Technological University

KARL DAUBMANN

Lawrence Technological University

Keywords: gestural modeling, VR design, immersive collaborative environment, physical body, digital design

This paper positions the work of a three-credit elective seminar that investigates the potential of an immersive VR collaborative design environment to realign the importance of the physical body in digital design. The students in the course engaged in the process of designing based on the human body, being exposed to the historical background in art and design practices as far as the contemporary digital culture. The research question that motivates the work arises from the fear of losing the agency of the human body in both dimension, movement, and gesture to inform the translation from 3D reality into a 3D representation. However, new VR technologies aim to directly connect designers and what they draw and model, filling the gap between input and output design workflows.

INTRODUCTION: REPRESENTATIONAL TRANSFORMATIONS

Since the arrival of digital to design, the fear of losing the importance of the physical body continues to increase. The “disembodiment” in the digital culture is made explicit by the tools professionals use to make design and architectural notations. Drawing on the computer, for instance, means drawing with the mouse, which is a surrogate of the human hand but constrained in a Cartesian 2D space. The physical input on the mouse initiates a process of mediations in the digital environment that allows for translating 3D reality into 3D digital representations.

The notion of translating perspectival reality through procedural translations is rooted in the Renaissance when the analog construction of one and two-point perspective was developed. The woodcut “Man Drawing a Lute” by Albrecht Durer shows the direct relationship between input and output, observation, and hand-drawn outcome. An artist and assistant are depicted tensing a string to draw a scaled-down image of a lute using a perspectival canvas. Later, in the first half of the nineteenth century, Charles Wheatstone advanced the studies on the human perception of space with the invention of the stereoscope. This technology consists of two mirrors rotated forty-five degrees reflecting a picture located off to the side of the user’s eyes.

Through the stereoscope, Wheatstone demonstrated the ability of the human brain to combine two photographs of the same object from different points of view and let the merge make sense three-dimensionally by the observer.

The scientific knowledge disseminated up to that moment is the historic premise to the development of immersive VR environments.¹ From the 1950s and in the following decades, this technology advanced due to massive investments in the entertainment and aerospace industries and entered design in more recent times.² Besides, it is not unusual for the design field to absorb innovation from other technology-driven sectors, early adopters of avant-garde tools. The Fourth Industrial Revolution³ is the most recent manifestation of this tendency, with a socio-technical shift occurring from manufacturing to product design and architecture.

Currently, the extended possibilities of VR tools bring new opportunities for digital representation and its inherent workflows. Among these opportunities, software like Gravity Sketch allows for creating a direct connection between designers and drawings because of the software’s ability to capture bodily movements and gestures. This connection is possible because the VR hand-held controllers are programmed to digitally interface spatial data recorded in real-time and informed by body motion. Therefore, VR tools can be deployed to recapture the importance of the human body in digital design and initiate a creative process with the generation of natively digital forms.

The role of the human body in digital design was the focus of the elective seminar “Digital Twins” offered at the undergraduate and graduate levels in Summer 2021. The course title refers to implementing the virtual replica of objects that can be continuously updated from their physical counterpart. The seminar required no previous VR, digital design, or software experience, foregrounding the intuitive nature of designing with the body and working in a VR collective space.

STATE OF THE ART: THE HUMAN BODY AS A TOOL OF ANALYSIS

The course “Digital Twins” was structured to leverage theoretical technical knowledge to design for the body with the body.



Figure 1. Students from the course “Digital Twins” working in a co-create immersive space within Gravity Sketch. Image by the authors.

The theoretical content covered the history of the body and the “drawing hand”⁴ in design as means to confront the phenomenological world of architecture. Connections were made between the possibilities given by VR and the development of technologies in the twentieth century that allowed for a deeper understanding of reality. These technologies came from areas such as cinematography and photography, which eventually crossed over to design.

One example shown in class was the chronophotography “Cheval Blanc Monté” from 1886 by the physiologist and photographer Étienne-Jules Marey. The image depicts the phases of movement of a running horse recorded on one photographic film. Through the documentation of the motion sequences, Marey could demonstrate that a galloping horse doesn’t touch the ground with any of the four hooves for a brief moment. He compared these visual experiments with images of joints and muscles that characterize animals of the same species to articulate in cohesive discourse chronophotography and anatomy. Using the same operational methodology, Marey photographed less tangible entities, like air movement in the form of smoke trails flowing around obstacles of various sizes and shapes.⁵ An analogy could be suggested in referring to design workflows in Gravity Sketch because VR design allows for capturing intangible bodily movements as geometry primitives. Therefore, it enforces a greater comprehension of body movements, spatial ranges, and rotational limits.

At the beginning of the twentieth century, photography informed painting. This translation is visible in “Nude Descending a Staircase” of 1912, where Marcel Duchamp freezes on canvas still frames of a human in motion dissolving into each other. A more recent example is the “Visible Human Project” by Frank Scott, a ghostly digital visualization of human anatomy obtained using cross-sectional photographs of a segmented body given to science for medical research.

In the 1930s, the invention of the stroboscope by Harold Edgerton contributed to further discoveries in photography.

The stroboscope enabled a breakthrough in the scientific representation of motion by replacing the analog flesh triggered by a controlled incandescent explosion with a device connected to a battery that could flash up to 120 times per second. Therefore, Edgerton made it possible to record 1/100,000th of second-long frames of motions not otherwise visible to the human eye. This equipment was then used by Gjon Mili, who is also well known for the long-exposure photos of Pablo Picasso. The long exposure photographs were used as drawing precedents for the class.

After the excursus about technology, the conversation within the course shifted from contemporary hyperrealism to the human body’s idealization in the Renaissance. The top-down idea of the body as the center of the universe is illustrated in a series of Francesco Di Giorgio Martini’s sketches. To mention one example, the drawing of a church’s plan overlaying a human figure implies the notion of the body as a form of architecture that undergoes geometric rules and proportional constraints. Not only is the body depicted as a physical entity governed by rules of architectural composition (and vice versa), but it is also an analytical tool to comprehend it. The design of human proportions evokes the Vitruvian Man by Leonardo Da Vinci, which illustrates a human body centered on a geometric form and captioned with a text inspired by Vitruvius. The input to produce this drawing came from Di Giorgio Martini in 1490 when he shared with Leonardo the translations from Latin of Vitruvius’ treatise *De Architectura*.

The theoretical connotation of Di Giorgio Martini’s drawings can be seen in parallel with the programmatic agenda of Le Corbusier’s Modulor Man. Le Corbusier’s system of dimensions related to the human figure manifests the rationality of architecture informed by the body’s characteristics. The Modulor Man recalls the current regulatory studies of ergonomics, which inform building construction related to the accessibility of standardized bodies with some approximations regarding different human capabilities to occupy built spaces. However, in this discussion, it’s worth speculating on possibilities to include in the design and decision-making processes a more

comprehensive range of bodily proportions, moving away from idealized dimensions.

The individuality of the human body is also manifested through subjective everyday experiences in the physical world. COOP Himmelblau conceptualized this idea in the late 1960s with the project “The White Suit.” It is portable hardware that connects architecture with sensory perceptions filtered from the external environment from a lightweight technological apparatus. The suit is composed of a television helmet that broadcasts visual imagery augmented by the insertion of smells and pulsations in the pneumatic vest. By maintaining the bodily territorialization of the internal intimate spaces, COOP Himmelblau made architecture “so transportable that it can be worn on its own body”.⁶ This futuristic project/performance has a practical application today with VR workspaces. Headsets allow for entering immersive 3D environments, as opposed to the 2D video interface of the computer. In addition, hand controllers mediate the initiation of the design by regulating the flow of information between outside/physical and inside/digital inputs.

Body performance ties to Greg Lynn’s description of the idealized human matter as a nonstatic (animate) form, especially when collaborating with other entities. Bodies result from “intricate connections, alliances, aggregations, and affiliations of base matter”.⁷ Therefore, it would be diminutive to describe bodies of any nature as pure wholes. They are mechanisms influenced by multi-scalar external factors and variate like viscous fluids. These variations are the gestures. Most of the time, bodily gestures are expressed using the hands.

Humans have developed a complex relationship with their hands over time. Hands communicate through fluid gestures and transfer information to the brain about the outer world. The tools that humans use in design and craft operate as translators of the designer/maker’s body and hand. The hand, according to Juhani Pallasmaa, “is everywhere in our body, as well as in all our actions and thoughts”.⁸ In support of this idea, in the *Thinking Hand*, Pallasmaa adds that “works of art and architecture extend the human hand through both space and time”.⁹ VR modeling makes explicit the connection between time and space while creating digital hand gestures-driven forms.

METHODS

“Digital Twins” aimed at realigning bodily gestures with design workflows, leveraging the possibilities given by a setting in Gravity Sketch called “co-create”. Co-create is a collaborative VR workspace that can be entered by a group of people who are digitally enabled to interact and communicate through their avatars/digital bodies. Classes met every week in a shared immersive space. Every person joining the co-create room could see what other participants were doing and look at the model-making of forms in real-time guided by the digital translation of the hands (Figure 1). Students acquired technical knowledge of VR modeling by drawing natively digital geometric elements of

increasing complexity. Several assignments were structured to find contact points between digital and physical, reversing the streams of inputs and outputs to find space for debate.

The first assignment, “Body Constraints,” introduced the students to Gravity Sketch. Students were asked to trace with thin lines the outline of their bodies in different positions using the stroke tool. The traces needed to highlight some key points of the body such as shoulders, knees, chest, and waist (Figure 2). This exercise built up a density of digital lines that represented movements, gestures, and dimensional limits. In this way, students were able to visualize the areas of the reachable volume containing their bodies. Through iterations of hand gestures, the results demonstrate the dynamism of each body carrying out the assignment. In *Body Matters*, Greg Lynn, citing Edmund Husserl’s *Origin of Geometry*, describes the body’s uniqueness as an “anexact but rigorous” form. The expression outlines entities that “are neither exact (they cannot be reduced to mathematical statements) nor inexact (they cannot be measured with precision).”¹⁰ These geometries, Lynn continues, “are capable of describing the architectural characteristics of bodies that are both more and less than a whole.”¹¹

The use of lines as an analysis tool continued with the assignment “Draw a Bernini Body.” An introductory lecture was given to the students by comparing sculptures from different historical periods, from Ancient Egypt to Classical Greece, Italian Renaissance, and Baroque. Egyptian artists worked mainly with two-dimensional surfaces to represent the real world. The statue King Menkaure and Queen portrays two human figures in a hieratic pose that are just three-dimensional enough not to be a bas-relief. Conversely, the “Doryphoros” by the Greek sculptor Polykleitos depicts the three-dimensional realism of a body in *contrapposto* (a technique used in the Renaissance as well), which means standing with most of the weight on one foot to create a visual twist between vertical and horizontal axial planes. Baroque sculptures instead deploy a complex geometric organization that guides the viewers’ eyes to move fluidly through the composition. In Gravity Sketch, the students captured this invisible motion. They drew the movement of their eyes over the Bernini bodies with gestural curves in space to exploit the software’s capability (Figure 2). “The Ecstasy of Saint Teresa” and “The Rape of Proserpina” are some of the precedents used in class. The assignment’s outcomes show the use of iterative gestures of students’ bodies to learn the volumes in space through their own bodily movement.

The third exercise established the first contact point between digital and physical by 3D printing a surface modeled in VR. The assignment “Still Frames of a Body in Motion” introduced sub-division modeling (subD) and modes for articulating and manipulating it. Students represented five keyframe positions of a singular/continuous body motion of their choice and analyzed the different positions/postures in a kinematic sequence. Each pose was embodied by a mannequin, which is a preset object

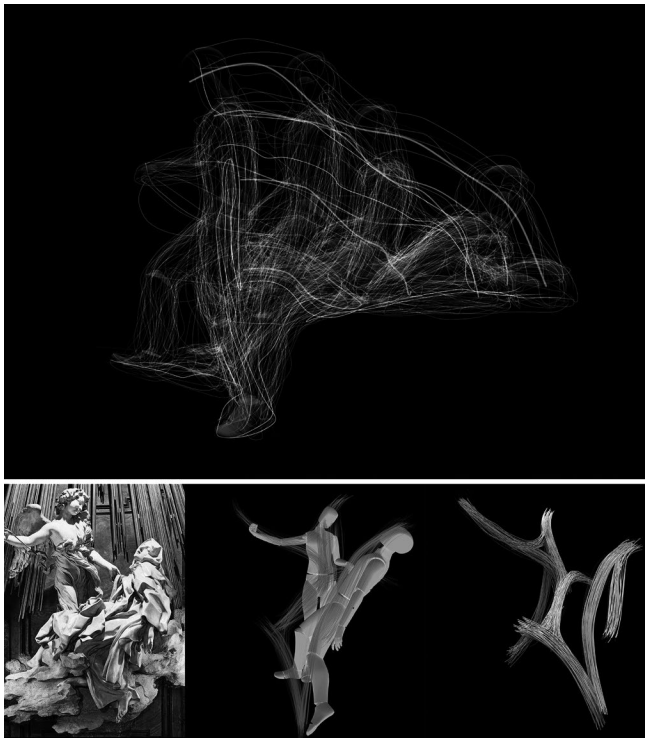


Figure 2. Above: Studies of the human body using digital lines in VR immersive design. Student's work (Kevin Piotrowski). Below: Interpretation of bodily dynamics in Bernini's "Ecstasy of Saint Teresa" using the stroke tool in Gravity Sketch. Student's work (Jacob Smith).

in Gravity Sketch. Given the knowledge of Bernini sculptures, the students considered his mastery of body positioning to accentuate dynamic movements as they placed the mannequins in the model. Then, they drew 3D strokes connecting elements keyframe to keyframe (right knee to right knee, left elbow to left elbow, etc.) to articulate the space/surface between the bodies. Finally, they combined these gestures to define a single surface that holds these bodies in space. They moved iteratively from acting as bodies to navigating around the bodies. The resulting 3D printed object embedded the temporal consistency of the deconstructed motion (Figure 3).

Throughout the semester, the notion of digital bodies/digital twins continued to span the realms of the virtual and corporeal. The assignment "Plaster Casting" asked the students to return to the physical world to find design opportunities and inspiration. The task was to create a series of freeform objects by casting plaster in fluid-like fabric formworks. The students used a physical bodily interaction to form the models. They selected a hand gesture to inform multiple iterations of model making and imprint gestural intelligence on the matter (Figure 4). The organic language of the outcomes was supported by examples such as Frei Otto's models created using soap bubbles and Sverre Fehn's inflated scale models of the proposal for the Nordic Pavilion at the Osaka World Expo in 1970.

"RoboPinch", a research project carried out in 2015 at the University of Michigan Taubman College, was a relevant precedent to elaborate on the assignment's methodology. The research team utilized two tabletop robots to craft fabric formworks and create proto-architectural volumes with no a priori form, only the action of the robots to determine the resulting objects. The robots acted as disembodied human hands to bring unique analog forces in the model-making and form-finding processes. Instead, using their own hands and no mediation tools, the students in "Digital Twins" tested the "animated matter", which was reactive to contingent actions such as grasp, poke, pinch, or pull. Then, in Gravity Sketch, the students modeled the solids created through plaster casting. This time, physical modeling was used as a descriptive and aspirational tool to inform the digital models with a layer of analysis. Once cured into a stable form, the interactions of the body with fluid and unpredictable shapes left visible traces, wrinkles, and stretches of the way the forms were generated. The external physical impositions (pinch) at one point of the object competed with the resultant reactive forces (lump) at another. The VR designers made explicit such forces in the matter.

The observation of real phenomena was an opportunity to reverse input and output workflows again. The model-making session triggered a process of "learning by doing"¹² by acquiring knowledge from the physical world's determinism. This knowledge was tested with digital simulations in a generative design environment using the Grasshopper plug-in Kangaroo2. The assignment "Parametric Simulation" sought to apply an inductive form-finding method to reveal design opportunities by simulating the behavior of objects within certain physical conditions and constraints. The requirement was to create a digital form in Gravity Sketch (formwork), import it in Grasshopper, inflate it computationally (plaster casting), and drop it on a plane that was then deformed/inflated, generating a topography (Figure 4). The goal was to simulate digitally the process of filling fabric formwork with plaster and suspending the objects that resulted in negotiation between internal and external forces, pressure, and gravity. Students concluded the workflow in Gravity Sketch by importing the models of the dropped inflated forms and deformed topography. Such forms were framed as early-stage studies of architectural concepts on a site. Populating the models with mannequins - the VR jargon for scale figures - informed the outcomes with scale, proportions, and suggestions for occupancy opportunities. Moving between different software applications extended the students' skills in developing future and interoperable workflows to their future design work.

The last assignment's objective was to converge the knowledge acquired in the course and develop a final project based on the concepts introduced by "Digital Twins." The course used the house as a prototypical object to investigate the concepts tied to the digital body. Domesticity prioritized a sense of scale informed by the body. "Gestural Domesticity" challenged the

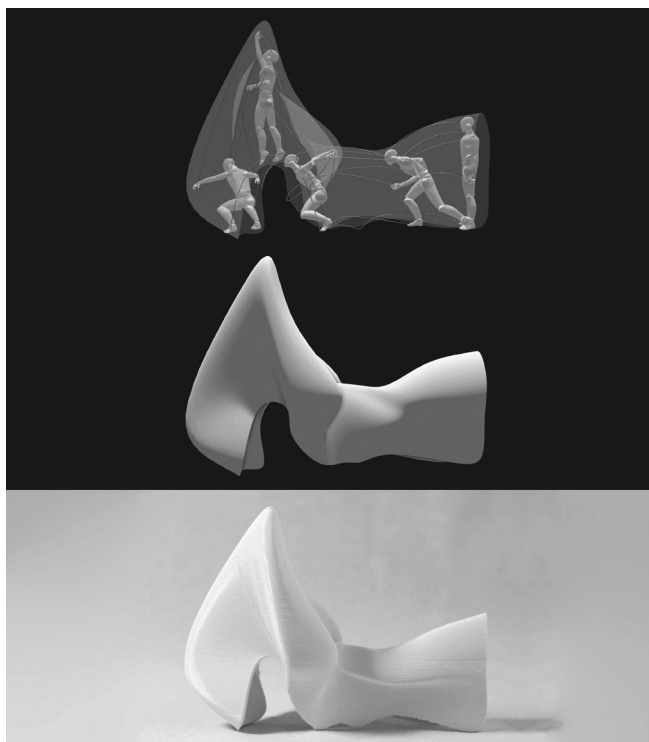


Figure 3. Application of VR design as an analysis tool to understand the still frames of a body in motion. Digital model and 3D printed outcome. Student's work (Aaron Baldwin).

students' craft in their design, digital modeling, and representational abilities. This last assignment required them to design a house concept located on a site/topography modeled entirely in Gravity Sketch.

Students started working with strokes to outline the essential programs of a domicile, having in mind the drawings of a dining table by Sarah Wigglesworth, where thin pencil lines show the invisible relationships between human bodies and objects. Lines represent bodily motions and reach limits of a body performing a domestic activity - examples might include sleeping, eating, cooking, hygiene, and socializing - tied to independent spaces, referred to as "organs." Tim Ingold would argue that linear entanglements are an instrument of sociality: "the principle of the line allows us to bring the social back to life. In the life of lines, parts are not components; they are movements" [...] "not a collage of juxtaposed blobs but a wreath of entwined lines".¹³

Surfaces were used to create solids based on the strokes informed by body performances within programmatic organs. These organs were aggregated in different configurations - for instance, stacked around a courtyard or along a path - and wrapped in a more extensive volumetric system. In doing so, the volumetric clusters were entwined, connected, and tangled like bodies without bones, like Renaissance cherubs and putti or the Baroque "Ecstasy of Saint Teresa." The bodies without bones were laid on a terrain that was used to expand the idea

of the house and investigate its relationship with the landscape/topography (Figure 5). This principle of territorialization recalled the structure of Bernini's sculptures, where bodies are draped and supported by secondary elements. An additional iconic architectural precedent referenced in the class was the "Endless House" by Friedrich Kiesler.

Through the various assignments, students became deeply skilled in aspects of designing with the human body. The densification of the VR environment with strokes, surfaces, and aggregation of solids was used to track the 3D space and understand the opportunities for occupancy. An analogy was suggested between construction tectonics and the multi-scalar interactions involving organs and bodies. Bodies are a rational organization of organs made of connected activities. This hierarchical coalition of parts embeds the intelligence to respond to internal and external forces creating clear relationships between constituent parts. Designing architecture for the human body results in the translation of bodily interactions with space.

RESULTS AND DISCUSSION

In *The Hand* by Frank Wilson, the author highlights the connection that results from the gestural organization through "cultivating intelligence" by "uniting, not divorcing, mind and body".¹⁴ The immersive VR environment allows designers to think with their hands and inhabit with their eyes, hybridizing the concept of learning-by-doing and collapsing earlier notions of drawing with modeling.

"Digital Twins" addressed a methodology to find speculative and practical value in VR design processes. VR design was framed as an analysis and early-stage design tool driven by the human body. Bodily movements and constraints informed decision-making phases. Mutual learning was encouraged by working in co-create. In this VR shared space, design steps are explicit. Everyone can see each other's sequences of operations. The procedure is different from software like Rhinoceros, where design inputs exist in the form of instructions, or Grasshopper, where generative functions are embedded in command components. In Gravity Sketch, designers work using geometry primitives and craft them "manually" by manipulating sub-division control points. Hand controllers put the users in touch with digital matter. In the immersive shared room, the cohort of students performed bodily motions to sculpt lines, surfaces, and solids. Design results depended largely on subD algorithmic approximations and their manual skills, in the same way a clay sculpture derives from the artisanal use of a chisel.

The outcomes express the mutual connection with the tools that generated them and the critical thinking beyond the software features. Every conceptual model created in Gravity Sketch was populated with editable mannequins to give scale and show occupation opportunities for singular architectural organs or aggregates. Mannequins were considered the static representation of gestures in a designated still frame. They indicated the

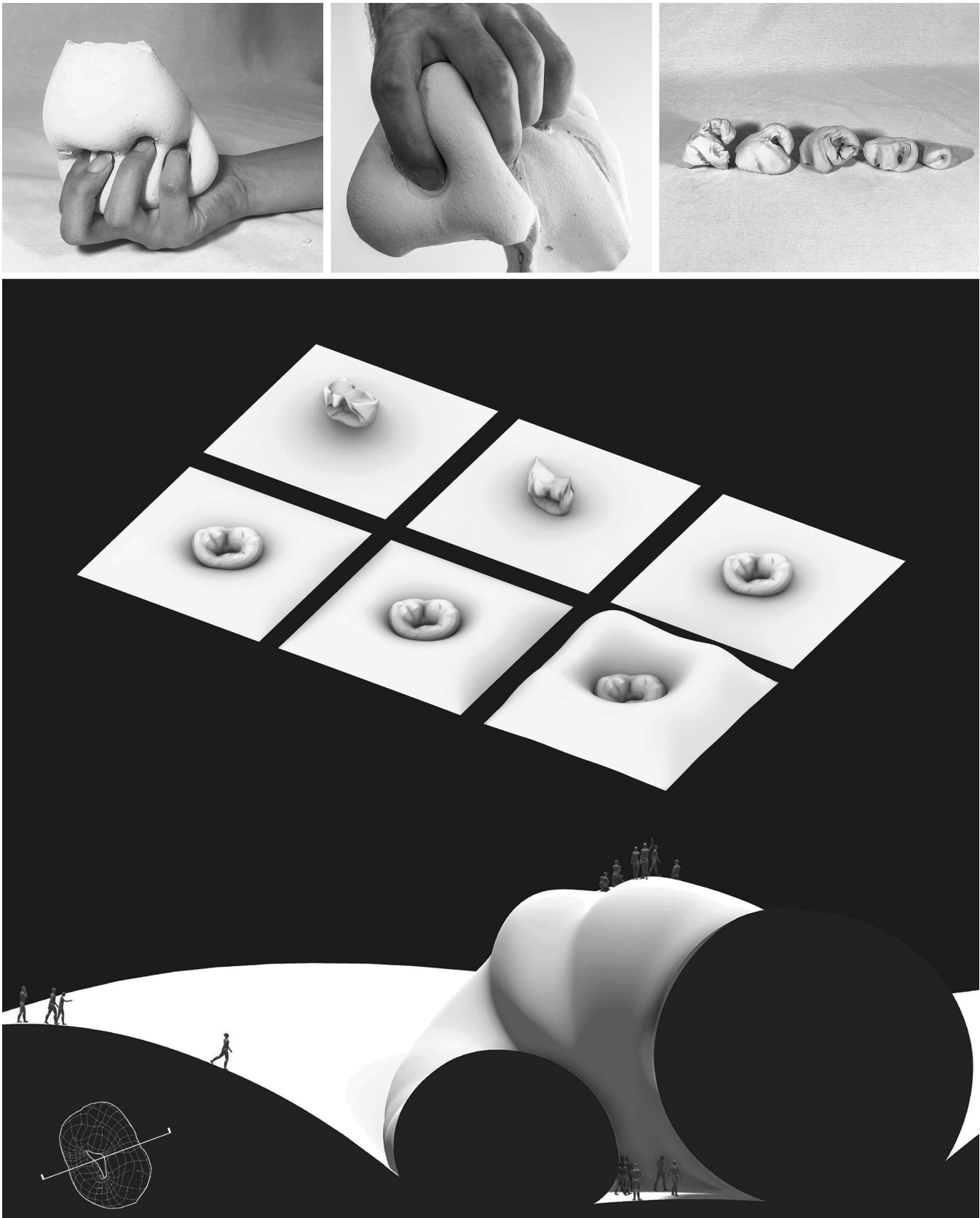


Figure 4. Above: plaster modeling informed by hand gestures. Students' work (Lia Jacques, Kevin Piotrowski, and Marisa Riley). Below: digital simulation in Kangaroo and architectural interpretation. Student's work (Aaron Baldwin).

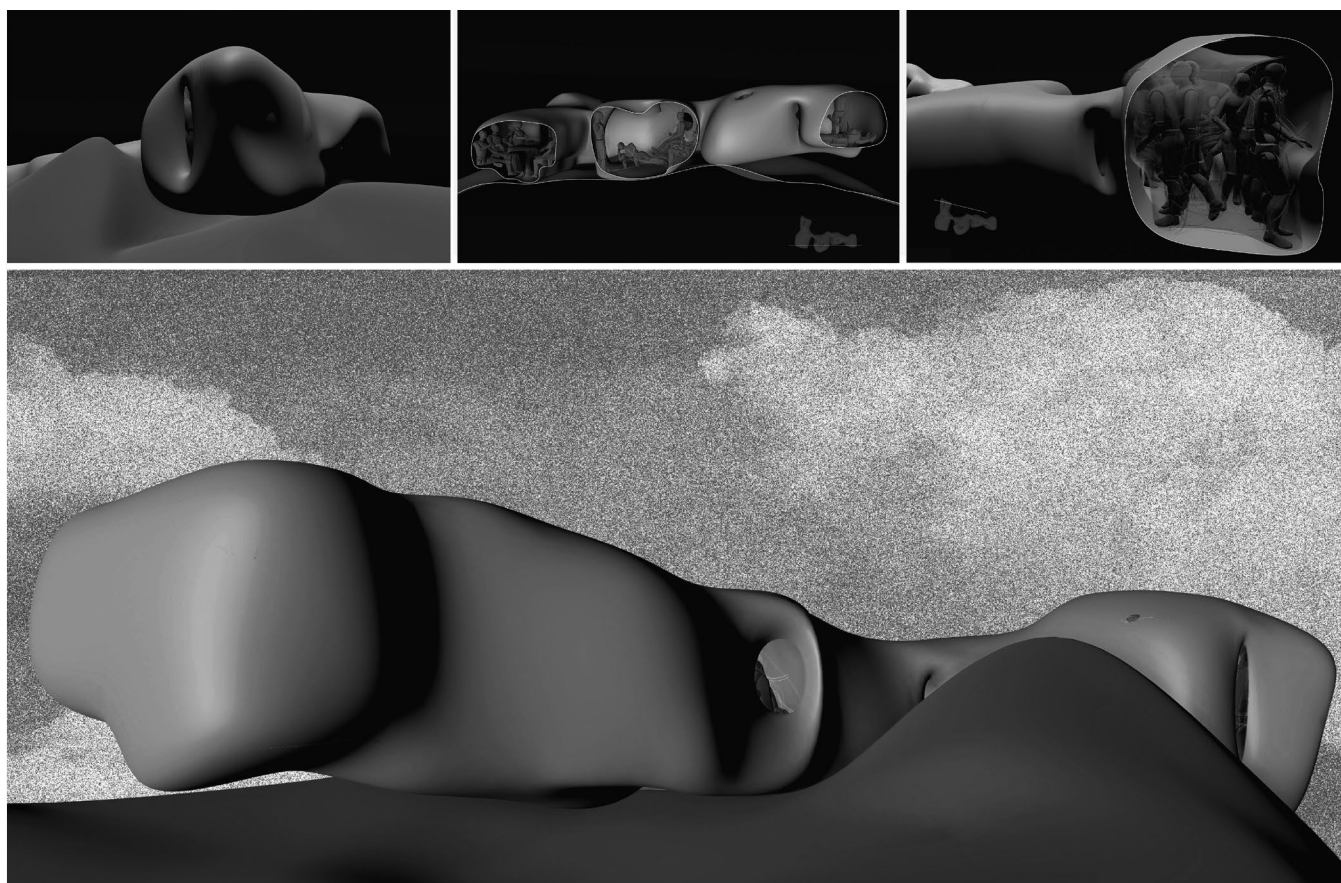


Figure 5. Speculative architectural form made in VR based on the assignment “Gestural Domesticity”. Student’s work (Kevin Piotrowski).

nature of indoor and outdoor spaces mediated by continuous surfaces and showed the implications of human gestures within an architectural envelope. Mannequins/scale figures are graphic elements coherent with the level of detail of the outcomes. As stated in *Lebbeus Wood’s Manifesto: The Reality of Ideals*, “Human scale in even uninhabited architecture is attained in two basic ways: the presence of tectonic elements required by human use” and “the presence of tectonic elements used to construct a building.”¹⁵ In work carried out with Gravity Sketch, stairs, walls, floors are informed by bodily dimensional constraints and are then embedded in massing studies, while windows and doors are understood as areas where geometry opens up.

An aspect that emerged from in-class conversations was the recursive association between gestural-driven design and sinuous/curvy forms. In the “Talk at Google,” Mario Carpo uses the metaphor of a potato to explain the difficulties in building a free-form object notationally without the help of a computer. Fluid-like forms were built seldom before computers arrived. Then, with the digital turn in architecture, parametric architectures arose.¹⁶ These kinds of buildings are similar to potatoes - Carpo says “potato-esque” - but formally more controlled, precise, round, and smooth. Unlike potatoes, parametric architectures are mathematically driven blobs. Potatoes are more comparable to the

outcomes from VR subD calculus because they are rough free-form expressions of a relaxed system; in other words, a dense network of lines or knots.¹⁷ While the course did not set out to design potatoes, the ease with which Gravity Sketch could develop and refine complex geometry gave the students far more freedom than they had previously experienced computationally.

CONCLUSION

The course “Digital Twins” argued that digital design loosened its relationship with the human body since architectural notations have been mediated by 2D surfaces such as the computer screen and the mouse. Durer’s early way of constructing perspective, mentioned earlier, fits in the conversation as a digital twin’s precursor before digital algorithms were programmed to do so. Bringing back the role of the body in the 3D space is an opportunity to reunite the mind and hand gestures to formulate strong design concepts. VR design demonstrated the possibility to extend thoughts using the hands in design workflows; to address design intents into an explicit form of human output.

The course covered introductory knowledge to work with geometrical primitives and create forms with subdivision modeling. The digital matter used by the students was a conceptual holistic idea. In the future development of the class,

the diversification of materials, building units, and tectonic elements could be taken into consideration for subsequent procedural transformations. The modeling strategy through lines, blobs, and clusters could be augmented with a level of detail regarding the use of construction units and materials. This approach could bring a VR design course closer to a design studio agenda given that, borrowing Lebbeus Wood's words: "buildings are not made of a single, solid material, but are constructed of many parts and pieces put together by human beings, and the pieces are sized accordingly."¹⁸

VR is a viable option for the creation of concepts of proto-architectural forms. Potentially, it allows for managing pre-design phases and sharing design thinking in a co-create space. VR brainstorming could become an add-on to architectural practice. Gravity Sketch could encourage users to think in 3D and think beyond geometric primitives and develop a new creative sensibility as a tool for designers. VR has the dual purpose of pushing creativity through form-finding and enabling the central role of the human body by using gestures to communicate thoughts. In design, computers allow us to carry out digital workflows in order to connect representation with documentation and - more downstream - fabrication. Everything is digital, but digital doesn't necessarily mean less human.¹⁹ In parallel, designers can become more human by becoming more digital.

The selected project/outcomes presented represent a speculative discourse manifested in a gesture-driven architectural formal language that, as in generative design, can be encoded into both inputs and outputs. In this context, the inputs came from multiple anthropometric conditions in the physical world. On the opposite side, the outputs were expressed by the students' intentions to translate gestures into inhabitable spaces using technically and theoretically body-centered VR methods. As a result, the designer's bodies embedded aesthetic value and speculative relevance. During an in-class session, a simple gesture captured in Gravity Sketch was quickly translated into robot readable code, and a long exposure photograph was created using an industrial robot and an LED light. This proof-of-concept demonstrates the ability to take body-informed data and output it precisely with the aid of a robot leading to future tectonic opportunities.

At a larger scale of observation, digital design can serve as a medium for conveying a less Fordist idea of the body, and overturning notions of standardization, uniformity, and idealized human body dimensional constraints. Working in VR encourages a design approach that results in a more human-centered architectural discourse toward customization in the digital for inclusive, diverse, and personalized ergonomic freedom.

ACKNOWLEDGMENTS

Gravity Sketch education program team, in particular Rebecca Miller and Emil Lukas. Digital Twins' class at Lawrence

Technological University, College of Architecture and Design, composed of Marino Ard, Aaron Baldwin, Miranda Brake, Noah Chan, Mason Chudzik, Charles Ecker, Lia Jacques, Daniel Kagan, Douglas Lake, Betina Latiker, Kevin Piotrowski, Bailey Ramirez, Jessica Reger, Marisa Riley, Nicholas Schmitt, and Jacob Smith.

ENDNOTES

1. Howard Rheingold, *Virtual Reality: the Revolutionary Technology of Computer-generated Artificial Worlds and How it Promises to Transform Society* (New York: Simon & Schuster, 1992).
2. Samuel Greengard, *Virtual Reality* (Cambridge: MIT Press, 2019), 21-36.
3. Klaus Schwab, *The Fourth Industrial Revolution* (New York: Currency Books, 2017).
4. Juhani Pallasmaa, *The Thinking Hand: Embodied and Existential Wisdom in Architecture* (Hoboken: John Wiley & Sons, 2017), 89-105.
5. François Dagognet, *Etienne-Jules Marey: A Passion for the Trace* (New York: Zone Books, 1992), 124-128.
6. Deborah Berke and Steven Harris, eds. *Architecture of the Everyday* (New York: Princeton Architectural Press, 1997), 205.
7. Greg Lynn, "Body Matters" in *Folds, Blobs, and Bodies: Collected Essays* (Brussels: La Lettre Volee, 1988), 136.
8. Pallasmaa, *The Thinking Hand*, 31.
9. Pallasmaa, *The Thinking Hand*, 29.
10. Lynn, *Folds, Blobs, and Bodies*, 136.
11. Lynn, *Folds, Blobs, and Bodies*, 136.
12. Marty Neumeier, *Metaskills: Five Talents for the Robotic Age* (San Francisco: New Riders Press, 2012), 194, 233.
13. Tim Ingold, *The Life of Lines* (Abingdon-on-Thames: Routledge, 2015), 24.
14. Frank R. Wilson, *The Hand: How Its Use Shapes the Brain, Language, and Human Culture* (New York: Vintage Books, 1999), 342.
15. Lebbeus Woods, "Four Ideal Houses", 01/2011 (accessed 10/2021), <https://lebbeuswoods.wordpress.com/2011/01/26/four-ideal-houses-first-year-studio-2/>.
16. Mario Carpo "The Second Digital Turn. Talks at Google" YouTube video, 5:00'-9:00', Mar 21st 2018, <https://www.youtube.com/watch?v=UVerq5DSdKU&t=514s>.
17. Ingold, *The Life of Lines*, 30-35.
18. Lebbeus Woods, "Manifesto: The Reality of Ideals", 06/2011 (accessed 10/2021), <https://lebbeuswoods.wordpress.com/2011/06/06/manifesto-the-reality-of-ideals/>.
19. Christian Kromme, *Humanification: Go Digital, Stay Human* (Gloucester: Choir Press, 2017).