Get Your Hands Dirty? A Comparative Study of Tool Usage and Perceptual Engagement in Physical and Digital Sculpting

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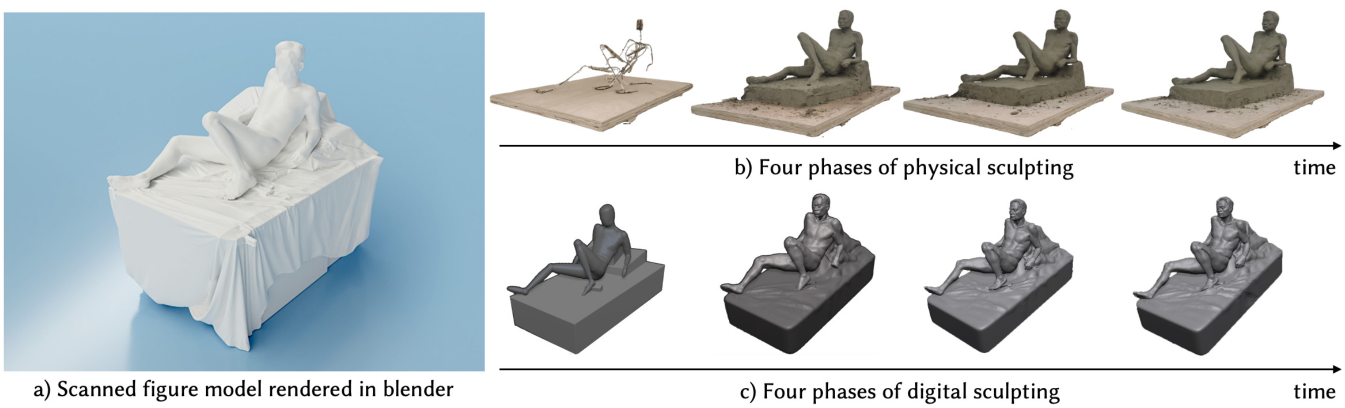

Figure 1: Progression of physical and digital sculpting. a) Scanned figure model rendered in blender. b) One of the participants' progression of physical sculpting. c) The same participant's progression of digital sculpting.

ABSTRACT

The creation of 3D content, crucial in various applications, is often challenging and time-intensive. While digital tools are prevalent for 3D content creation, traditional clay sculpting offers an embodied experience that fosters artists' perceptual engagement with physical space, enhancing their interactive and cognitive connection with the creation process. We conducted an eight-day live sculpting session at an art academy, systematically comparing the creative workflows of eight professional artists in both physical and digital mediums. Our qualitative and quantitative analysis include artists' differences in tool usage between physical and digital sculpting, variations in visual and tactile perceptual engagement, and the potential for future integration of the two modalities. Our study provides insights into the benefits of physical and digital sculpting and may inform future design of hybrid interfaces for 3D content creation.

CCS CONCEPTS

• **Applied computing** → **Fine arts**; • **Computing methodologies** → **Shape modeling**; • **Human-centered computing** → **Empirical studies in HCI**.

KEYWORDS

sculpting, fine arts, physical and digital interactions, 3D content creation

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1 INTRODUCTION

Perceiving and creating 3D shapes are core to human intelligence and creativity. 3D content is ubiquitous in figure sculptures, architecture, and computer animations. 3D content can be created physically or digitally, reflects our understanding of the world, and involves embodied interaction and engagement during the creative process.

3D content creation methods have evolved from ancient techniques like clay sculpting to modern practices such as digital modeling. The digital transition has offered advanced tools that expand the boundaries of what can be created. However, 3D content creation remains challenging, as it requires specialized expertise and a significant investment of time and has a steep learning curve for novices. These obstacles stem from the complexity of tools and interactions involved in the 3D content creation process.

Despite advances in digital technologies, traditional clay sculpting retains its relevance for several reasons. First, clay as a plastic medium aligns closely with human sculpting intuition and perception compared to other sculpting methods and materials. Second, the creative process in clay sculpting has been honored over generations and contains universal sculpting procedures across various mediums. Last, art research has investigated various aspects of clay sculpting, including perceptual engagement and tool usage.

We take inspiration from traditional clay sculpting to inform new digital sculpting mediums and methods. While clay sculpting is limited by physical constraints, digital technologies could aid in making it more efficient, lowering both entry barriers and production costs. However, there is a lack of systematic investigation into the differences between physical and digital sculpting. It remains a challenge to understand artists' perceptions and interactions in these creative processes and how they inform future interface design to provide a more intuitive experience.

In this paper, we present a study that systematically compares physical and digital sculpting to fill this research gap. Specifically, we formulate research questions to examine the tool usage, visual and tactile perceptual engagement, and reflections of eight professional artists in physical clay sculpting and digital sculpting using ZBrush. Our study provides insights into the strengths and weaknesses of physical and digital sculpting. For example, physical sculpting offers synthesized visual and tactile feedback and embodied spatial perception, fostering a tighter connection between the artist and the sculpture. On the other hand, digital sculpting excels in flexibility and efficiency but leads to more homogeneous outcomes. Based on these insights, we propose future research directions that integrate the benefits of physical and digital sculpting such as 3D content creation tools that fuse multimodal perceptions and interactions.

This paper makes the following contributions:

- A comparative study of physical and digital sculpting based on an eight-day workshop involving eight professional artists and various tools for 3D creation.
- An investigation of artists' perceptual engagement and reflections in physical and digital sculpting, highlighting the differences in visual and tactile engagement across four creative phases.
- An exploration of possible directions for future research, with an emphasis on preserving sensory experiences and integrating physical and digital prototyping.

2 RELATED WORK

In this section, we review previous research related to our comparative study of physical and digital sculpting, which includes three main topics, digital modeling, computational fabrication, and figure sculpting.

2.1 Digital Modeling

Digital modeling tools are essential to 3D content creation. Dated back to the invention of *SketchPad* [57], digital tools have been evolving and have played an important role in computer-aided design (CAD), computer graphics, and digital art. While CAD modeling tools focus on the accurate control of shape and have a steep learning curve, other tools have more freeform support such as creating 3D shapes of characters through sculpting operations. Software packages like ZBrush [41], Blender [10], and Autodesk Maya [6] have been widely used for 3D digital content creation.

However, existing 3D modeling software still requires a significant amount of training time and a certain level of expertise. This is partly due to the unintuitive interactions in 3D content creation using traditional GUI. Some previous research explored hand-based interactions to mitigate this problem. The advantages of two-handed input have been investigated by previous works [12, 28, 32, 40], showing that the simultaneous participation of both hands can improve the efficiency of humans and devices in different interaction tasks. Pfeuffer et al. [46] combined gesture and pen input to facilitate 3D content creation. Paczkowski et al. [45] and Naumann et al. [44] used hand input to directly edit the model. When studying the collaborative modeling of both hands, previous work focused on using the input of both hands as a control signal, which is convenient for artists to manipulate 3D objects on the 2D screen. Other works resorted to sketching to facilitate 3D digital modeling. *Teddy* [24] and its subsequent works [17, 24, 34, 36] proposed an important method that allowed artists to directly sketch objects on a 2D plane to express the shape, and then generate a 3D mesh model from the sketch. Other works [7, 15, 61] provided a platform to make people more intuitively feel the three-dimensional shape by drawing 3D curves in modeling software so that artists can model more accurately. While some interesting previous research leveraged different modalities for digital modeling, there is a lack of systematic comparison between the creative processes of physical and digital modeling.

2.2 Computational Fabrication

The advances in computational techniques enabled digital modeling and its interaction with the physical world. For example, augmented reality technologies have broken down the barrier between the digital and physical worlds. Huo et al. [23] discussed advanced interactions for creating and manipulating digital content in an intuitive manner. To achieve that, some commercial applications [3, 51, 56] have provided a range of features that allow users to move, rotate, and sculpt 3D models using gamepads in a VR environment. However, their interaction was based on gamepads, which lacked the combination of physical sculpting tools and could not further edit the model. In order to address these issues, *Virtual Materiality* [43] refers to traditional sculpting tools to create a similar set of digital sculpting tools, enabling users to manipulate digital clay in a more realistic and convenient way. In addition, Jang et al. [20] and Han et al. [26] developed AR platforms that allowed users to use gestures and fingers to make more flexible and diverse adjustments to 3D models in AR environments. *Sculpting in Augmented Reality* [52] has gone a step further, with research emphasizing the possibility of developing interactive experiences that include a variety of human senses in addition to hand input.

Other tools have also creatively been proposed to assist artists in modeling in the physical world. For example, *Finger sculpting with Digital Clay* [50] has proposed a creative method to use a computer-controlled solid surface device for 3D shape input and output of finger sculptures. Callens et al. [13] also designed a device with a pressure-sensitive surface that enabled users to manipulate 3D models in the digital world using their fingers on a tangible interface. *FreeD* [63] developed a device that allowed as to wear sculpting equipment on their hands to shape physical materials directly. Golsteijin et al. introduced *Materialise*, a building set that incorporates digital media into physical constructions using tangible blocks that can display images or play audio, offers new creative opportunities and challenges, and can lead to novel forms of creative expression [19]. While these systems can serve as a bridge between digital and physical modeling, they did not focus on the analysis of users' visual and tactile perception during the creative process. Our work conducted a systematic comparative study on the perceptual engagement of experienced sculptors in digital modeling and physical sculpting processes, which could inform the future design of modeling tools and systems.

2.3 Figure Sculpting

A substantial body of research focuses on studying the creative process in art and related fields. Studies have delved into cognitive issues in performance and theatre [37], instrumental interactions in music composition [8], processes of art-technology collaboration and human-AI co-creation [48, 62], as well as HCI approaches to sculptural trails design [18]. Figure sculpture, particularly in clay, constitutes a significant focus in art research. Puppe et al. [47] conducted a comparative analysis of creative approaches between professional sculptors and art students, employing eye-tracking and interviews to gain insights into the evolution of sculptural skills and the influence of visual perception on artistic creation. The creative process in human clay sculpture has been generally categorized into four stages: armature construction, shape abstraction, musculature addition, and surface refinement [2, 31, 35, 59]. This process demands significant perceptual engagement, and extensive research exists on this topic [4, 49, 60]. Such studies categorize human perception primarily into two types: vision [5, 14, 55] and touch [27]. Moreover, tools play a significant role in artists' interaction and creation with mediums [16]. Therefore, our study chose to use two commonly used mediums, clay and ZBrush, to understand various stages of physical and digital sculpting with an aim to identify their respective advantages to inform future research.

3 STUDY DESIGN

We provide a detailed description of our study design and setup, with a goal to compare the creative processes of physical and digital sculpting. We invited eight professional sculptors to participate in our study in a workshop style. The theme of the workshop was inspired by Michelangelo's "River God" sculpture. We had a male model initially sitting upright, laying down on one side and turning to the left side with the right leg resting on the ground and the left leg bent. The participants were asked to sculpt the reclining figure model in four days using clay and ZBrush, respectively.

3.1 Preparation

3.1.1 Experiment Space Setup. Our experiment space is approximately 7 m × 7 m, including a central figure model platform with the figure model lying in a reclining position. Four clay sculpting stations and four computer modeling stations were positioned around the figure model's platform (Fig. 2a). This arrangement facilitated a smooth workflow for both physical and digital sculpting.

3.1.2 Participants. We recruited eight volunteers (P1 to P8) to participate and divided them into two groups (A and B). These individuals were professional artists specializing in figurative sculpture. Their expertise lies primarily in physical sculpting, characterized by extensive practical experience and theoretical knowledge in this domain. They also have experience with computer-assisted 3D modeling software, except for one participant (Table 1). Our workshop provided a tutorial that equipped everyone with the essential skills for basic digital sculpting and physical sculpting. We also provided an instructional session covering the background of the study, a postural analysis of the "River God" sculpture.

3.1.3 Tools for Sculpting. In our study, we prepared a thorough set of necessary tools and materials for physical sculpting for each participant, as shown in Figure 2b. This setup included clay, wire, pliers, hammers, nails, other essential tools for constructing clay armatures, and sculpting tools like files. For digital sculpting, we provided laptops with identical specifications and Wacom digital tablets. We chose ZBrush as the digital sculpting software because it is commonly used by professional digital sculptors. ZBrush offers a comprehensive set of tools that closely mimic the nuances of physical sculpting, making it ideal for a comparative study between digital and physical mediums.

3.1.4 Recording Equipment. We prepared eight iPhones with the same specifications and phone stands. Each phone is set to 1080P at 30 FPS to record the entire sculpting process of each physical sculptor and the hand movement of each digital sculptor. We also used an Einstar handheld portable 3D scanner to scan clay sculptures.

3.2 Experimental Process

Our physical and digital sculpting workshop lasted eight days. In the first four days, Group A engaged in clay sculpting while Group B used ZBrush for digital sculpting. The tasks were then switched for all participants in the last four days. Each day has two three-hour

Figure 2: Overview of the experiment. a) Setup of the experiment space. b) Prepared Tools for Physical Sculpting. c) Physical sculpting in progress. Two participants are sculpting with the opposite view of the figure model. d) Digital sculpting in progress. A participant is sculpting facial details and a fixed camera is recording.

Table 1: Years of experience in physical and digital sculpting.

	P1	P2	P3	P4	P5	P6	P7	P8
Gender	Female	Male	Female	Male	Female	Male	Male	Male
Age	24	27	25	25	25	27	25	21
Expertise level in physical sculpting (years)	5	5	5	3	6	5	2	2
Expertise level in digital sculpting (years)	2	2	0	3	5	3	3	2

sessions, one in the morning and one in the afternoon. Throughout the process, the model lay on their side on a table, replicating the pose of Michelangelo's "River God" sculpture. Every 15 minutes, we rotated the model table by 45 degrees clockwise, allowing each participant a comprehensive view of the model. Participants could also walk around the model to get close-up views or take measurements.

In physical clay sculpting, participants were required to work on a sculpture that was half the size of the original model. All participants were asked to consider various factors such as tool usage, perception, reflection, and expression of their thoughts during both physical and digital sculpting processes, all within a specified time frame. Participants had four days to complete each task and were required to divide their progress into four phases. They were free to draw upon their own experience to determine the completion level for each phase.

3.3 Data Collection

3.3.1 Data Types. To comprehensively record the entire physical and digital sculpting processes, and facilitate subsequent review, comparison, and data analysis, our data recording included several types:

- **Physical sculpting data:** 3D point cloud scans of the clay sculptures with a precision of 0.2 mm, where each scan has over 20 million points. 360-degree videos around the clay sculpture. Photos from 7 different directions: front, back, left, right, above, and two angles shifted 45 degrees to the left and right of the front view (3/4 view).
- **Digital sculpting data:** Files of the ZBrush project. Screen recordings of the entire digital sculpting process on the computer. Logs of keystrokes and mouse actions.
- **Fixed-position video recordings:** For physical sculptors: Cameras were positioned to the side to capture most of the hand movements without obstruction. Positioning behind would obscure the process, while in front would block their view of the model. For digital sculptors: Cameras were positioned opposite their dominant hand. Since all participants were right-handed, cameras were placed on their left, ensuring their digital pen actions were visible without being obscured by their right hand back.
- **Reference data of the figure model:** The full body of the figure model was 3D scanned and stored as point cloud data, so it can serve as a reference for further analysis.

3.3.2 Semi-Structured Interview. Upon the end of each phase, we interviewed the participants individually to inquire about the overall progress of the past phase and detailed information from different aspects. The interviews were conducted after each phase as defined by the participants. Each session was documented using a smartphone that captured audio and visual data from the interview, including any visual illustrations referenced during the interviews. Alongside video recording, an interview form was used to organize key information. This form helped researchers to address both overall and specific questions, which are listed below. During each sculpting process over four days, participants spent an average of 67 minutes in interviews for physical sculpting and 71 minutes for digital sculpting. Interviews conducted after each phase lasted approximately 17 minutes. The final phase was generally longer, ranging from 25 to 50 minutes.

Overall Questions These questions require participants to have an overall review of the finished phase.

- Q1: What criteria did you use to define the completion of this phase, and what were your underlying objectives?
- Q2: Can you elaborate on why you believe the phase is completed once these criteria are met?
- Q3: In which part of this phase did you invest the most effort in adjustments, overall structure, or specific details?

Specific Questions These questions inquire about detailed information of the past finished phase on three aspects: main viewing angles, tool usage, and observation and measurement methods.

Viewing Angles. For phases 1 and 2: What angles of the model are your focus during this phase (photographic evidence needed)? What specific viewing angles, such as frontal, three-quarter, or side views, do you frequently use for comparison (photographic evidence needed)? For phases 3 and 4: How do the angles you observe from the model differ from earlier phases?

Tool Usage. For phases 1 and 2: What tools do you use during this phase (please list them and provide photos)? Which tool do you use the most, and for which part? For phases 3 and 4: What new tools are employed for greater detailing? What parts are they used for? How does tool usage differ from using your hands, and what unique effects are achieved?

Observation Method. For phases 1 and 2: What techniques do you employ to ascertain volume and thickness to resemble the object closely? Where do you usually draw auxiliary lines for comparison, if any? How do you determine dynamism in your sculpture (relative positioning of head, torso, pelvis, limbs, etc.)? For phases 3 and 4: How do you fine-tune the orientation of smaller forms and their relationships? What are the more specific calibration techniques employed?

Follow-up Questions. For physical sculpting: When using a ruler, what specific measurements are you taking? In this phase, how involved are your hands in the process? What specific tasks do you use your hands for?

For digital sculpting: Do you pay attention to the viewing angle? Do you consider the center of gravity when posing?

3.3.3 Legal, Social, and Ethical Issues. The figure model and all participants involved in this experiment possess a comprehensive understanding of the intended use of the data. We have obtained explicit consent from each participant and the figure model regarding the use of collected data exclusively for research purposes. Stringent measures have been implemented to ensure the anonymization of all personal information, and any individuals featured in the images have undergone thorough pixelation processing.

4 PHYSICAL VS. DIGITAL SCULPTING

Our comparative analysis focuses on tool usage and artists' perceptual engagement in physical and digital sculpting processes, offering insights into their similarities and differences. We documented videos, screen recordings, and 3D scans and conducted semi-structured interviews with eight professional artists, laying a foundation for our analysis. We present the key findings at the beginning of each item followed by our evidence and analysis.

4.1 Tool Usage

We initially investigated how artists used different tools across four phases in physical and digital sculpting. The four phases are categorized based on artists' primary purposes: posing, abstraction, specification, and adjustment.

4.1.1 Phase 1: Posing. **Finding: Physical sculptors employed a diverse set of tools to construct the armature, whereas digital sculptors tended to simplify the task by merely adjusting the Mannequin Skeleton for posing.** In the initial phases, all participants engaged in posing their sculptures, both physical and digital. In physical sculpting, tools like pliers, wires, hammers, and wooden slats were used to construct the armature on a board, a process demanding precise measurements of critical anatomical features such as the chest and pelvis size, and the joints' relative heights. Estimating the required clay volume also adds to this phase's meticulous nature. P1 highlighted the importance of this phase and said, *"I usually spend more time making an armature to ensure proper posing. Otherwise, adjustments become challenging... This time, I used tape for base height and wooden slats for guiding the clay sculpture's shape and volume."* This emphasis on detailed armature construction sets the foundation for the subsequent sculpting process.

In ZBrush, artists have several options to begin sculpting, including using custom or default mannequins. Our study primarily used the default Mannequin Skeleton, as demonstrated in an introductory tutorial, which most participants (seven out of eight) chose for posing (Fig. 3). The Mannequin Skeleton, known for its user-friendly interface, allows for rapid adjustments through "ZSpheres," efficiently establishing the model's core dynamics, pose, and volume. While there are other digital tools and methods for posing, our analysis focuses on ZBrush and Mannequin Skeleton, which are commonly used tools according to our conversation with digital sculptors.

Overall, physical sculpting is more complicated in tool usage and time-consuming compared to digital sculpting (Fig. 4). ZBrush's Mannequin Skeleton streamlines tool usage and offers immediate visual feedback, allowing faster modifications. Section 4.2.1 provides a further discussion on the perceptual differences concerning size and scale between physical and digital sculpting.

4.1.2 Phase 2: Abstraction. **Finding: Physical sculptors predominantly used their hands with fewer tools to abstract large forms and establish mass orientations. Digital sculptors tended to use a subset of tools offered by ZBrush with second thoughts on the necessity for abstraction before specifying details.**

The second phase in both processes could be characterized by participants adding material to block in shape and developing it

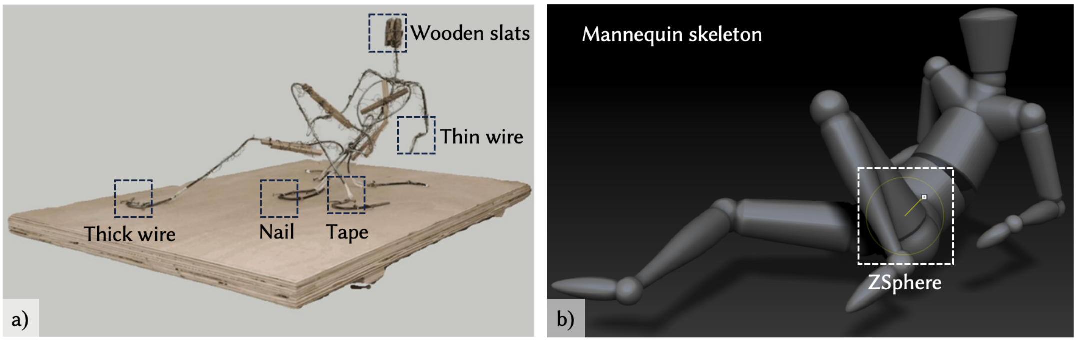

Figure 3: Tool usage in physical sculpting and digital sculpting. a) Armature by P1 with a set of materials and tools. b) The Mannequin Skeleton by P1 posed in ZBrush using ZSpheres.

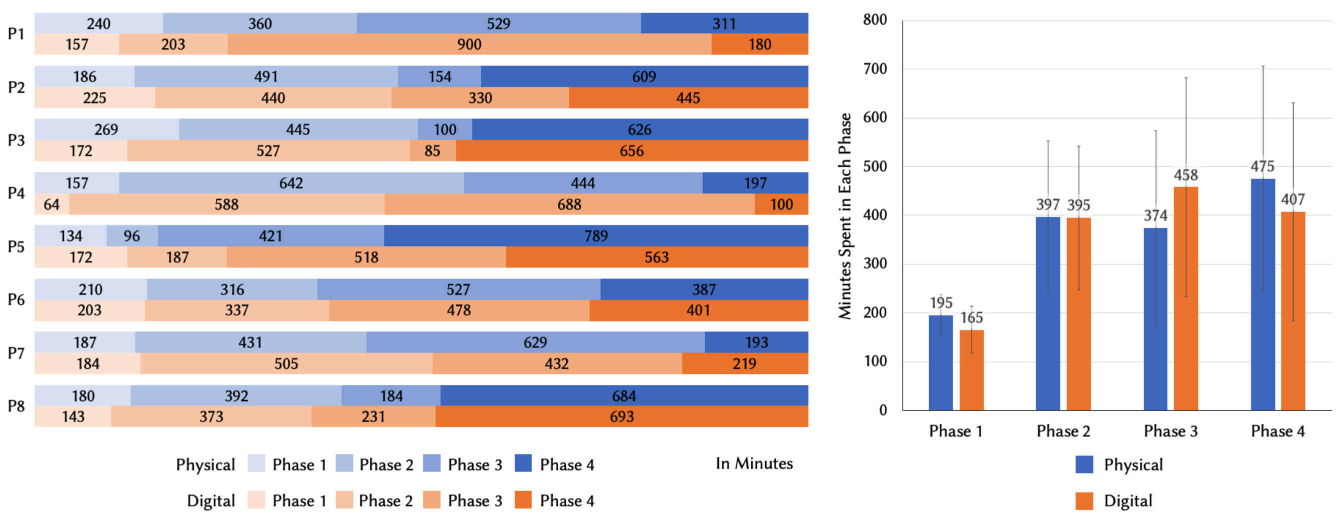

Figure 4: Duration of 4 phases. Left: Timeline detailing phase durations for 8 participants. Right: Bar chart illustrating average minutes spent in each of the 4 phases across both methods.

with tools. During this phase, participants used wooden mallets, steel knives, and hands to abstract the big forms into a block, aiming to establish the orientation of mass faces (Fig. 5) in physical sculpting. They employed auxiliary lines with knives to assist in determining masses' horizontal and vertical axis angles, such as the chest and pelvis. However, P4 and P8 noted that these tools require expertise for precise manipulation. Some participants favored a hands-on approach, arguing that it allows better feedback on the sculpting process. P1, P5, and P7 exhibited more frequent and intuitive pressing, smoothing, wiping, and pinching to shape the masses and joints uniquely, although P2 and P3 preferred less hand usage.

In contrast, ZBrush offers an extensive selection of brushes with specialized functions such as Clay, Flat, Smooth, Curve, and Mask. Users can even create custom brushes. According to our study, participants emphasized the digital brushes allowed for quick and detailed modifications. Six out of eight participants highlighted the utility of specific brushes, such as "ClayBuildup," "Smooth," "Move," and "DamStandard." Participant noting, *"the 'ClayBuildup' brush add materials with a special square effect, which with the addition of the Smooth brush effect will be an angular and rounded effect" (P2)*. P5, P6, and P7 noted that although the "Smooth" brush was universally used and could efficiently smooth surfaces, this often led to over-detailing, resulting in the disorder of the surfaces and it could inadvertently blur the definition of the mass contour.

Our study also identified the views on the necessity of an abstraction phase in digital sculpting. P3 noted that digital brushes "Flatten" or "Smooth" were less efficient than traditional wooden mallets for abstracting mass surfaces. P1 questioned the need for abstraction, stating, *"Given the ease with which digital brushes can render detail, I'm unsure whether focusing on shape abstraction is even necessary."* Section 5.1.2 further discusses participants' abstraction activities.

4.1.3 Phase 3: Specification. **Finding: Digital brush tools make it easier to specify details compared with physical sculpting tools.** In our study, most participants focused on detailing the head, hands, feet, and joints of the body in both methods. For this

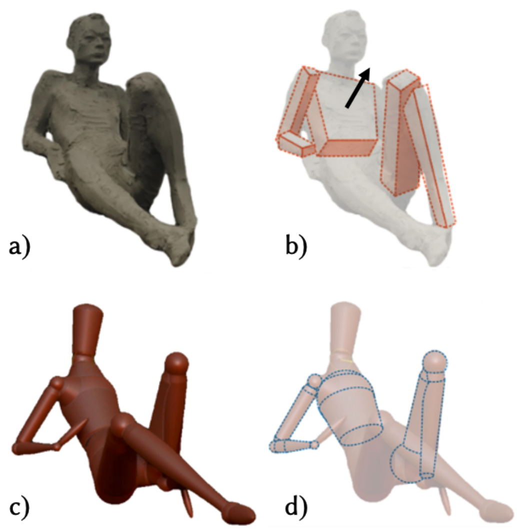

Figure 5: Abstraction illustration by P5. a) and b) P5's clay sculpture focusing on body abstraction. c) and d) Corresponding the Mannequin Skeleton in posing.

purpose, it becomes more challenging to specify these details in physical sculpting since some tools can be regarded as too large for efficient detailing. For example, it is challenging for participants to use a scraper in physical sculpting for hand. In contrast, modeling software allows for easy hand capture and unlimited zooming. By adjusting the size of digital brush tools, participants can precisely carve fingers and even fingernails (Fig. 6).

On the other hand, the digital environment eliminates the physical constraints, making the specification phase isolated from the physical environment and agnostic about the physical scale. Additionally, like in the previous phase, participants were divided regarding the efficacy of hands versus tools for detailing in physical space. Section 4.2.2 further discusses the tactile perceptions associated with hand manipulation.

4.1.4 Phase 4: Adjustment. **Finding: Digital sculpting offers superior flexibility for adjusting details, whereas physical sculpting is strongly affected by errors made in previous phases, making subsequent adjustments difficult.** The adjustment phase and specification phase occur simultaneously in both physical and digital processes. The focus shifts to the adjustment of the details. Participants working in physical and digital sculpting focus on adjusting and refining the relations among different masses. Digital sculpting tools, mainly the "Move" brush, offer operational flexibility that surpasses that of physical sculpting tools, participant stating *"the 'Move' brush has a good function that can modify the shape easily without breaking the details" (P5).* This contrasts with physical sculpting, where corrections of initial errors become more challenging and can lead to complex issues or even unfeasible to rectify at later phases, as experienced by P3 with armature wire protruding from clay and P4 with size discrepancies. In contrast, P2's sculpture is too large and located on the edge of the plywood board, lacking central placement (Fig. 7).

On the last day, participants concentrated on refining details, with digital sculptors paying close attention to smaller mass specifics. In contrast, physical sculptors, using hard tools, made subtler adjustments, especially on heads, limbs, and joints. These observations highlight the distinct approaches and limitations inherent in each sculpting medium, which will be further explored in Section 4.2.

4.2 Perceptual Engagement

As an art form rooted in three-dimensional space, sculpting engages creators in complex perceptual activities throughout the process. In this section, we assess similarities and differences in visual and tactile engagement between these two modalities.

4.2.1 Visual Engagement. Spatial information plays a crucial role in influencing visual perception, especially within the context of sculpture. Hopkins [22] argued that sculpture uniquely engages with its surrounding space in a way that pictorial art does not. Inspired by previous theories, our research delves into participants' varying perceptions of space and objects within both digital and physical methods. Through comparative analysis between these two mediums, we discuss four key aspects including viewpoint, scale and proportion, and depth, which account for variations of spatial perception among participants.

Viewpoint. **Finding: Most participants in both processes chose front, side, and three-quarter views to assess their work. Viewpoint preference is more pronounced in physical sculpting than in digital sculpting.** We first focused on the differences and similarities in participants' selection of a main viewpoint during the physical and digital sculpting processes. The main viewpoint refers to the angle most frequently used by artists to observe the figure model across different sculpting phases. It is distinct from the optimal viewpoint, which is a fixed best angle of view of an object.

According to interviews, the participants preferred to choose one or two main viewpoints in physical sculpting compared to digital sculpting. In terms of phases (Fig. 8), participants prefer to choose the front, side, and three-quarters viewpoint in the beginning two phases and have no clear preference in choosing of main viewpoint in the latter phases. For example, in phases one and three, P1 mentioned *"I chose the frontal and side view as the main viewpoint to observe the relationship between the pelvis and the chest."* She admitted that she selected the viewing angles more evenly during the first phase of the digital sculpting process.

Finding: Participants were more active in moving their viewpoints to observe the model from multiple angles in physical sculpting than in digital sculpting. Our study explored the differences and similarities in participants' multi-angle observation behavior. We found that participants are more active in changing their viewpoints on physical sculpting than digital sculpting. Physical sculptors often work standing up, allowing them to move around and observe the subject actively. The sculpting turntable's 360-degree freedom further aids this process. In contrast, digital sculptors generally stayed stationary and seated when observing the figure, although they could observe the digital model more flexibly and display different parts.

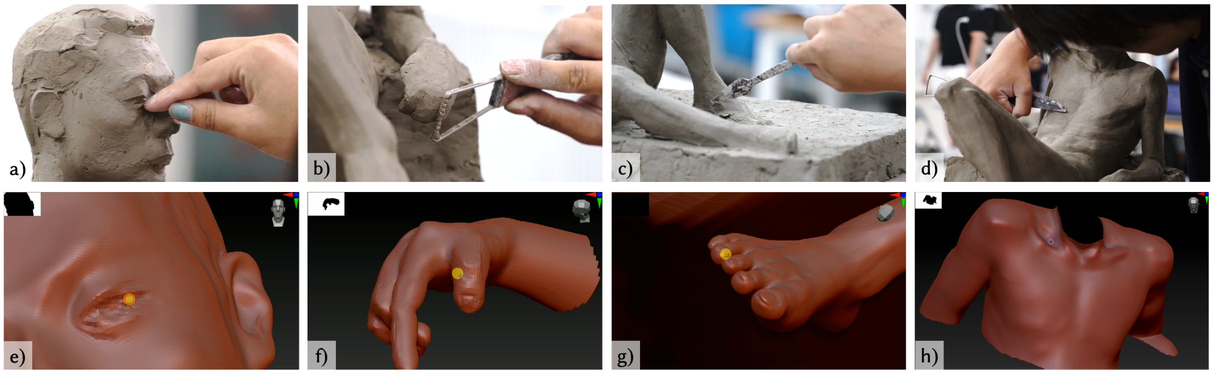

Figure 6: Specification of the body parts in physical and digital sculpting. a)–d) Physical sculpting with tools and hand. e)–g) Sculpting isolated parts in fine-scale detail in ZBrush.

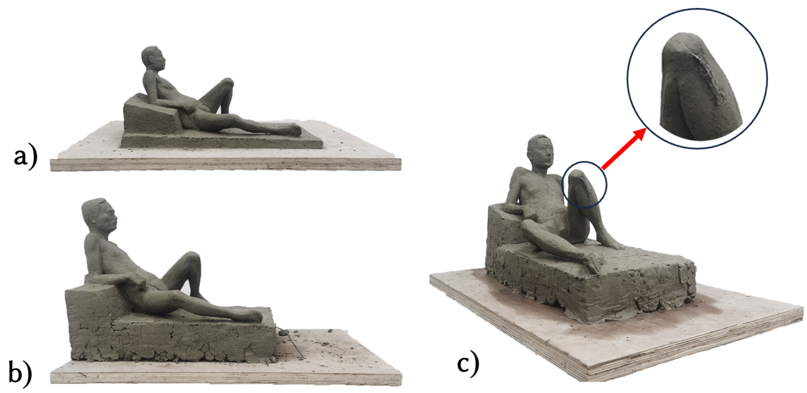

Figure 7: Problems occurred in physical sculpture. a) P4's sculpture is less than half the figure model size. b) P2's sculpture is larger than half of the figure model size and positioned at the board's edge. c) Wire protrudes from P3's clay model.

The digital environment affords participants more flexibility and freedom in observing their digital models. Participants can conveniently zoom in, zoom out, and rotate the view to examine any part of the sculpture and its finer details. Besides, the "Mask" brush and "Solo Mode" in ZBrush allow different parts of the digital sculpture to be displayed individually. Some participants even mentioned that the absence of gravitational constraints in the digital medium offers a novel perspective for observing 3D objects. However, there were concerns about the workflow in digital sculpting, such as the need for additional manipulation to present brush depth accurately. P2 noted in the first phase of digital sculpting that *"Hatching requires more judgments based on software experience—it lacks a sense of depth, and it's difficult to determine on the screen, which could potentially affect work efficiency."*

In the physical sculpting process, participants face constraints, like obscured views due to posture or inability to observe the sculpture from the top or bottom. This limitation has been confirmed by participants, such as P1, who noted that some parts are always hidden in the shadows during the detailing phase.

Scale and Position. **Finding: Participants' perception of scale is more important in physical sculpting, which may provide a "sculptural" sense. They predominantly focused on larger-scale masses in earlier phases and smaller ones in later phases.** Participants typically focused on larger body parts like the torso, chest, and pelvis in the beginning, using them as reference points for observational analysis. They usually began by assessing the size, position, and orientation of a prominent mass, then compared it to other masses for relative sizing and alignment. For example, P6 and P7 mentioned that they started digital sculpting by concentrating on the chest mass in the initial phase. As they progressed, attention shifted to smaller areas such as the head, hands, joints, and feet in the later phases.

Finding: Although a figure model served as a standard reference, the physical sculptures created by the eight participants showed significant variation in size. This indicates that, despite having a measurement standard, the sculptors' perceptions of scale are diverse and unique. The object's actual size in space offers a tangible sense of scale. This sensory engagement is absent in digital sculpting, which is nonexistent in the virtual space.

Furthermore, participants noted that physical sculpting provided more intuitive visual feedback than digital sculpting. For example, P1 states, *"An important aspect of the sense of 'sculptural' might be related to the scale of the sculpture in the physical environment, a particular scale will bring a particular sense of 'sculptural,' but the*

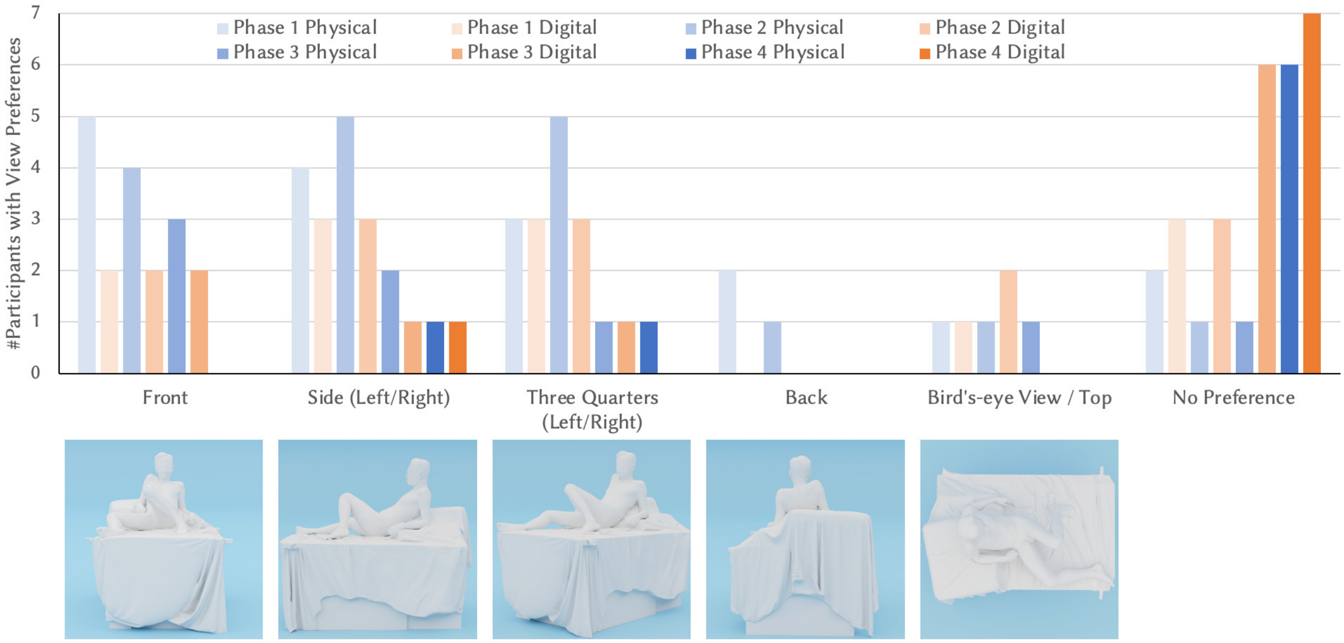

Figure 8: Number of participants with view preference. Top: The number of participants' preferences in the fixation of viewpoints through four phases across the two processes. Bottom: The illustration of different viewpoints.

process of digital sculpture lacks such a sensation as it has no actual size. Perhaps when the screen of a computer is big enough, there will be a different sense of the digital sculpture." Instead, participants commented that sculpting in the ZBrush lacks engagement with actual size and induces a sense of perceptual dislocation or what P3 describes as a sense of "floating."

We also observed that the torso mass is more accurate to the figure model compared to the limb masses. The torso consists of the chest and the pelvis, and the limb masses refer to arms, legs, and joints like knees, wrists, and ankles. Aided by point cloud registration comparison (Fig. 9), this discrepancy can be attributed to participants' perceptions of scale and position. Concerning scale, our previous analyses indicate that the torso mass, being more substantial and centrally located, tends to garner more focus from participants, resulting in a more closely aligned sculpture with the figure model. Regarding position, the torso serves as the human body's core and exists in a relatively static state compared to the limbs and joints. This static nature makes it easier for participants to adjust their spatial attributes accurately. Additionally, the decision-making process regarding selecting the core parts of the object is related to participants' cognitive activities, which we elaborate on in Section 5.1.2.

Depth. **Finding: Participants generally found it easier to perceive depth in the physical environment than in a digital interface, whose perspective settings often led to confusion about depth.** Our analysis investigates the variances in participants' perceiving depth information between physical and digital sculpting processes. Participants generally find it easier to perceive the depth in physical environments compared to digital interfaces. This ease of perception in the physical environment contrasts digital sculpting, where participants often reported they needed to adjust the camera position multiple times in ZBrush to gain an accurate understanding of the digital 3D model's spatial attributes. This frequently required adjustment can be traced back to a limitation in digital sculpting, the difficulty in translating three-dimensional depth onto a two-dimensional screen.

Further insights were obtained from the necessity for multi-angle observation. Participants agreed that observing a model from multiple angles aids in understanding depth. This observation method to perceive the object's depth is naturally more feasible and intuitive in the physical environment than in the digital space, where limitations on viewpoint adjustments may exist in the digital interface.

The digital environment offers perspective settings that may lead to confusion. Participants commonly report uncertainty using virtual perspective parameters, "Angle of View" with realistic viewpoints. The extensive adjustability of perspective focal lengths in ZBrush modeling adds another layer of complexity, overwhelming users and contributing to a misalignment with real-world perspectives. As P5 summarized, "The clay sculpture is presented in an authentic environment, and I can easily notice the depth of the masses...I intuitively focus on the masses' orientation and the shape's contour in the digital model."

Participants offered varied experiences with perspective settings in both physical and digital sculpting. P4 was noted when adjusting the software's camera settings. There are challenges in achieving a realistic perspective in the digital environment. P2 felt the adjustability of perspective settings brought him visual uncertainty, so he closed the Perspective throughout the sculpting process. Similarly, P1 toggled perspective settings based on whether the view

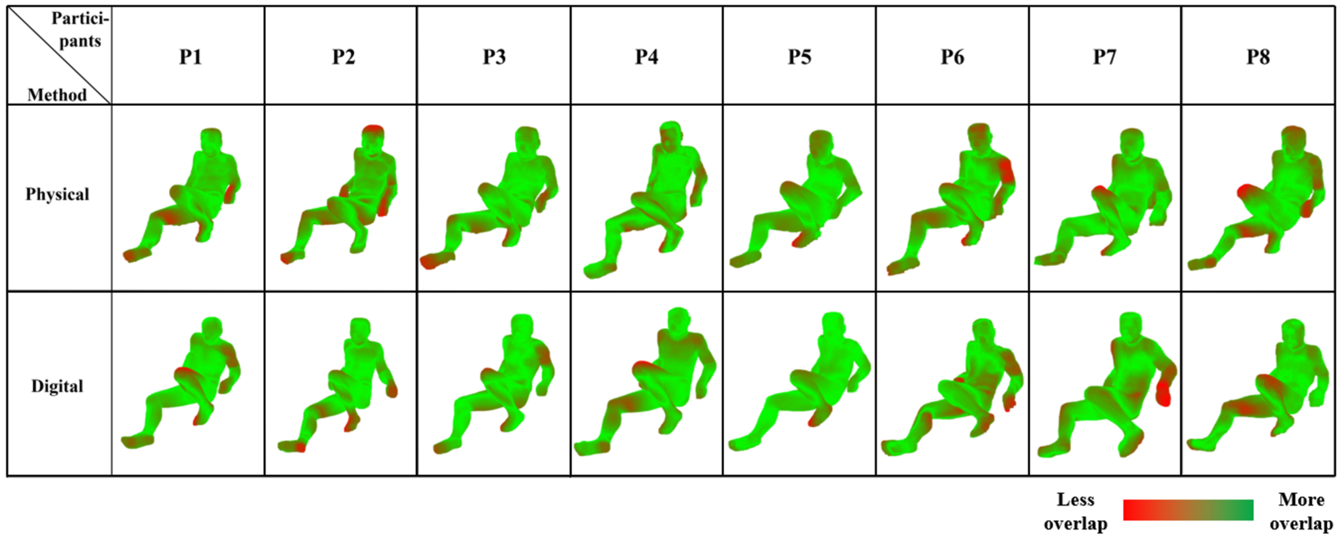

Figure 9: Visualization of accuracy in digital and physical sculpting of eight participants to figure model, which is the ground truth (GT). We visually represented the alignment accuracy between the participants' physical and digital sculptures and the GT. Regions with a reddish hue signify a more significant divergence from the GT, whereas areas with a greener coloration indicate a closer proximity to the GT.

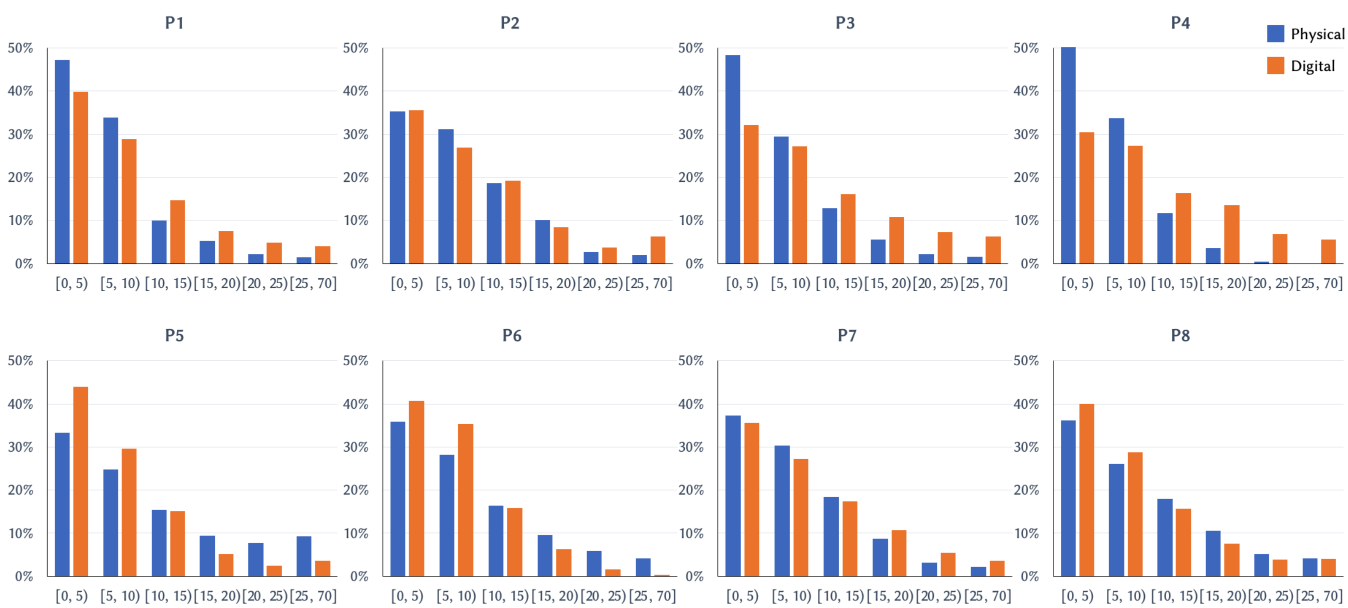

Figure 10: Quantitative analysis of accuracy between eight participants' digital or physical sculpting and the figure model which is the ground truth (GT). In our study, we sampled 50,000 point clouds on each digital model and scanned clay sculptures of eight participants, as well as the scanned figure models (restricted to the body portion only). We subsequently employed the Iterative Closest Point (ICP) algorithm for point cloud registration [9], using the GT as the reference to align all participants' modeling and scanned models. We calculated the distance (in mm) for each scanned and modeling point cloud to the nearest point on the GT. The percentile range of these distances serves as an indicator of the alignment accuracy between the models and GT.

was from the front or side, using it to double-check the work. P6, after four days of digital sculpting, largely refrained from using the perspective settings, relying instead on standard views (frontal, top-down, side) for most of the sculpting process, only occasionally using perspective for specific angles. This participant feedback highlights the challenges and inconsistencies faced when adapting traditional sculpting skills to ZBrush. Notably, the options provided for perspective manipulation within the digital environment can lead to confusion and a lack of confidence in visual references, emphasizing the need for improved software design to bridge the gap between traditional and digital methods.

4.2.2 Tactile Engagement. Lee-Cultura and Giannakos [33] stated that embodied interaction explores how the mind and body work together to influence our meaningful engagement with technology. Sculptors' tactile engagement is also a significant embodied interaction behavior in both physical and digital sculpting.

Tactile engagement is crucial for understanding the nuances and limitations of physical sculpting. When sculpting in clay, the hands and tools are extensions of the sculptor's will, enabling a rich tactile interaction with the material. On the other hand, digital sculpting often lacks this direct tactile feedback, which could affect a sculptor's sense of spatial and textural relationships of the sculpture. Influenced by Herder's theory and Zuckert's analysis of sculpture as an art form grounded in the sense of touch and the starting point for articulation of embodied aesthetics [64], we explored how sculptors engage tactically with both hands and tools during the sculpting process. This focus allows us to investigate the relationship between the creator's tactile perception and their ability to represent shapes in digital and physical methods accurately. Further, our analysis tries to envision future scenarios in 3D content creation, which will be discussed in the next section.

Finding: Tactile feedback in physical sculpting offers diverse sensory experiences, significantly influencing the artistic process. For instance, P7's feedback during the initial phases of adding clay to the armature highlights that tactile feedback from hands provided stronger force feedback. This was instrumental in grasping the posture and movement more intuitively, thereby playing a critical role in shaping and perceiving sculptural forms. P5's confidence in using hands for shaping from the start further illustrates this point. She states, "Tools act as mediums... but my hands offer richer feedback..." This underscores the importance of tactile feedback in physical sculpting, which is not replicated in ZBrush.

Finding: Compared to using only digital tools, hand-tool synergy in physical sculpting allows for more diversity and captures artists' sensations more effectively. The type of feedback during the specification phase is classified as direct (hands) and tool-mediated. Participants like P5 highlight that hands offer more direct input than tools, particularly in the early sculpting phases. However, others like P2 and P3 note that hand movements can disrupt clarity, thereby preferring tools for specific tasks. This finding underscores the balance and the critical role of tactile engagement in physical sculpting, where both hands and tools have distinct advantages and limitations in shaping the sculpture's form.

Finding: Physical sculpting demonstrates a clear advantage in leading to diverse visual quality than digital sculpting. The variety in sculpting styles achieved through physical tools contrasts with the homogeneity in digital sculptures. This is attributed to the lack of tactile feedback in digital interfaces like ZBrush, which impacts the perceived quality and diversity of artistic outcomes. The significant contrast between diverse outcomes in physical sculpting and the homogeneity in digital sculpting will be further discussed in the next section.

While there is extensive research on tactile or force feedback in fields like game design and interaction design, which could be relevant to our study, the scope of this paper limits a deep exploration of these parallels. However, it is important to note that the force feedback discussed here pertains to the subtle, perceptual experiences of professional artists, distinct from the application-focused research in other areas. This specificity in the artists' tactile experience highlights an intricate aspect of physical sculpting that is not fully replicated in digital environments.

5 DISCUSSION

In this section, we further summarize the key findings from our analysis and propose possible future research directions informed by our study.

5.1 Key Findings

The discussion of key findings from the previous section will be divided into three parts. We first discuss artists' perceptual engagement in the two processes. Second, we discuss the participants' abstraction of the masses and their reflections on the two creative processes. Last, this section explores the concept of homogeneity by studying the physical and digital sculpting processes.

5.1.1 Perceptual Synthesis. Our findings highlight the differences in complexity and efficiency of tool use between physical and digital sculpting. However, during the interview, some artists emphasized that the synthesized visual and tactile perceptions involved in the physical sculpting process are worth discussing.

In exploring perceptual engagement in sculpture, the perceptual theories of Maurice Merleau-Ponty, particularly his critical rework of Gestalt psychology [29] in "Phenomenology of Perception," provide a rethinking of the relationship between the body, perception and consciousness. He suggests that perception transcends mere sensory aggregation, representing a holistic and spontaneous organization into meaningful wholes. This perspective departs from the traditional mind-body dualism, promoting an integrated understanding where bodily experience, perception, and consciousness are deeply interconnected. Additionally, his concept of the "body schema" further highlights the role of kinesthetic awareness and spatial understanding in perception, thereby reinforcing the embodied nature of human existence and experience [42, 58].

In a corresponding discussion, F. David Martin extends the conversation into the realm of sculpture [39]. In conversation with Merleau-Ponty's holistic approach to perception, Martin emphasized sculpture's three-dimensionality and spatial engagement and his theories reflect a unique understanding of sculpture as an immersive, direct experience. His work thus provides a critical extension of Merleau-Ponty's theories, applying them specifically to the art sculpture and highlighting its distinctive characteristics and perceptual demands.

Based on these ideas, we suggest that the perceptual synthesis in physical sculpting, where the hands' tactile and the eyes' vision converge, contributes uniquely to the sculptor's understanding of shape and space. This embodied experience contrasts with the predominantly visual and less grounded embodied interaction in digital sculpting, underscoring the need for hybrid sculpting interfaces that better emulate the tactile sensations of clay sculpting.

As previously mentioned, in physical sculpting, artists achieve a profound sense of dimension and shape facilitated by an enhanced visual and tactile interface. This interaction, as evidenced by the sense of "sculptural" described by P1 and the spatial depth articulation noted by P7, underscores a rich perceptual synthesis. Conversely, while affording ease in perspective alteration, digital sculpting often sacrifices the tangible aspect of dimension, yielding a sense of "floating" in visual perception, as P5 articulated. Such sensory detachment is magnified by the absence of physical constraints like gravity, highlighting a perceptual disparity between mediums. This perceptual divergence in digital sculpting is also insightfully addressed in Kühn's study [30]. Kühn argues that digital sculpting, defined by spatial orientation and unrestrained limits like gravity, must enhance the sensory and cognitive dimensions that differentiate it from traditional physical sculpting.

Our findings stress the need for multi-sensory feedback integration in sculpting interfaces. The perceptual synthesis in physical sculpting presents a foundational element for future hybrid interface design, aiming to unite the perceptions of physical sculpting with the flexibility of digital tools, which is detailed in 5.2.

5.1.2 Abstraction and Reflection. This sub-subsection explores participants' abstracting behaviors during the sculpting process and their active engagement with the perceived shapes. Our research indicates that after sensing shape changes, artists in both physical and digital sculpting actively interpret and attempt to abstract the features and spatial relations of the object. This cognitive and behavioral activity and its significance in the sculpting process are worth discussing.

Abstraction of Shape. Based on the study, we proposed an "Abstraction of Shape" flow diagram that illustrates this abstraction process within a sculpting procedure. It emphasizes the artists' understanding and proactive abstraction, contrasting mere mimicry of observed exteriors (Fig. 11). This means artists perceive the raw data of the object, abstracting the essential shapes and ignoring disordered information to create a sculpture. As one of the paradigms that understanding and abstracting of the masses of human figures to be conceived as blocks, Bridgman states, *"Whatever their (Masses of head, chest, and pelvis) surface form or marking, they are as masses to be conceived as blocks"* [11]. Specifically, to explore the abstraction of shape, we observed participants' process of practice through the aspects of high points or vertex, contours, and orientation to present masses.

A notable aspect of this behavior is the participants' shape of high points in both clay and digital sculpting to abstract shape characteristics. In clay sculpting, the spatial position and size of high points on the mass are clearly defined, requiring precise confirmation. High points are interconnected and are structured symmetrically along the body's central axis. The characteristics of high points reflect the shape's features, varying across individuals, more pronounced in clay sculpting, and influenced by each person's integrated perception.

However, although participants also attempt to abstract forms with digital brushes in digital sculpting, this process is not as direct or fluid. Instead, brushes excel in delving into details.

Creative Phases. In addition to abstracting forms, participants reflected on the creative phases in the sculpting processes (Fig. 12). Per our study protocol, participants divided their process into four phases, with some indicating an initial phase of active sensory engagement to capture the shape's whole structure and movement and later phases utilizing analytical thinking for rational sculpting details.

Finding: Based on the analysis of self-assessed completion levels during the sculpting process, participants generally perceived their digital sculptures to be more complete, accurate, and representative of the figure model compared to their physical sculptures over the four days.

In the posing phase of physical sculpting, participants indicated a heightened level of engagement in perceiving the shape of their sculptures. The synthesized perception elicits instantaneous feedback, which plays a crucial role in shaping. In particular, this tactile interaction evoked emotions of excitement and activation, highlighting the sensory richness of the early phases of physical sculpting methods. As the process advances into the abstraction and specification phases, there is a discernible transition toward a more analytical and reasoned approach to judgment, moving away from the initial instinctive responses to force perception.

In contrast, those engaged in digital sculpting experienced a more uniform sensory and emotional experience throughout their process. The consistency of digital tools facilitated a steady engagement, perceived as less emotionally intense but more controlled and predictable. Participants appreciated the precision and undo capabilities of digital sculpting, reducing frustration and allowing for easier corrections than clay sculpting. At the end of the study, some participants indicated exploring alternative representations of the figure model using the two processes. They were interested in sculpting the digital model in distinct ways.

Finding: Particularly in the phases of specification and adjustment, a divergent focus on detailing seems to emerge. Contrastingly, digital sculpting exhibits a different flexibility in detailing the sculpture. The digital medium allows for complex detailing, but often at the expense of losing a holistic sense of the artwork's force dynamics.

5.1.3 Homogeneity and Subjective Perspective. The interplay of perceptual synthesis and the cognitive abstraction and reflection activities in the artistic process underscores the nuances that define individual sculpting styles. However, a notable difference occurs in comparing physical and digital sculpting processes.

In digital sculpting, homogeneity seems to outweigh diversity. P2 observed that the facial features created within the software by various artists bore a striking resemblance to one another, suggesting a dilution of personal sculpting style, which remained pronounced and diverse in clay sculpting. For instance, some participants preferred the sharp and hard presence of the high points of their sculptures to create cohesive structures. In contrast, others enjoyed the manual process of shaping or applying clay incrementally. Here,

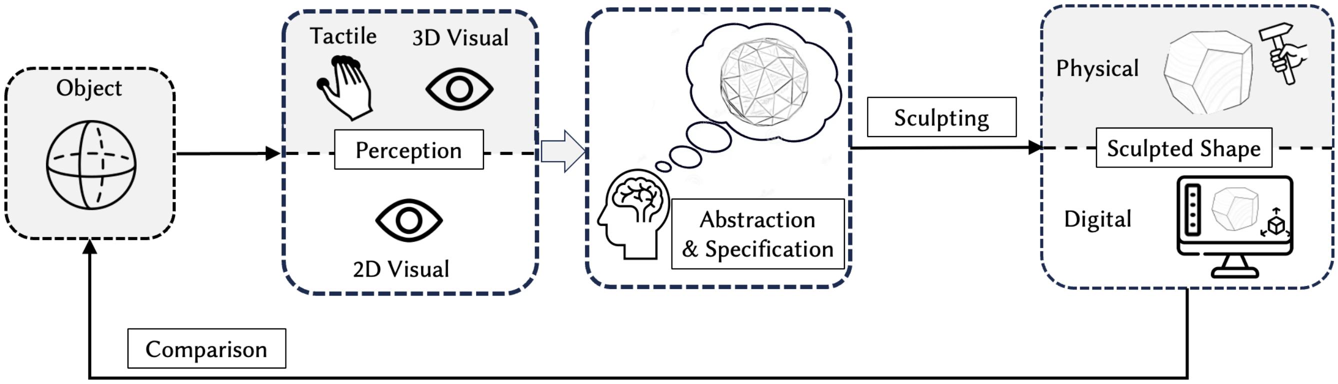

Figure 11: The mechanism of Perception-Practice system in the sculpting process.

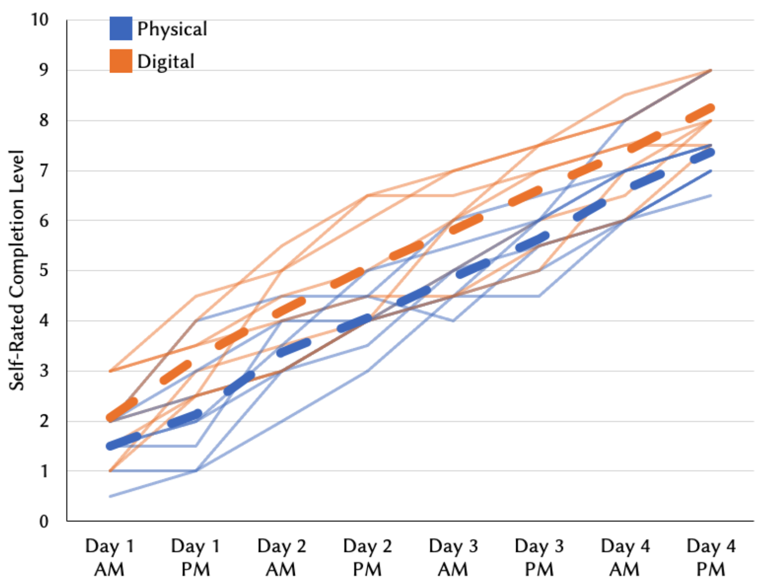

Figure 12: Self-assessment of completion. The line graph illustrates the self-assessed completion levels of eight participants in both physical and digital sculpting across four days. Generally, the orange line consistently outperforms the blue one, indicating a higher average completion level in digital sculpting.

we propose a quantitative measure of how physical and digital sculptures are presented differently (Table 2).

More importantly, a transition between physical and digital sculpting introduces a shift in the subjective perspective. They were further discussed by P2, physical sculpting positions the sculptor objectively, with the artist adjusting their viewpoint around the physical sculpture, thereby emphasizing its subjectivity. In contrast, digital sculpting centralizes the artist's control, allowing for free manipulation of the model. This difference in perspective, heightened in the virtual environment of digital sculpting, suggests a model that feels more like a composition of planes than a singular, cohesive entity. This impression may contribute to the homogenization effect.

Clay sculpting's objective existence in physical space fosters a creation process where the sculpture's subject position is unequivocally clear. In this light, the homogeneity observed in digital sculpting could be linked to the medium's inherent separation from the tactile and spatial cues that guide the artist's sensory and cognitive engagement in physical sculpting.

The questions posed by this difference are critical for the future of artistic creation. What should the position of the "human" element be in the creative process, and how can the richness of human perception, particularly its integrated form, be amplified and preserved in digital sculpting?

Summarizing our discussions into perceptual synthesis, abstraction, the distinct stages of creative reflection, and the issues of

Table 2: Representation of the local feature richness through Laplacian values in the model. We first standardized the number of vertices for each model to 35,000 and normalized the models (confining the coordinates of each vertex within the range of -1 to 1). The richness of the models was characterized by calculating the average value of the Laplacian on each vertex. Our computations showed that physical models exhibited a richer and more diverse range of details.

Laplacian value ↑	P1	P2	P3	P4	P5	P6	P7	P8	Average	Variance
Digital	0.00145	0.00158	0.00158	0.00143	0.00137	0.00158	0.00155	0.00160	0.00152	6.69×10^{-9}
Physical	0.00148	0.00158	0.00150	0.00157	0.00174	0.00168	0.00186	0.00162	0.00163	1.41×10^{-8}

Figure 13: The eight participants' physical and digital sculptures in three-quarters view. Top row: Final results of physical sculpting (P1 to P8). Bottom row: Final results of digital sculpting (P1 to P8).

homogeneity and subjective perspective, we discern key physical versus digital sculpting. Additionally, We acknowledge that some findings, such as the flexibility of digital sculpting options, the physical constraints in traditional tools, and the limitations in perceiving depth and tactile feedback in digital tools may be predictable. However, it is important to emphasize that our study systematically documented these observations as they reflect the embodied experiences and perceptions of the participating artists. Recording these may reinforce the importance of these factors in real-world sculpting applications and offer a detailed context for integrating physical and digital sculpting methods.

5.2 Future Research Directions

The findings of our study can inform future research directions, including preserving sensory experiences in 3D content creation, balancing sensory richness under physical constraints, and integrating the benefits of both physical and digital prototyping.

5.2.1 Force Feedback in Human-Object Interaction via Digital Tools. Most current work and devices focus more on tactile feedback when the hand touches materials [1, 21, 25, 38, 53]. In our study, we have observed that incorporating force feedback mechanisms associated with different artistic tools may play a pivotal role. This encompasses the tactile feedback experienced when an artist employs a hammer to shape clay, capturing the vibrational sensations in the palm. Similarly, when using a sculptor's iron knife for molding and carving, the sensory response involves the nuanced pressure sensations felt in the fingers. *Virtual Materiality* [43] introduces a suite of clay sculpture creation tools within a virtual reality (VR) environment, designed to replicate the physical sculpting process. While these tools excel in mimicking the tool-to-model interaction, they currently lack the simulation of force feedback inherent to various physical-world tools. Enabling the emulation of force feedback within a digital environment can significantly enhance user immersion and provide artists with a more intuitive sense of how tools influence model manipulation.

5.2.2 Enhancing Details on Physical Sculptures. Our study findings found it impossible to enlarge the model at will for detailed carving like in modeling software due to the limitations of tools and clay sculpture size. *ModelCraft* [54] facilitates a transition from physical to digital. Inspired by this method of transforming the role of virtual-real editing, we recommend a solution that navigates the inverse path, from the digital to the physical, achieved by synergizing AR and robotics technologies. This approach maintains the perception of real-world perspective within the AR medium while combining the freedom of model manipulation in a virtual environment to enhance the precision of physical sculpting. When artists necessitate refining the fine details of a comprehensive physical model, they can transfer the physical model into the digital domain through scanning. Subsequently, artists donning AR glasses can seamlessly manipulate, magnify, and meticulously refine the model within the digital realm. Meanwhile, the robotic arm dynamically switches between pre-fitted tools of varying sizes in real time, performing commensurate carving operations on the physical sculpture.

This potential solution might alleviate artists' constraints when sculpting intricate models in the physical world. Unlike conventional methodologies, where artists construct a model within modeling software followed by 3D printing, we advocate a real-time collaborative system that empowers artists to tune model details, significantly enhancing creative efficiency.

6 CONCLUSION

This paper has presented a comparative study of physical and digital sculpting, involving eight professional artists and their tool usage and perceptual engagement in the creative processes (Fig. 13). The key findings can be summarized as follows. First, digital sculpting tools provide greater flexibility in viewpoint manipulation and shape adjustments, thus expediting the creative process, whereas traditional sculpting involves a more complex and time-consuming workflow due to considerations like armature construction and measurements. Second, the study emphasizes unique perceptual engagement in digital and physical sculpting methods, providing empirical evidence of the importance of visual and tactile engagement. Last, our findings inform possible research directions, such as integrating the benefits of both physical and digital sculpting for the future design of 3D content creation tools.

Our research has a few limitations that could impact the interpretation of our findings. One constraint was the session environment for live sculpting, where fixed poses and limited time may have restricted the creative freedom of participants, particularly in physical sculpting contexts. Additionally, the focus of our participant pool on artists predominantly experienced in physical mediums may have biased their reported experiences with digital tools.

Despite these limitations, the feedback from our participants on the intuitive and perceptual engagement with physical sculpting provides invaluable insights. They highlight the impact of embodied interaction on the creative process and suggest how digital sculpting tools could integrate possible physical engagement to enhance user experiences.

Future research includes a more balanced mix of artists equally proficient in physical and digital sculpting. This could not only help relieve the potential bias but also enrich our understanding of how the integration of these sculpting processes could be optimized in real-world artistic practices, fostering a more holistic approach to contemporary sculpture. In addition, it is worth exploring the material properties used in 3D content creation. Technological enhancements to artists' perceptual engagement and integration of physical and digital methods also offer promising directions. Overall, this paper has paved the way for future studies and systems that further bridge the gap between physical and digital sculpting methods, providing new possibilities for 3D content creation experiences with enriched perceptions and interactions.

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