Drawing on Air: Input Techniques for Controlled 3D Line Illustration

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Abstract—We present Drawing on Air, a haptic-aided input technique for drawing controlled 3D curves through space. Drawing on Air addresses a control problem with current 3D modeling approaches based on sweeping movement of the hands through the air. Although artists praise the immediacy and intuitiveness of these systems, a lack of control makes it nearly impossible to create 3D forms beyond quick design sketches or gesture drawings. Drawing on Air introduces two new strategies for more controlled 3D drawing: one-handed drag drawing and two-handed tape drawing. Both approaches have advantages for drawing certain types of curves. We describe a tangent preserving method for transitioning between the two techniques while drawing. Haptic-aided redrawing and line weight adjustment while drawing are also supported in both approaches. In a quantitative user study evaluation by illustrators, the one and two-handed techniques performed at roughly the same level and both significantly outperformed freehand drawing and freehand drawing augmented with a haptic friction effect. We present the design and results of this experiment, as well as user feedback from artists and 3D models created in a style of line illustration for challenging artistic and scientific subjects.

Index Terms—Artistic interface, tape drawing, haptics, modeling, bimanual interaction.

1 Introduction

Three-dimensional modeling approaches based on direct sweeping input of the hands [1], [2] typically offer artists immediacy, intuitive interfaces, and exciting new artistic directions. The problem with these tools is that artists cannot control them enough to address challenging subjects such as the ones we find in scientific visualization [3] and even in representational art. Although more traditional 3D modelers used in industry (typically driven by tablet, mouse, keyboard, and programming input) can achieve the precision needed to address these subjects, these systems are not accessible to an artist who has not trained with them and they lack the physicality and directness that artists find so compelling with hand-based 3D interfaces. In this work, we investigate alternative 3D, hand-based drawing interfaces that maintain the advantages of direct 3D input but improve the control and precision to the point where artists feel comfortable addressing challenging 3D subjects. Modeling based on a 3D input paradigm has already proven useful for initial concept design and for artistic gesture sketching. We hope these tools will facilitate a new application area that goes beyond quick 3D sketches and moves toward illustration and more controlled drawing of difficult subjects.

In 2D, one of the most controlled approaches to drawing lines on a surface is tape drawing, a two-handed technique employed by car designers and recently adapted to digital media [4]. Although such a deliberate approach to drawing lines is not always needed for 2D illustration, it is often used in car design because of the unusual constraints imposed by cars. First, tape drawing is used for large-scale drawings, typically, life size or near life size. Second, the curves in these drawings need to be exceptionally smooth and controlled. Often, measurements for blueprints are taken directly from the drawings. Tape drawing techniques overcome many of the difficulties of drawing controlled lines on such a large scale.

Like the exceptional size of tape drawings, drawing precisely in 3D is complex. In this paper, we introduce and evaluate two 3D drawing interactions inspired by tape drawing which address the complexities of drawing in 3D. Our first technique is a true 3D variant of tape drawing where, just as in car design, both hands are used together to draw precisely. For the second technique, first proposed in 2D by Balakrishnan et al. [4], just one hand is used to draw. The one-handed approach proves to be easier to learn and easier for drawing certain types of shapes in 3D, whereas the two-handed approach is very precise for expert users and adapts well to many styles of curves.

Both styles of drawing have their advantages and both belong in a complete 3D tool set. In fact, it is useful to transition between the two even in the middle of drawing a curve. We show how to handle this situation and produce smooth tangent-preserving transitions. Recovering gracefully from a mistake is particularly important since 3D lines are harder to draw than their 2D counterparts. Thus, users often want to back up to redraw portions of the line. Both of our interfaces support this style of editing. Finally, Drawing on Air supports creating stylized 3D lines by allowing line parameters (orientation, thickness, and color) to be adjusted while drawing. These parameters serve as a 3D counterpart to line weight in traditional drawing.

One of our scientifically motivated illustration results is shown in Fig. 1 and the Virtual Reality (VR) drawing environment used to create it is shown in Fig. 2. To create this model, the artist had to have a great deal of control over line shape, line weight (thickness and color variation), and 3D proportion. Drawing on Air enables artists to create 3D drawings like these. Note that the smooth shape of the

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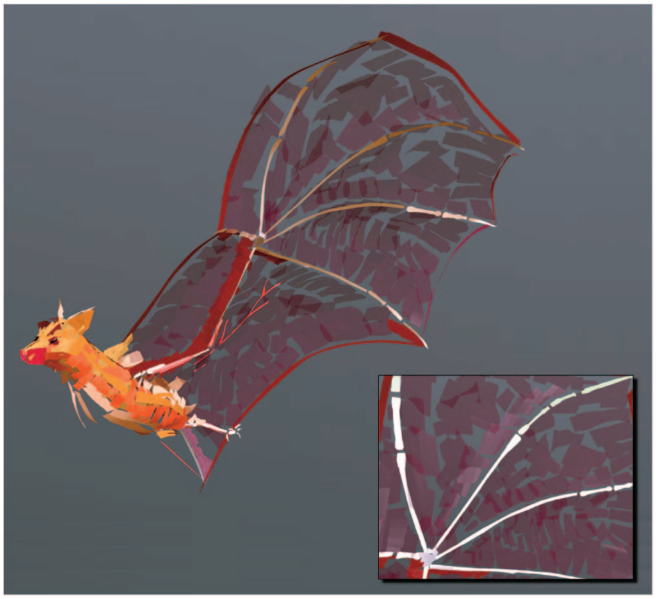


Fig. 1. One view of a 3D line illustration of a bat in flight created with Drawing on Air. Three-dimensional input techniques inspired by tape drawing enable artists to create smooth controlled 3D lines, as we see in the wing bones, with far more precision than is possible with freehand 3D drawing. The inset picture is a zoomed-in view of the wing from a different angle, showing artistic use of line weight to highlight joint locations.

Fig. 2. Drawing on Air uses a stereoscopic desktop display. A Phantom haptic device and a 6-Degree-Of-Freedom (DOF) tracker are used for two-handed input.

bones of this bat would be nearly impossible to draw using freehand 3D input.

In Section 2, we contrast our techniques with related approaches in bimanual drawing, freehand 3D modeling, and haptic-aided modeling. Then, we describe our methods in detail. We present a formal user evaluation of the one and two-handed drawing techniques, as well as results in artistic anatomy and medical illustration. Finally, we present a discussion of lessons learned and future directions, along with conclusions.

2 Related Work

This work builds on several areas of related research. Here, we contrast our approach with techniques in bimanual drawing, freehand drawing via 3D input, and haptic-aided modeling.

2.1 Bimanual Approaches to Drawing Lines

Our bimanual approach to drawing lines builds on tape drawing, which was first introduced in digital form by Balakrishnan et al. [4] and later extended to a 3D application [5]. This 3D implementation required two 2D curves to be drawn to construct a single 3D curve. High degree-of-freedom input devices have also been used to create 3D curves using a similar two-step approach [6]. This approach is practical and potentially preferable in some applications in industrial design, where parts fit together and curves can be constructed based on constraints imposed by related curves. However, a more direct, 3D approach to constructing curves is desired for depicting organic subjects in an illustration style. Our technique introduces a form of tape drawing based on true 3D input coupled with haptic constraints.

2.2 Freehand 3D Drawing Systems

There have been many approaches to using direct 3D input for geometric modeling. A chief concern in many of these approaches is achieving control over the input. The 3-Draw system [7] pioneered the use of constraints such as snap-to-grid and snap-to-line modes. Like the two-step 3D curve drawing techniques described above, these constraint-based approaches, while appropriate for industrial design, are less applicable to our organic modeling subjects.

Closely related to our work, both in spirit and in the VR form factor used, is Deering's Holosketch [8] system. Holosketch was the first system that we know of to combine a head-tracked stereo VR environment with a modeling system that was geared toward artistic creation. Several of its drawing modes used continuous sweeping input, including a variable width toothpaste stroke controlled with a tracked wand in one hand and a mouse in the other.

Other more recent approaches have also included a notion of changing the width of form as it is swept through space. The artist Mäkelä [9] explores this concept with a custom-built ultrasonic fingertip tracker. In Surface Drawing [2], the shape of the swept-out form bends in response to the hand. Some variation in the thickness of CavePainting's [1] ribbon forms can be obtained by twisting the tracked brush prop as it is swept through space.

In all of these completely freehand approaches, refinement of a line or surface is difficult to achieve. Holosketch uses arm and sometimes wrist rests, which are impractical for our approach because the arm and wrist need to move freely to specify orientation, as well as position. A 10 times input reduction mode can also be used in Holosketch to change the mapping from input to output space. This reduces the apparent effects of muscular error, but is also reduces the size of the curve that can be drawn in a single gesture. Surface Drawing uses a multiple-pass approach where smoothing and magnet tools can be brushed over the form to edit and refine the resulting triangle mesh. Even with multistep approaches like this, the form that typically results from 3D freehand modeling systems is characteristically loose, gestural, and sketchy. These are fine qualities for artistic work, in fact, they offer a hand-crafted aesthetic that is rare and exciting in computer graphics, but they are inappropriate when artists turn their attention to problems in a more refined illustration.

Alternative approaches, such as Freedrawer [10] and Fiorentino et al.'s stroke segmentation and filtering [11], filter freehand input into smooth spline approximations. Tape-drawing-based approaches like ours act as user-driven filters. We avoid the difficult problem of separating noise from artistic intent and the resulting errors that often frustrate artists by having the artist drive the filtering process explicitly. Some additional filtering may help, but does not seem necessary. We implemented an anisotropic filter in the style of Fiorentino et al.'s initial processing step, but found it of little utility in our situation because the haptic friction and viscosity forces seem to reduce muscular noise and help users hold their hand still at roughly the same level as the filter.

2.3 Haptic-Aided Drawing and Modeling

Our use of haptics is closely related to the springs and constraints for 3D drawing of Snibbe et al. [12] in that both approaches use haptic forces to create drawing guides rather than simulate realistic surface contact forces. Although Snibbe et al. focus on exploratory doodling, our focus is on controlled drawing.

The DAB system [13] contains a sophisticated 3D haptic model of a brush that, like traditional painting and drawing, inherently supports adjusting line quality by twisting and pushing the brush against the canvas. Our work achieves similar continuous variation in line weight but with a 3D "canvas" and a simplified 3D brush model.

Galyean and Hughes [14] first introduced a passive haptics system for 3D modeling with a sculpting metaphor and many systems for creating and painting haptic-aided sculpture have followed [15], [16], [17]. These systems strive to achieve control over the generation of 3D form through proper simulation of contact forces with the virtual clay that the user manipulates. The resulting forms often look blobby, but can also achieve a refined aesthetic, as clearly illustrated by results in the industrial design domains [18]. Although these tools target 3D models in the traditional sense of watertight triangle meshes, our approach targets 3D illustrations. With our approach, illustrators can suggest complicated 3D form with just a few careful strokes through the air.

3 Drawing on Air

Drawing on Air integrates two complimentary approaches to drawing 3D curves, one-handed drag drawing and two-handed tape drawing. Both techniques have advantages. One-handed is generally easier to learn to control than two-handed, whereas two-handed feels more controllable to expert users. One-handed is also more appropriate for circular shapes that would require one's arms to cross if drawn with the two-handed approach.

The key to both techniques is providing the user with explicit control of the tangent of the curve being drawn. This direction-explicit approach to drawing can be described in terms of two subtasks: 1) defining the direction (tangent) of the drawing and 2) advancing the line along this direction. In the one-handed drawing mode, both of these operations are performed with one hand. The artist drags around the brush like a water skier being towed behind a boat. The drawing is constrained to move along the "tow rope," which describes the tangent of the curve. In the two-handed case, control of the two subtasks is separated. The drawing direction is set by moving the nondominant hand and the line is advanced by moving the dominant hand.

This direction-explicit approach to drawing helps with control at both a low motor-control level and a higher cognitive level. At a low level, the techniques function as user-guided filters, greatly reducing tracker and muscular noise while biasing results toward important styles of curves. When an unsteady hand causes some jitter in the 3D input, the effects are minimized by the lever arm formed by the tangent. Three-dimensional positional error at the end of the lever shows up as a much smaller angular error at the point of the brush.

At a higher cognitive level, three factors aid control: 1) The visual guidelines displaying the direction of drawing help to measure space and plan drawing. 2) Backup and redraw features help artists to "explore" a curve, redrawing sections of it as they go. 3) Artists are able to work deliberately without introducing additional jitter, advancing the line only when they see it is going in the right direction.

In our implementation, drawing takes place at a fishtank (desktop-based) VR setup, as shown in Fig. 2, with two Polhemus magnetic trackers, one tracking the artist's head and one tracking his nondominant hand. The tracked device worn on the nondominant hand also has one button on it which is used primarily for clutching and reframing the virtual artwork. This is done frequently while working to examine the model and to position it appropriately for the next curve to be drawn.

The stylus of a SensAble Phantom force feedback device is held in the dominant hand and small friction and viscous force effects are applied to the stylus throughout the interaction to give the user some slight resistance as the pen is moved through the air. In this form factor, an offset exists between the physical working space of the hands and their virtual representations on the screen. Alternative hardware designs that allow for collocation and maintain a wide range of motion for both hands might be possible. We expect such a design would further enhance control.

In the sections below, we describe the details and implementation of the two drawing modes. Then, in the third section, we describe how to transition between the two modes while drawing.

3.1 One-Handed Drag Drawing

In the one-handed drag drawing technique, a virtual brush from which the curve is drawn is towed behind the physical stylus that the user manipulates. The "tow rope" used can be thought of as a rope of length l in that, when the stylus is a distance l away from the brush, the rope pulls tight and the brush is dragged directly toward the stylus. When the stylus moves toward the brush, the rope goes slack and the stylus is free to move anywhere within a radius of l of the brush without doing any towing. The position of the brush at each new frame $b(t)$ can be updated given the latest reading returned from the Phantom for the position of the stylus $s(t)$ as follows:

Let $\vec{d}$ be the current drawing direction,

$$\vec{d} = s(t) - b(t-1), \tag{1}$$

then, when the brush is in a drawing state, $b(t)$ is computed as

$$b(t) = \begin{cases} b(t-1) & \text{if } |\vec{d}| < l \\ s(t) - l\vec{d} & \text{if } |\vec{d}| \geq l. \end{cases} \tag{2}$$

There are two cases where this metaphor is complicated slightly. First, when the artist first begins to draw, it is

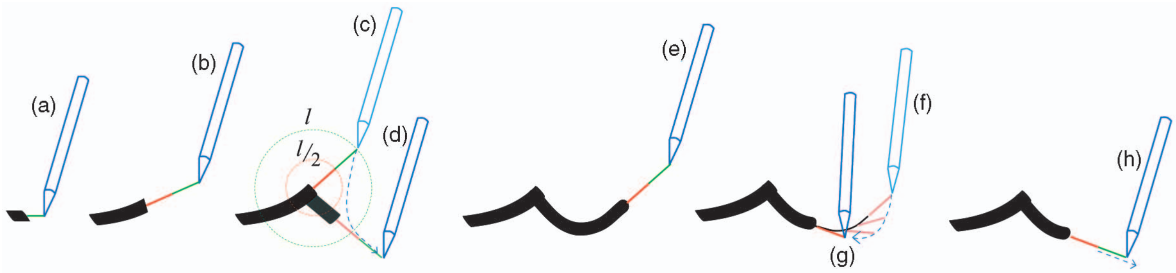


Fig. 3. The progression of a Drawing on Air one-handed drag mode interaction. When drawing first starts (from positions (a) to (b)), the drag line grows to its maximum length, l. From positions (c) to (d), the user has backed up slightly and then made a sharp change in direction before continuing to draw until position (e). Then, he backs up to within a distance $l/2$ of the end of the drawn curve and begins to erase a portion of the curve (positions (f) to (g)). The haptic constraint imposed during the erasing motion guides the user toward a tangent preserving transition when he begins to draw again (position (h)).

annoying to start in a state where the tow rope is slack because quite a bit of movement is required just to start to draw. To address this, we start with a very small tow rope and gradually lengthen it while the curve is being drawn. The second case arises when we introduce the ability to back up and redraw portions of the curve. We discuss both of these in more detail in the next sections.

3.1.1 Dynamic Tow Rope Lengthening

The length of the tow rope, l, changes dynamically, so drawing starts almost immediately when the brush button is pressed and there is no tow rope ($l = 0$) when the brush is turned off. As drawing begins, the user moves the stylus a minimum distance, l_{min} (0.5 cm in our implementation), away from the brush before any drawing occurs. This distance should be just far enough that the user can establish an initial drawing direction but not so far that he becomes frustrated that he is trying to draw but instead is only lengthening the tow rope. Then, the tow rope gradually grows to its maximum length, l_{max} (4.5 cm), as the curve is drawn according to the following relationship, where a is the arc length of the curve drawn so far:

$$l = \begin{cases} \max(l_{min}, a) & \text{if } a < l_{max} \\ l_{max} & \text{if } a \geq l_{max}. \end{cases} \tag{3}$$

The lengthening of the tow rope is represented in the first two illustrations in Fig. 3. The blue pen is the stylus s that the artist holds. At position a (Fig. 3a), the virtual brush, $b(t)$, in the equations above, is at the end of the black mark, where it meets the green tow rope. Here, the tow rope represented by the green line is growing longer as the curve is just starting to be drawn. By the time the stylus reaches position b (Fig. 3b), the tow rope is at its maximum length, where it will stay as the rest of the curve is drawn.

3.1.2 Haptic-Aided Curve Redrawing

To signal the beginning of a back up and redraw operation, the stylus is moved backward to be within a distance of $l/2$ of the brush. A better metaphor for the tow rope here is a stiff rod of length $l/2$ (the red portion of the tow rope in Fig. 3) attached at one end to the brush and at the other end to a rope of length $l/2$ (the green portion of the tow rope in Fig. 3) that is tied to the stylus. In the third illustration in Fig. 3, notice the two circles. The outer circle is at a distance l from the brush and marks the region outside of which any stylus movement will drag the brush along and add to the drawn curve. The inner circle marks the backup region with radius $l/2$. Stylus movement between these two regions does not cause the brush to move and allows artists to create sharp discontinuities in the curve, as is illustrated in Fig. 3 between positions c (Fig. 3c) and d (Fig. 3d). When the stylus is moved to the edge of the inner circle, the redrawing mode is engaged.

While backing up to erase the curve, haptic forces steer the stylus to a position where forward drawing will result in a smooth transition in the tangent of the curve. The rod in our metaphor needs to be swept around so that it always points in the direction of the tangent of the last sample of the curve. This is achieved through a haptic polyline constraint, which we render to the Phantom with SensAble's OpenHaptics toolkit. The polyline sweeps out the arc formed by each sample of the curve offset by $l/2$ times the tangent vector at that sample, similar to the dashed blue line between positions f (Fig. 3f) and g (Fig. 3g). Thus, if the drawn curve C is defined by a set of samples $c_0 \ldots c_n$, the haptic constraint polyline P is defined by $p_0 \ldots p_{n+1}$ such that

$$p_i = \begin{cases} c_i + \frac{l}{2}\overrightarrow{d_i} & \text{for } i = 0, \ldots, n \\ c_n + l\,\overrightarrow{d_n} & \text{for } i = n+1, \end{cases} \tag{4}$$

where $\overrightarrow{d_i}$ is the direction of drawing (tangent) at sample i along C. The additional line segment added for the $(n+1)$th sample allows the user to easily move out of the back up region and begin forward drawing while preserving tangent consistency.

We back up and erase the portion of the curve that we pass up to the sample c_{backup}. Thus, we can rewrite (2) to a more complete form that includes the case for curve redrawing:

$$b(t) = \begin{cases} c_{backup} & \text{if } |\vec{d}| \leq \frac{l}{2} \\ b(t-1) & \text{if } \frac{l}{2} < |\vec{d}| < l \\ s(t) - l\vec{d} & \text{if } |\vec{d}| \geq l. \end{cases} \tag{5}$$

In informal testing of several users with a nonhaptic version of this technique, some users had trouble engaging the mode initially and then frequently moved out of the backup region and accidentally started drawing backward. In addition to enabling a tangent preserving transition, the haptics serve to keep the user's pen on track to quickly execute this operation, avoiding the miscues we found without the haptics.

3.1.3 Varying Line Weight

To begin drawing and then to adjust the line weight of the curve, the user pushes with his finger tip on a custom elastic controller, shown in Fig. 4, made from a spring-loaded hinge

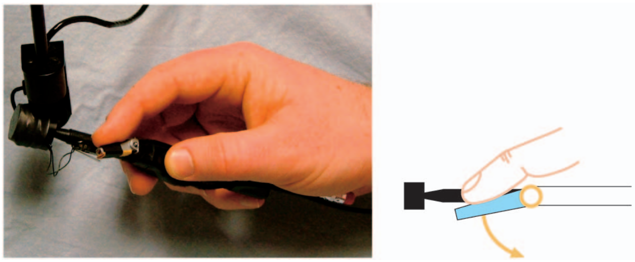


Fig. 4. A custom elastic controller is mounted on a second pen attached to the side of the Phantom stylus. For 3D drawing, comfort and range of wrist motion is improved by holding the stylus with the finger tips as an artist holds a piece of charcoal. In this position, the index finger is properly positioned to apply pressure to deflect the spring-loaded hinge, as shown in the diagram on the right.

fastened to the stylus of the Phantom. As more force is applied and the hinge deflects, the width of the mark is expanded and the color is adjusted to create a heavier 3D line. Releasing the spring device makes a thinner line.

Colors are interpolated from a gradient selected by the user. Artists often import their own color palettes and adjust the gradients to increase contrast with the background color as pressure increases.

As in traditional artistic tools and other pressure-based interfaces [19], visual feedback is important for control. The width of the curve geometry and a pressure meter drawn to the right of the brush model provide continuous visual indications of the current line weight.

3.2 Two-Handed Tape Drawing

Drawing a curve with the two handed tape drawing interface requires coordinated movement of both hands, as depicted in Fig. 5. Throughout the interaction, the tape drawing tangent or drawing direction $\vec{d}$ is updated based on the last sample of the curve c_n and the latest tracker reading for the hand $h(t)$:

$$\vec{d} = \begin{cases} h(t) - s(t) & \text{if } n = 0 \\ h(t) - c_n & \text{if } n > 0. \end{cases} \tag{6}$$

For the initial case, the stylus location is used instead of the last curve sample.

The brush is advanced along the drawing direction by movement of the stylus:

$$b(t) = \text{projection of } s(t) \text{ onto the line segment } (h(t), b(t-1)). \tag{7}$$

Straight lines can be easily drawn by holding the nondominant hand in place and moving the stylus directly along the tangent line. To draw a curve, the nondominant hand is moved while drawing to dynamically change the tangent as the dominant hand advances along the tangent, as we see in Fig. 5 from position a (Fig. 5a) to c (Fig. 5c). The artist can stop his dominant hand at any point and make a drastic change in the curve tangent before proceeding to create jagged or bumpy lines.

Force feedback in the form of a dynamic line constraint is used to constrain the stylus tip to remain on the line segment connecting the two hands. This helps the user concentrate on specifying the drawing direction and advancing deliberately along this tangent rather than concentrating too heavily on the 3D position of the dominant hand.

It is unclear whether a consistent preference exists for the role of each hand in tape drawing. Traditionally, 2D tape drawers draw from left to right, regardless of handedness. In this 3D interaction, artists seem to be most comfortable drawing toward the nondominant hand, so the dominant hand can play the key role in adjusting line weight via haptic interaction, as described below.

3.2.1 Varying Line Weight

The haptic line constraint provides a control for varying line weight that mimics physical media. Just as a brush or a piece of charcoal is pushed against the paper to make a dark, thick line, users push against this line constraint to change the weight of the mark. The pressure from this interaction, p_{tape}, is combined with the pressure from the elastic finger controller, p_{finger}, to produce a total value for the line weight of the mark:

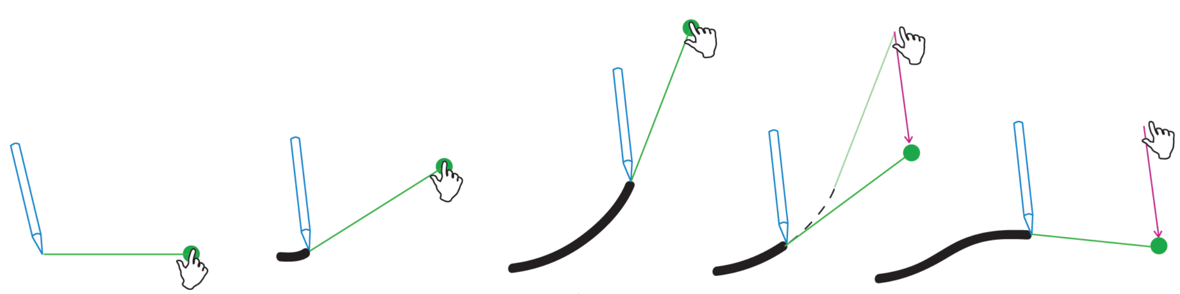
$$w = p_{finger}/p_{maxfinger} + p_{tape}/p_{maxtape}. \tag{8}$$

This value is used to adjust the color and width of the mark being drawn.

As the user pushes against the haptic constraint, the position of the stylus physically moves off the line constraint somewhat. In fact, the distance that it moves off the line serves as our measure for p_{tape}, but its virtual position is constrained in software to remain precisely on the tangent line so that a smooth curve is drawn.

3.2.2 Haptic-Aided Curve Redrawing

As with drag drawing, we extend the basic tape drawing interaction to support backing up and redrawing the mark. Balakrishnan et al.'s 2D tape drawing [4] included a similar



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

Fig. 5. The progression of a Drawing on Air tape mode interaction for a left-handed user. The drawing direction is determined by the position of the hand and the endpoint of the curve being drawn. To draw a curved path, both hands must move together (positions (a) through (c)). As the user backs up to redraw a portion of the curve (d), a virtual offset (shown as a magenta vector) is applied to the hand position so that a tangent preserving transition is made when forward drawing resumes (e).

procedure for lifting up tape. We extend this to 3D and remove the need for a button press to explicitly enter redrawing mode.

This feature requires the use of four haptic states: Brush Off, Drawing Forward, Backing Up, and Hands Too Close. When the brush is off, no haptic forces (other than the constant friction and viscosity) are rendered, allowing both hands to move freely. The Drawing-Forward state is also straightforward and consists of rendering the normal line segment constraint going from the last sample of the curve to the hand position, as described above.

To enter the Backing-Up state, the user pushes backwards against a small force until he "pops" into the new state. Initially, this feels as though the stylus is trapped by the bounds of the normal forward drawing constraint, so it cannot move back. Once a sufficient force is applied, this constraint is lifted. (See Komerska and Ware for discussion and analysis of similar haptic pop-through effects [20].) Now, the stylus slides effortlessly along a haptic polyline constraint defined by all of the previous samples of the curve and connected in the forward direction to the position of the hand. By following the haptic guide, the user can easily slide backward to erase a portion of the curve or start moving in a forward direction to resume drawing.

As the curve is erased by moving backward, a virtual offset is applied to the location of the nondominant hand in order to set up a tangent preserving transition when forward drawing resumes. In Fig. 5c, notice the position of the hand. In Fig. 5d, the brush has backed up, but the hand has stayed in the same place. An offset, illustrated by the magenta line, is applied to the virtual position of the hand so that, when the brush starts moving forward again, as we see in the final illustration, a smooth tangent-preserving transition is made between the old part of the curve and the newly drawn portion.

The final state, Hands Too Close, is entered if the hand and the brush positions are closer that 2.25 cm from each other. At such close distances, the tracker readings can cross quickly, drastically changing the direction of the curve tangent and causing the haptic simulation to become unstable. If the hands reach this state, we render a haptic point constraint to keep the brush stuck at its current position and visually indicate to the user to move his hands apart.

3.2.3 Visual Feedback

As in traditional tape drawing, sighting and measuring space with the tangent guide line both in preparation for drawing and as an interactive preview while drawing is extremely important. Feedback is rendered, as seen in Fig. 6, with an orange line connecting the center of the brush model to the position of the nondominant hand surrounded by a black rectangle indicating the surface upon which a ribbon form will be drawn and the maximum width of the ribbon. A pressure meter drawn with yellow and red bars to the side of the brush indicates the current line weight and a yellow crossbar at the tip of the brush also changes length in response to pressure.

3.3 Integrated One and Two-Handed Drawing

Drawing on Air begins in the drag drawing mode by default. The user transitions to the tape drawing mode by pressing and holding the button in the nondominant hand. To return to drag mode, the button is released. Through each of these transitions, virtual offsets are applied to the position of the hand and brush in order to maintain a smooth transition in the drawing direction. The calculation for line weight is also adjusted to maintain a constant value across the transition.

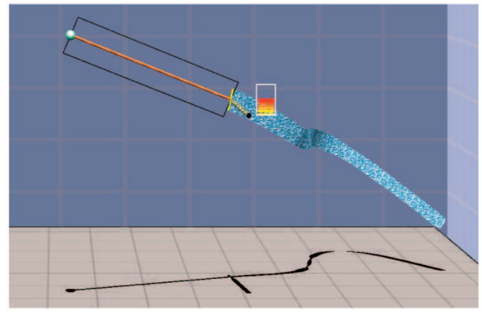


Fig. 6. Visual feedback while drawing a blue ribbon form with tape mode. The sphere on the left is the location of the nondominant hand. A yellow cylinder facing out of the screen marks the location and orientation of the brush.

To begin a line with the tape rather than the drag mode, the user holds down the button on the nondominant hand before starting to draw. Recall that, when not drawing, this button is usually used to clutch and reframe the artwork. To disambiguate these two operations, we make a logical distinction based on the positioning of the two hands when the button is pressed. If both hands are close together, the button press activates tape mode and if the hands are far apart, it activates the artwork reframing operation.

3.3.1 Drag to Tape Transition

Upon the transition from the drag to the tape mode, the mapping from the stylus to the virtual brush needs to be adjusted. In drag drawing, the stylus tows the brush behind it, but, in the tape mode, the stylus and the brush are collocated. To make the transformation, an offset from the raw stylus input values to a virtual location is maintained. The offset is set to zero at the beginning of each line, and for each drag to tape transition, $\overrightarrow{(b-s)}$ is added to the offset.

This alone does not guarantee a smooth transition in the tangent of the curve since the tape mode drawing direction is also determined by the location of the hand. Thus, a second offset is applied to the hand. It is also initialized to zero. When the transition occurs, the "goal" hand position is the closest point to the hand along the line defined by the last sample on the curve and the tangent previously defined in drag mode. The hand offset adjusts the raw hand input so that it matches the goal hand position.

3.3.2 Tape to Drag Transition

To transition from tape drawing to drag drawing, the stylus position needs to jump forward along the drawing direction so that it is again pulling the brush through space. A new ideal position for the stylus is

$$s_{new} = c_n + l\vec{d}, \tag{9}$$

where c_n is the last sample on the curve, l is the length of the drag rope, and $\vec{d}$ is the drawing direction established by tape drawing. The stylus offset described above is adjusted to make the current raw input match the value of s_{new}. The hand offset is reset to zero on this transition to avoid accumulating a large offset if multiple transitions are made while drawing the same line. Accumulating a large offset is not a problem for the stylus since the offsets applied there are always small.

In the tape mode, two pressure terms contribute to the line weight calculation, pressure from the elastic finger controller and from pushing against the haptic line constraint. On the transition from tape to drag mode, the line constraint term (p_{tape} in (8)) goes to zero. Thus, the mapping from finger pressure to line weight needs to be adjusted such that 1) the total line weight stays constant through the transition and 2) line weight returns smoothly to zero as the finger controller is released. To accomplish this, the gain of the device is adjusted by changing the $p_{maxfinger}$ term from (8):

$$p_{maxfinger} = p_{finger}/w. \tag{10}$$

$p_{maxfinger}$ is reinitialized to 1.0 at the beginning of each line.

3.3.3 Reverse Tape Drawing

During the transition from drag drawing to tape drawing, the drawing direction established by the drag technique may point away from rather than toward the hand. This is a problem for maintaining a consistent drawing direction before and after the transition to tape mode. When we encounter this situation, we switch to a technique we call reverse tape drawing where all calculations based on $\vec{d}$ are performed with $-\vec{d}$. Rather than drawing toward the hand, users draw directly away from it. In practice, this technique is far harder to control than normal tape drawing, but it is useful for drawing small sections of a curve in this situation.

3.4 Brush Model for 3D Geometric Pigment

A variety of geometries could be generated by the user's input, which includes several continuously varying parameters: position, orientation, and pressure along a controlled 3D path through space. We have found two simple geometric forms, ribbons and tubes, to be very useful for generating a variety of artistic and scientific line illustrations. Ribbons are useful for depicting the 3D form because they act visually as a tiny patch of evenly lit surface. Particularly when seen in stereo, the human visual system effortlessly composes these patches into a coherent 3D surface. Unlike ribbons that *suggest* a larger form, the solidity of tubes evokes the sensation of *being* the form. Thus, whereas a few appropriately placed ribbons may suggest the skin moving over the cheekbone on a face, tubes are more appropriate for representing thin tendons or muscles that can be drawn completely with one stroke.

Ribbons require the user to specify an orientation as the curve is drawn. Care must be taken in designing the mapping from user input to the ribbon surface normal so as to avoid requiring the user to move his wrist into uncomfortable positions while drawing in order to maintain a correct normal. For ribbons drawn roughly within a plane parallel to the film plane, using the component of the handle of the brush stylus that is perpendicular to the drawing direction as the normal works well:

$$\vec{n}_{default} = \vec{h} - \vec{h}(\vec{h} \cdot \vec{d}), \tag{11}$$

where $\vec{h}$ points in the direction of brush handle. However, for more difficult to draw curves that move in and out of the screen, $\vec{h}$ and $\vec{d}$ become roughly parallel and the normal becomes unstable or gradually spins as the curve progresses through a turn. The user can avoid this situation by carefully adjusting the handle of the brush while drawing, but this can become uncomfortable and annoying.

A solution attempts to do what the user typically expects to happen in these unstable situations, which is to maintain something very close to the previous normal throughout the period of instability. The following pseudocode describes the algorithm:

$$\begin{aligned}
&\text{if } |\vec{h} \cdot \vec{d}| < 0.7 \text{ then}\\
&\qquad \vec{n}_{new} = \vec{n}_{default}\\
&\qquad \vec{n}_{lastgood} = \vec{n}_{default}\\
&\text{else if } |\vec{h} \cdot \vec{d}| < 0.8 \text{ then}\\
&\qquad a = (|\vec{h} \cdot \vec{d}| - 0.7)/0.1\\
&\qquad \vec{n}_{new} = \text{linearInterpolate}(\vec{n}_{default}, \vec{n}_{lastgood}, a)\\
&\text{else}\\
&\qquad \vec{n}_{new} = \vec{n}_{lastgood}.
\end{aligned} \tag{12}$$

We default to returning the normal as the component of the brush's handle not pointing in the direction of drawing. If the handle and drawing direction are close to being parallel, then we return the last good value for the normal and, in a small range of values between these two cases, we linearly interpolate between the two potential values for the normal to achieve a smooth transition between the cases.

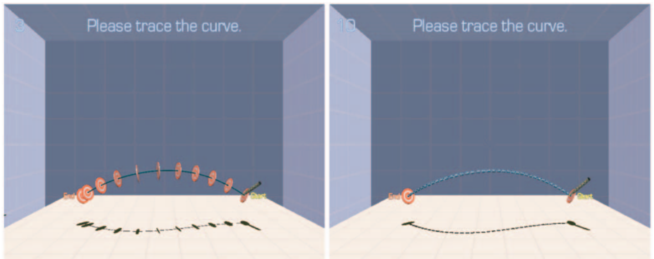
4 User Study Evaluation

We designed and executed a formal evaluation of the drag mode and tape mode drawing techniques that comprise Drawing on Air in order to better understand how they compare to each other. We also compared to a baseline of two freehand drawing techniques to establish the benefits of working with Drawing on Air relative to standard approaches. We asked users who know how to draw with physical materials to participate in this study. Another goal was simply to see whether these users, who were typically inexperienced with computers, would be able to learn to use Drawing on Air in what was typically their first exposure to VR.

4.1 Conditions and Hypotheses

The study contained four conditions corresponding to the four input techniques for drawing 3D lines that we tested. The first, "drag," is the drag mode technique of Drawing on Air. The second, "tape," is the 3D tape drawing mode of Drawing on Air. For the purpose of the study, transitioning from one mode to the other was disabled, along with backing up to redraw a line and adjusting line weight. The third condition, referred to as "sand," is a freehand drawing technique. There are no constraints on the movement of the stylus or the resulting line, but the friction and viscosity forces that are part of Drawing on Air are applied to the Phantom. Users describe the effect as feeling as though they are moving the brush through a bucket of loose sand. The final technique, "free," is also freehand but without any haptic forces. All techniques used the Phantom device for input.

Our hypotheses entering the experiment were 1) that drag and tape would considerably outperform sand and free and 2) that sand would outperform free by a noticeable margin but less than the difference between the Drawing on Air techniques and the freehand ones.



(a) (b)

Fig. 7. Participants' view of the tracing task during (a) training and (b) after training.

4.2 Methodology

Users performed repeated tracing tasks under each of the four conditions (Fig. 7). Each participant used each of the four 3D drawing techniques; thus, the study was a within-subjects design. A Latin square was used to randomize the ordering of the drawing techniques across participants. Measures of positional and directional accuracy and drawing time were computed for each tracing trial.

Tracing was performed directly on top of a 3D curve displayed in VR. In each trial, the participant was asked to trace one of five *prompt* curves that were carefully constructed to be characteristic of what we expect to find in 3D anatomical illustrations. The same prompts were shown repeatedly in blocks of five throughout the experiment. Within each block of five trials, each one of the prompt curves appeared once in a random order.

Care was taken to place the curves appropriately within the working volume of the Phantom to avoid accidentally reaching the limits of the Phantom's armature. The curves were also oriented to minimize drawing from left to right. For right-handed users, drawing in this direction is difficult enough with the tape technique that artists typically move their drawing around to a better position rather than draw with their arms crossed. Users were required to cross their hands slightly to complete some of the curves, but were never required to draw an entire curve in such an orientation. The orientation and position of the prompts and the direction of drawing was held constant for all drawing techniques.

4.3 Training

Participants were trained in two stages. The first stage was a scripted introduction to VR and to each of the four techniques. Participants were shown how to hold the pen, as in Fig. 4, and practiced drawing a straight line and several curved lines with each technique. They also practiced tracing some of the lines that they drew themselves. Participants were also instructed about the keys to drawing controlled lines with each of the techniques. For both freehand techniques, the key described was finding the right balance for the speed of the drawing. Drawing too fast lacks precision, whereas drawing too slow makes it hard to avoid jitter. For the drag and tape techniques, the key was to pay close attention to the guideline and to work deliberately by only advancing the drawing along the guideline after it looks as though it has reached the right orientation. The freehand techniques were always introduced before drag and tape because they served as an easier to understand introduction to VR and 3D drawing. The two scoring measures "position" and "direction," discussed in more detail in the results section, were also introduced during training.

The second stage of training was a mini version of the entire experiment. Participants did five tracing trials with each of the four input conditions. The order of the conditions was the same as for the rest of the experiment. To make spatial judgments a bit easier for this training stage, additional depth cues were added by displaying 10 bull's-eyes evenly spaced along the length of the prompts. Participants were shown their position and direction scores after completing each trial in the training stage.

After these initial 20 training trials, the participants did one block of 20 trials for each of the four input conditions for a total of 80 nontraining trials.

4.4 Participants

There were 12 compensated participants in the study. Six of them were male and six female. All had significant experience at drawing with physical media. All except one were enrolled in a leading design school and reported drawing with physical media daily on a post questionnaire. The one who was not also had significant collegiate-level artistic training and reported drawing with physical media at least monthly. Seven of the participants had never experienced VR before, three had experienced it one to five times before, and two had experienced it more than 20 times. Five participants had never used a 3D modeling program before, three had used such programs one to five times before, and four had used them more than 20 times before. All participants were right handed.

4.5 Results

Two primary measures of error were used to describe performance on the task. The first, "position," computes a mean of closest distances for the prompt P and the drawn curve D:

$$pos(P,D) = \frac{d_m(P,D) + d_m(D,P)}{2}, \tag{13}$$

$$\text{where} \quad d_m(A,B) = \underset{a\in A}{\mathrm{mean}}(\min_{b\in B} |a-b|). \tag{14}$$

The second measure, "direction," computes the average angle between the tangents of the two curves at corresponding samples:

$$dir(P,D) = \underset{d\in D}{\mathrm{mean}}(\arccos(d' \cdot (p' \text{ for the } p \in P \text{ closest to } d))). \tag{15}$$

Before computing the metrics, both curves are resampled at a constant interval of 0.3 millimeters.

Data from 20 of the 960 total nontraining trials (2 percent) were considered outliers and removed from the analysis. The measures for the remaining trials were averaged to find per participant means. Mean scores for position, direction, and time were analyzed with an analysis of variance with input technique (drag, tape, sand, and free) as a within-subjects factor. The sphericity assumption was met for position, but not for the other measures. Huynh-Feldt corrections were applied in the latter cases. The main effect of input technique was significant for position $F(3,33) = 37.78$, $p < 0.01$, for direction $F(1.62, 83.41) = 201.67$, $p < 0.01$, and for time $F(2.51, 27.60) = 34.69$, $p < 0.01$.

TABLE 1
Experimental Results

Measure	Condition	Mean	SD
position (mm)	drag	1.45	0.45
	tape	1.81	0.69
	sand	2.37	0.65
	free	2.68	0.75
direction (degrees)	drag^A	7.37	1.61
	tape^A	7.38	1.98
	sand^B	18.01	2.32
	free^B	19.25	1.60
time (seconds)	drag^C	23.88	6.03
	tape^C	19.89	6.97
	sand^D	13.57	5.34
	free^D	12.75	4.92

Values with corresponding superscripts are not statistically significant.

Post-hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons and $p = 0.05$. The results are summarized in Table 1 and Fig. 8.

In a postquestionnaire, participants were asked to rank the four drawing techniques in order from best to worst for control of position, control of direction, and control of both position and direction combined. The sand technique was always ranked third and the free technique was always last. For position, tape received nine first place votes to drag's three. For direction, tape received five first place votes to drag's seven, and, for control over both position and direction, tape received eight first place votes compared to four for drag.

Participants were also asked to rate how likely they would be to use each of the techniques if they were to create a 3D medical illustration with the Drawing on Air tool. On a scale of one to seven, with one being "not likely" and seven "very likely," their mean responses were drag 6.5, tape 6.5, sand 4.0, and free 2.0.

4.6 Analysis

The Drawing on Air (drag and tape) techniques outperformed sand and free on both positional and directional measures, with mean errors that were roughly half those of the two freehand-based techniques. Thus, the data support our first hypothesis. In artistic practice, we see that this difference in error makes a real difference in style and subject matter.

Drag had less positional error than tape, but tape was favored for control of position and overall control, as reported by participants in a postquestionnaire. The difference in drawing time between drag and tape was not statistically significant; however, we have observed a trend that is consistent with the data collected. Drag seems to be faster than tape for drawing approximate shapes, but slower for drawing very exact shapes. The difference is probably attributable to the separation of the two tasks of setting the drawing direction and advancing along it. Once the difficulty reaches a certain threshold, it may be faster to assign one of these tasks to each hand rather than overloading a single hand.

The tape drawing technique does take longer than drag to learn and, based on our experience with artists that have used the tool for more extended periods of time, we hypothesize that the slight difference we see in the performance between drag and tape would diminish over time or perhaps even reverse itself, with tape coming out on top. Nevertheless, we can conclude that both the drag and tape techniques are valuable parts of a controlled 3D drawing suite. User preference given a particular line to draw may be the best way to select a drawing approach; thus, the tight integration of both techniques into Drawing on Air makes sense given the level of control participants exhibited with each.

Fig. 9 provides an indication of the types of differences we see in the lines drawn with each technique. Shown here are the four *best* tracing results obtained by one participant with each of the techniques. The prompt curve in these results is inspired by an anatomical feature on the human scapula. Thus, if we imagine this line as being part of a medical illustration, the various inflection points and shape changes are important to capture because they mark regions where particular muscles of the shoulder attach.

In the versions drawn with tape and drag, the participant has followed along the path of the line quite precisely. This is somewhat hard to see in these 2D projections but is much clearer when viewed in stereo. Notice that the two lines overlap significantly and we see from the shadow that this is also true in the Z direction. The best of the sand and free drawings are unable to accurately capture the shape. There is considerable error. Sometimes it appears as jaggy bumps in the line, whereas sometimes the shape is just completely off. For example, we can see a large error in the Z direction from looking at the shadow in the sand result. If we imagine a more

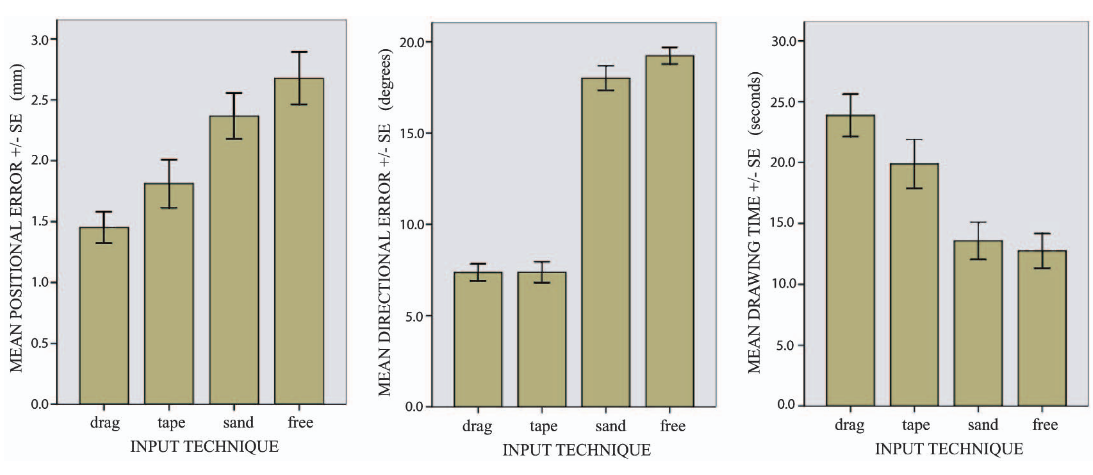


Fig. 8. Mean positional error, directional error, and drawing time across the four input conditions.

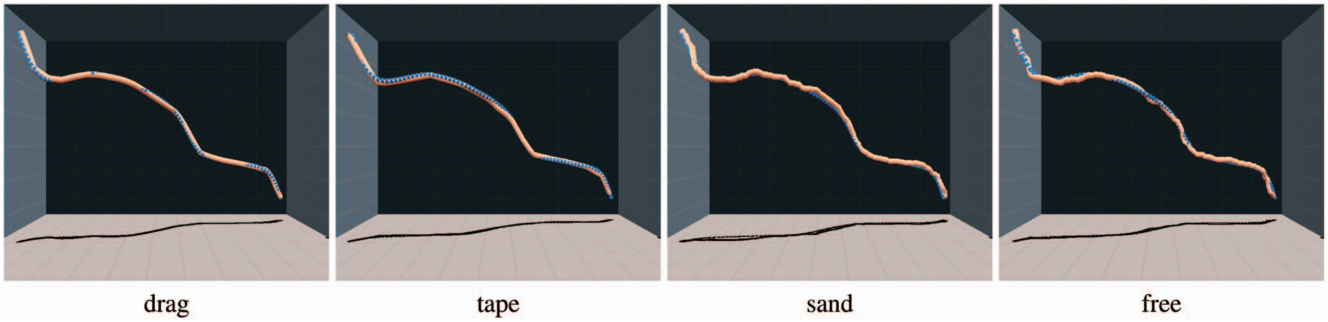


Fig. 9. One participant's best tracings of a line inspired by an anatomical feature. The prompt is shown as a dotted blue line. The user drew the solid orange line.

complete drawing formed by many lines like this, we can see the problem that typically arises with freehand input. The drawing quickly becomes loose and imprecise. We get a sense of what the artist means, but not the clarified understanding we desire in applications such as medical illustration.

More sophisticated input filtering techniques might improve some of the jaggy type of error that we see in the sand and free results. However, for anatomically inspired lines, small kinks and shape changes in line are often used to indicate important features and they regularly occur at the same scale as the muscular error we see with the sand and free techniques. Thus, it is very difficult for automatic data filtering to separate user error from artistic intention. The two Drawing on Air techniques successfully avoid this issue by putting the user in continuous control of the drawing direction, which we can think of as a user-guided filter.

The drawing times for both the drag and tape techniques took significantly longer than for the freehand techniques. This raises the question, would performance with sand and free be better if the participants spent more time while drawing when using these techniques? In practice, we find that the answer is no. The sand and free techniques have a "sweet spot" in terms of drawing speed. If the drawing is done too quickly, it is difficult to correctly capture the shape of the curve. If the drawing is done too slowly, it is difficult to maintain a smooth movement of the hand, thereby controlling directional error.

In contrast, the Drawing on Air techniques enable deliberate drawing. There is no motor control penalty associated with drawing slowly and carefully and, at a high level, guidelines built into the techniques allow for continuously checking the position and orientation in space while drawing. As a result, we find the familiar speed accuracy trade-off that we desire in a drawing tool. Performance only increases when artists wish to invest more time in the drawing.

Of final note is the significant difference found between the sand and free techniques in the mean positional error. The difference found supports our second hypothesis. The addition of haptic frictional and viscosity forces appears to aid control in this 3D task, although not to the level of the more sophisticated Drawing on Air techniques.

4.7 Appropriateness of the Task

Clearly, not all lines in an illustration are tracings. Thus, the question of whether a tracing task is the most appropriate for testing control of the various drawing interfaces is raised. In fact, we piloted other tasks, such as replicating a line seen in the distance. One of the main obstacles in nontracing approaches is making sure that the participant has an accurate 3D understanding of the shape they are about to draw. This is very difficult to achieve across various participants with anywhere near the level of certainty we have with tracing. Thus, with tracing, the participant has fewer errors due to lack of understanding of 3D shape and our error measures are more reflective of how much control the participant has over the particular technique.

Tracing is also not so different from what illustrators typically do, as we learned by working closely with illustrators and by doing our own serious illustrations. When artists work at an intricate level, drawing a line that has a particular bump on it to convey exactly where a tendon attaches to a bone, for example, they draw precisely and deliberately. They are most definitely not sketching when working at this level. The exact shape of the line is extremely important, just as it is in tracing. Lines are often drawn relative or even parallel to other lines and, in these situations, the act of drawing is almost exactly tracing.

The five prompt curves used in the tracing trials were chosen to be representative of curves found in anatomical illustration, ranging from the simple bend of a tendon going over a knuckle to a tracing of the spine of the scapula, an extremely important anatomical feature in figure drawing and illustrations of flying bats. All of the prompt curves contain variation in all three dimensions.

4.8 Importance of Training and Depth Cues

Most participants were introduced to many new concepts during this study. The various drawing techniques were, of course, new, but so was the very idea of virtual reality and interacting with a 3D stereo display. In pilots, we found that understanding depth relationships in VR was one of the most important and challenging hurdles for novices to overcome. In normal use of Drawing on Air, artists build up an entire drawing, checking depth relationships and even drawing guidelines or scaffolding as they go. In this study, however, the prompt curve is seen completely in isolation, so there are no "relative size" visual cues and very few "occlusion" cues. Cutting and Vishton provide an overview of these and other relevant cues in perceiving spatial layout in near visual space [21].

To help participants learn to judge depth within this new environment, we paid special attention to the rendering of the experimental scene, as shown in Fig. 7. Everything in the scene is textured, which helps with the perception of shape. Shadows and a ground plane, along with the bull's-eye forms used extensively during the training session were also added to provide additional cues for clarifying depth relationships. After adding these cues, a few of the participants still complained that they were having difficulty getting used to

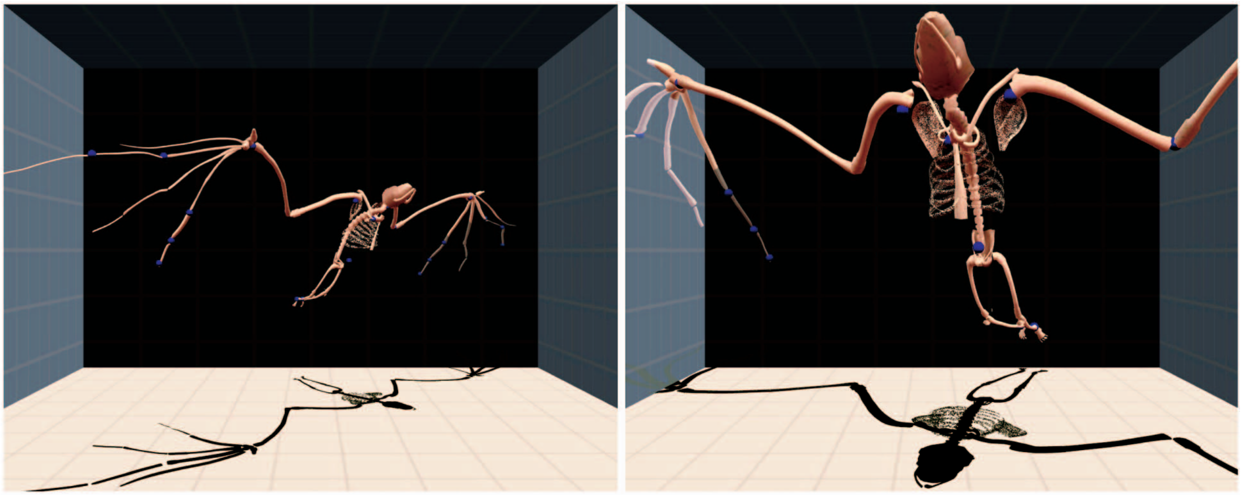


Fig. 10. Two views from an illustration of a bat skeleton posed in a flight. The blue spheres are markers from motion captured data of a bat flying in a wind tunnel.

working in 3D space, but, after the training trials, they became comfortable enough to accurately perform the task.

5 Illustration Results

Many artists have used Drawing on Air and provided valuable feedback along the way. A few of these have returned repeatedly to work on their own projects with the tool. We have guided these artists toward working on scientific illustrations of bat flight since it is a real-world illustration problem that requires a 3D treatment. In this section, we report on these results, as well as the more artistically motivated results of the first author. Each of these works took between two to five hours to create. They are designed specifically to be viewed in stereo and admittedly lose a great deal of their impact and 3D character when printed on paper, but control of form and line quality can still be clearly seen in many of the examples.

5.1 Illustrations of Bat Flight

The illustrations in Figs. 1 and 10 were made by two different artists as part of an ongoing collaboration with an evolutionary biologist studying bat flight. Traditionally, almost all anatomical illustrations, and even preserved specimens of bats, have been presented with the wing membrane and skeleton completely flattened, as we would expect of a bird's wing or a fixed wing aircraft. However, recent research has demonstrated that bat flight is several orders of magnitude more complex than that of birds, in large part because the flexible wing membrane and bones undergo tremendous 3D deformations during flight [22].

Because 3D understanding is so critical in this problem, 3D presentations of bats posed in flight are extremely important tools for the biologist researchers. Figs. 1 and 10 show initial results working toward the goal of an animated 3D anatomical illustration of a bat, including bones, muscles, and tendons with clear insertion and attachment points. The illustration in Fig. 1 served as our initial proof of concept, whereas Fig. 10 is more representative of actual experimental flight data. Several features of Drawing on Air are highlighted in aspects of both drawings. First, the smooth curves of the wing bones are clearly indicated. These bones actually bend during flight. Thus, their shape is important and would be impossible to convey accurately with a freehand approach to drawing. Also, in the bones, notice how the artist has adjusted the line thickness (see inset detail in Fig. 1) to clearly indicate the joints.

The illustration in Fig. 10 is an illustration student's second 3D bat drawing. It was drawn on top of 3D markers that were imported into the system from data collected by flying bats in a wind tunnel. Twelve markers were placed on important joints in the wing and tracked by cameras. We imported a frame of the resulting motion data into our tool and displayed the markers as blue spheres. Then, the artist drew within the reference frame created by the markers to create an illustration that is highly representative of the scientific data yet stylized to clarify the role of the skeletal system in flight.

5.2 Artistic Anatomy

The lead author, who is also an artist, did a series of works based on artistic anatomy in collaboration with a professor of illustration who teaches anatomical drawing. Each work was critiqued in VR from an artistic standpoint, and the direction for the next work was decided upon based on the critique and the goal of exploring the possibilities of the medium for representing complex natural forms. Three of the results are shown in Figs. 11, 12, and 13. When seen together, we see that an interesting variation in style is possible with Drawing on Air. Although the first bat illustration and the bearded man are quite sculpted, the Swahili bride is created with minimal use of line. One theme that came out of critiques of this work was the effectiveness of this minimal style. When seen in head-tracked stereo, we receive enough depth cues that a line drawing like this exerts a tremendous 3D presence. The artistic effect is as compelling, if not more so, as what we would see with a more traditional full-surface representation for the face.

The use of ribbons as the drawing primitive is important for making this style work because they suggest a small portion of a larger surface. Fig. 13 is an experiment in using this minimal style for medical illustration. The end points of the bones are drawn out in detail, but the anatomically less interesting flat regions in the middle of the bones are merely suggested. In many ways, this focus on detail in important regions mimics the way an illustrator would work with 2D

Fig. 11. Bearded man.

physical media. Notice the control in the lines of the tendons running over the knuckles in this example, drawn with the tape mode.

6 Discussion

Drawing in 3D and drawing with two hands are both new ways for most artists to work. In this section, we discuss some lessons learned about effective strategies for drawing with correct proportion and picking the right lines to draw to make compelling 3D illustrations. We also discuss the derivation of the design for our elastic finger controller and some nuances of working with tape drawing in 3D.

6.1 Strategies for Effective Use

Frequent reframe operations are an important part of the artistic process with Drawing on Air. Repositioning and rotating the form increases 3D understanding of the shape. It is also important for positioning the model appropriately for drawing the next mark. This has special importance for the tape mode, where there is a clear preference for orienting the artwork so that lines can be drawn toward the nondominant hand. Reframing and scaling is also necessary to deal with the limited range of the Phantom device, which was the most frequent criticism of the tool in responses to an open ended question in the postquestionnaire for the user study.

Fig. 12. A Swahili bride wearing a green veil.

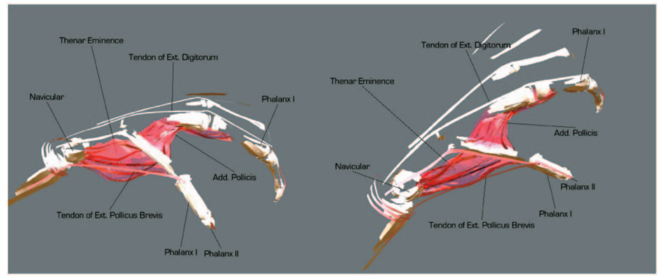


Fig. 13. Muscles and tendons in the hand.

Artists also find it useful to create guidelines or scaffolding for refining 3D proportion before drawing a final version. Our application supports drawing layers that can be turned on and off. Often, at least one layer is used for rough guidelines and working out 3D proportion.

In 3D line illustration, picking the right lines to draw is far more difficult than in 2D because multiple viewpoints must be considered. Silhouettes are often used in 2D to bound and define a form, but they break down in 3D when the form is intended to be viewed from multiple directions. Rather than drawing multiple 2D silhouettes, 3D illustrations are much more compelling when they are composed of lines that cross many planes of the form, often following along some important feature. In figure drawing, for example, the serratus and oblique muscles of the side of the torso are a good choice for this type of characteristic curve because they naturally spiral around the form from almost every viewpoint. When the edge of one of these muscles is traced out with a ribbon, the orientation of the ribbon at each point in space helps clarify the 3D shape to the viewer and lead the eye around the form.

One feature we plan to explore in the future is the view-dependent rendering of these 3D line illustrations. The minimalist style of 3D drawing, as opposed to more sculptural approaches, lends itself to creating models with clear regions that we can see through. In some situations, such as the faces in Figs. 11 and 12, looking from the perspective of the rear of the model is interesting but distracting because we see the features of the face inside out, ruining the impression of the back of the head. For some subjects, faces in particular, view-dependent display of marks, including the ability to hide marks from certain views, might facilitate clearer illustrations.

6.2 Controls for Line Weight

Pushing against the haptic line constraint in the tape drawing mode to adjust line weight mimics the approach used in traditional media of pushing the drawing implement into the paper to thicken and darken a line. The difficulty with moving this approach directly into 3D is knowing where to simulate the surface of the paper, given that, in the general case, it is impossible to predict where the artist will want to draw next. Tape drawing avoids this prediction problem by separating the controls for setting the drawing direction and advancing along it.

We did explore a one-handed technique that also separates these controls. The position of the brush is used to advance the line, while its orientation sets the drawing direction. This allows us to push against the linear drawing direction constraint as we do with tape drawing to adjust line weight. The problem with this approach is that it requires extreme and unnatural bending of the wrist in order to move in and out of a plane and create complex marks.

The elastic hinge device for line weight adjustment is the result of several design iterations, beginning with the mouse-based control in Holosketch [8]. We also explored a touch pad-based variant and an isometric pressure sensor used in either hand. In informal testing, the isometric controller was preferred to the isotonic mouse and touch pad and the final elastic design was preferred to the isometric one. Zhai notes greater ease of learning with elastic verses isometric controllers in 6-DOF manipulations [23]. We note a similar preference for the elastic over isometric controller for untrained users, but have yet to explore how this may vary with additional experience.

Both methods for controlling line weight (the elastic hinge and pushing against the tape drawing haptic constraint) have their advantages. The finger-based method is easier to hold at a constant value while drawing intricate curves, whereas the haptic-based method seems easier to control for simple curves, especially those that lie roughly within a plane.

6.3 Three-Dimensional Tape Drawing without Haptics

We tried a nonhaptic digital implementation of 3D tape drawing, but, because there is no haptic constraint, the trailing hand can stray from the curve. This makes our tape mode control for line weight impossible to realize. However, even if we disable that feature, users are still frustrated by a lack of control. As in 2D digital implementations [4], we advance the drawing along the tangent line by projecting the position of the trailing hand onto the tangent. Drifting of the trailing hand slightly off the curve is not significant enough in 2D to pose a problem, but, in 3D, keeping the trailing hand close to the curve is much more difficult. When it drifts too far, its projection onto the tangent drawing guide can be in an unexpected place. As the 3D nature of the curves becomes more complex, this drifting increases until an unexpected projection causes the drawing to appear to jump forward to the user.

6.4 Nondominant Hand Offset Mode

One of the limitations of tape drawing is the difficulty of drawing complete circles and other shapes that would require the hands to cross. We explored a mode in which the position of the nondominant hand is offset horizontally by six inches toward the dominant hand for all calculations. In this mode, the hands can easily cross virtually without crossing physically, allowing the user to draw full circles with tape drawing. Although this solves the circle limitation in theory, in practice, it requires much more of the user's concentration to work with such a large offset applied to the hand.

7 Conclusion

Drawing on Air enables artists to work with direct hand-based 3D input for creating controlled 3D models in a style of illustration. It provides simultaneous control of position, orientation, and line weight of a 3D mark through two modes of interaction, each appropriate for important classes of 3D curves. Mechanisms for transitioning from one-handed to two-handed drawing preserve the fluidity of the interaction and the smooth quality of the curves. Haptic-aided curve redrawing, which preserves smoothness, enables artists to explore subtle line variations with precision. Drawing on Air, like other VR tools, leverages the benefits of working directly in space but also provides the rich controllable interaction necessary for refined 3D illustration.

Our illustration results demonstrate that artists can effectively address challenging visual subjects in both visual art and science using Drawing on Air. We attribute this to the increased control afforded by Drawing on Air, coupled with the ability to adjust line weight. Our user study quantified a statistically significant improvement in accuracy with Drawing on Air as compared to freehand techniques. Drawing on Air is an important first step toward making refined 3D illustration as accessible as drawing on paper. We believe advances toward this goal will enable both important artistic results and more effective scientific and medical illustrations.

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