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ORIGINAL RESEARCH

A calligraphy training system based on skill acquisition through haptization

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Abstract We present a virtual reality system targeted at building a calligraphy training environment. Our main goal is to construct a virtual space enabling learners to intuitively acquire hard-to-inherit skills through the development of a Japanese calligraphy training system. The proposed system provides a haptic interaction channel allowing the learners to intuitively master instructor's fine motor skills through the sense of touch. We utilize a commercially available haptic device called PHANTOM for simulating a writing brush in a virtual training space. The system implements a function for recording and replaying instructor's hand motions via the PHANTOM device. The instructor's writing techniques such as brush-strokes and pen pressures are recorded when he/she is writing characters and they are effectively reproduced and presented to the learners via the PHANTOM device. The learners can master how to write the recorded characters by feeling the instructor's style of handwritings. We implemented a simple yet powerful 3D brush model for real-time visualization of handwritten characters without compromising the quality and reality of the visualized characters. The learners can start training at any time and iterate training sessions without worrying about resource consumptions such as papers and ink as much as they like. We conducted two experiments to validate the effectiveness of the proposed system for learning calligraphy in a virtual environment.

Keywords Haptic interface · Virtual reality · Computer graphics · Calligraphy training · E-learning

1 Introduction

Visual and acoustic sensations have been dominant interaction modalities in traditional virtual reality (VR) systems. General VR contents consist of 3D computer graphics and sounds. In recent years, haptic technologies receive attentions from many VR researchers to build an additional communication modality. The haptic interface allows users to feel various touch sensations such as weights, shapes, and surface textures of virtual objects when they touch and grasp them (Salisbury et al. 2004). The haptic sensation makes the VR contents more realistic and tangible entities.

One of the most practical VR application fields is training and education. A multimodal VR interface with the haptic sensation is a useful tool for carrying on the tradition of skills and know-how that are difficult to describe in words and images. Japanese calligraphy and Asian paintings are such promising applications.

Figure 1 shows a typical way of teaching Japanese calligraphy in the real world environment. An instructor grabs a learner's brush and passes his writing skills such as brush-strokes and writing pressures by writing characters together. This instruction style, however, has some problems as follows: the instructor can teach only one learner at a time, both the instructor and learner should be in the same place for the training, the instructor may have some

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different feeling of stroking the brush because he/she needs to grab the brush over the learner's grip, the instructor should write the characters with different viewpoints from when he/she writes them alone because he/she needs to stand behind the learner for teaching. The proposed multimodal VR system can provide not only a similar training environment as shown in Fig. 1, but also allow the instructor to write model characters with usual positions and viewpoints. Additionally, the system can accurately reproduce and present the instructor's handwriting motions with the visual and haptic feedbacks at any time when the learner wants to practice.

Figure 2 shows the system organization of the proposed Japanese calligraphy training environment. It enables users to intuitively learn how to handwrite characters and become a good writer by self-education. The system provides a haptic modality on handwriting guidance in addition to the realistic 3D graphics rendering of handwritten characters. We utilize a haptic device called PHANTOM OMNI™ model developed and marketed by SensAble Technologies Corporation as shown in Fig. 2 (Massie and Salisbury 1994). The PHANTOM device has a pen-shaped end effector called a stylus. The users grab it and handwrite characters as if they use a real calligraphy-brush. The system renders penicillate trajectories according to the users' hand movements on a display. As shown in the figure, we set a tablet display directly under the PHANTOM device's range of motion to realize consistent hand-eye coordination. This gives the users a feeling as if they are writing the characters on a paper (tablet display). The system presents a virtual canvas, an invisible and flat surface, just above the display for presenting various haptic effects in conjunction with the users' motions. The system generates a reaction force when the users press the brush (stylus) on the virtual canvas. The users, therefore, feel as if they are writing the

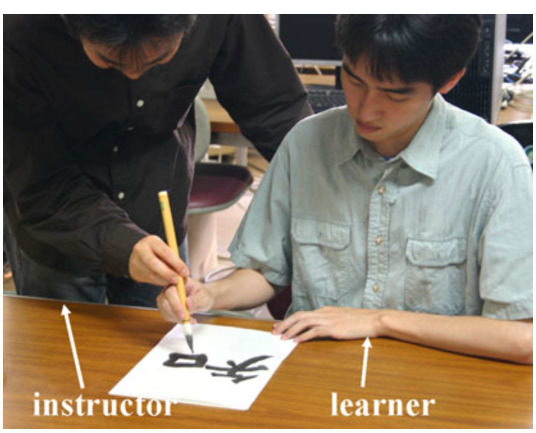

Fig. 1 A traditional way for handing an instructor's writing skills on to a learner in Japanese calligraphy. An instructor grabs a learner's brush and passes his writing skills such as brush-strokes and writing pressures by writing characters together

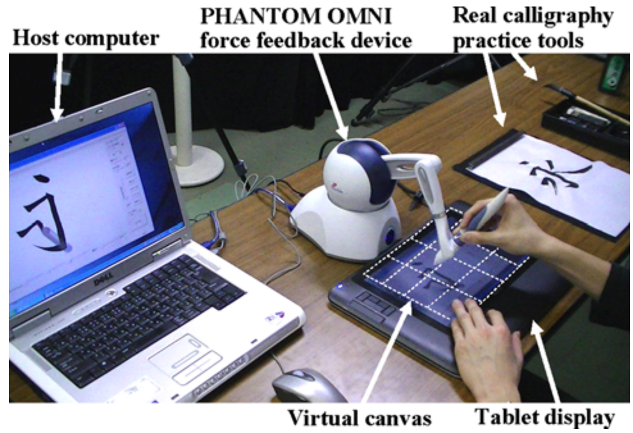

Fig. 2 System organization of proposed Japanese calligraphy training environment

characters in a real calligraphy environment as shown in far right of Fig. 2. The system also presents a frictional force when they are writing the characters on the virtual canvas for improving the reality of a textured Japanese writing paper. The system calculates these forces, adding them to compose a reaction force, and presenting it through the PHANTOM stylus. The generated reaction force gives the users a realistic feeling of writing handwritten characters on a real Japanese calligraphy paper (Nishino et al. 2010).

A best way to acquire and improve handwriting skills is to mimic a professional instructor's handwriting style in Japanese calligraphy. The proposed system implements a function for recording and replaying the instructor's hand motions with the written characters through visual and haptic modalities. The instructor's writing techniques such as brush-strokes and pen pressures he/she performs and adds when writing characters can be recorded and replayed in the system via the PHANTOM device. Accordingly, the learners can intuitively study how to write the recorded characters by feeling the instructor's style of handwritings. The system uses the PHANTOM device as an input device for recording a sequence of stylus movements with its positions and tilting angles in 3D space when the instructor is writing the characters. Then, it replays the movements with appropriate forces and graphics drawings afterward. The learners lightly grip the PHANTOM stylus and go through the recorded motions whenever they like to study the instructor's brush-strokes. They can iterate the exercise as much as they like without worrying about resource consumptions such as papers and ink.

The remainder of this paper is organized as follows. After some related research projects are reviewed in Sect. 2, we present the system organization and functions in the proposed system in Sect. 3. Next, we describe the implementation details of the 3D brush model and training support functions in Sect. 4 and Sect. 5, respectively. Then, we describe the user interface of the system in Sect. 6. After that, we elaborate two experiments conducted to verify the effectiveness of the system in Sect. 7. Finally, we conclude with some future work in Sect. 8.

2 Related work

There are some precedent application systems for teaching handwriting in Japanese calligraphy and Asian paintings. Inami et al. (2004) developed a system focusing on visually reproducing realistic brush-strokes from a character database. Chu and Tai (2004) proposed a light-weight 3D brush model for visualizing realistic Asian brush paintings including calligraphic characters. They developed a system with a real painting brush with a set of attached sensors as an input device. The system captures user's motions, calculating the resulting strokes based on the brush model, and rendering the result on a display. Wada et al. (2009) designed and implemented a similar brush model and a system with tablet input. These systems mainly aim at realistically visualizing the writing results with some effects such as ink depositing and scratching.

There are some trials mainly focusing on training aspects with the haptic modality. Saga et al. (2005) developed a system for learning handwriting Japanese characters. They designed a function for replaying the instructor's motion through the PHANTOM haptic device. Teo et al. (2002) and Wang et al. (2006) developed systems for learning Chinese characters and Eid et al. (2007) implemented a system for studying multiple language alphabets through the haptic assistance. These systems are focused on producing effective haptic guidance in learning handwriting work.

These preceding research trials target at providing a single fine modality, a visual or a haptic channel, for training character handwriting. Our goal is to synergistically utilize both haptic and visual modalities and build a virtual environment to intuitively learn some expressions endemic to Japanese calligraphy such as sweeping and holding up and down. Appropriately tilting the brush and giving pen pressures are very important skills for neatly writing characters. We also prove the effectiveness of the proposed system for the calligraphy training through experiments.

3 Virtual training system: organization and functions

Figure 3 illustrates the implemented virtual handwriting environment. The system presents a virtual canvas, an invisible and flat rigid surface, to the user underneath the PHANTOM working space. The user can write the characters by pressing the stylus on the canvas. The system calculates and feeds back reaction forces in proportion to the user's pen pressures through the PHANTOM stylus during his/her writing operations. The user can stably write the characters on the canvas and feel as if he/she is using a real brush on a real Japanese writing paper.

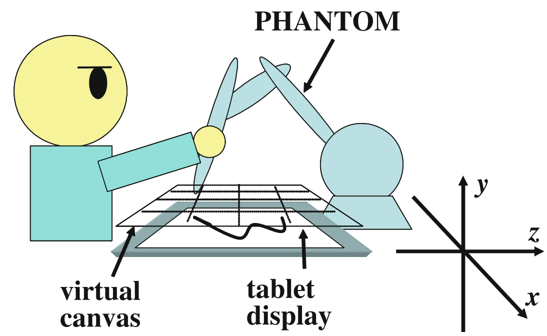

Fig. 3 Proposed virtual calligraphy training environment with PHANTOM force feedback device

The strength of the reaction forces returned from the system is proportional to the penetration depth of the user's stylus into the virtual canvas. Therefore, the system feeds back the forces corresponding to the user's pen pressures. The reaction force is defined based on the simulation method called S-D model as shown in Fig. 4. The reaction force F_v is calculated by using the following equation:

$$F_v = k_b \cdot (P - Y) - d \cdot V \quad (1)$$

where the first term $k_b \cdot (P - Y)$ is a spring force term and the second term $d \cdot V$ is a damper term. The spring force term defines the stiffness of the brush tuft, where k_b is the constant value defining the hardness of the brush tuft and $P - Y$ is the penetration depth of the PHANTOM stylus tip (P is the height of the virtual canvas surface in y direction and Y is the y-coordinate value of the stylus tip inside the virtual canvas). As described in Sect. 6, the user can adjust

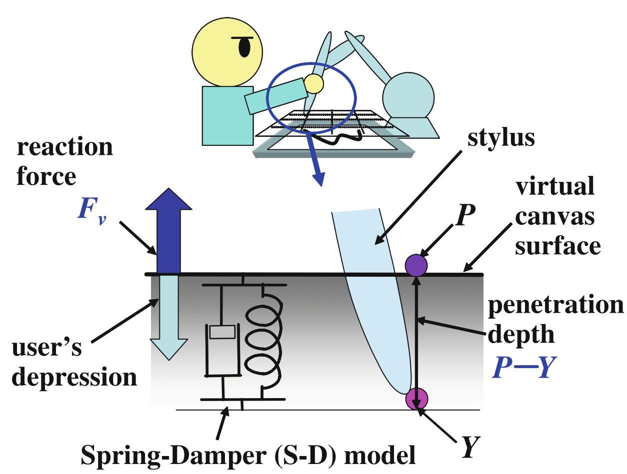

Fig. 4 Reaction force calculation based on Spring-Damper model

the brush tuft hardness and canvas height by changing the values k_b and P, respectively. The damper term is used for reducing vibration caused by the spring term, where d is a damping constant and V is a velocity of the stylus tip in y direction. The system uses the y-up coordinate system as shown in Fig. 3. The detailed description about the S-D model can be found in somewhere (Nishino et al. 2005).

As shown in Fig. 5, the system also presents a texture effect on the surface of the virtual canvas for improving its reality as a Japanese calligraphy paper. The system attaches infinitesimal bumps on the canvas surface by mapping sine-waves defined as the following equations:

$$\begin{aligned} Y_x &= a \cdot \sin X \\ Y_z &= a \cdot \sin Z \\ Y' &= Y + Y_x + Y_z \end{aligned} \tag{2}$$

where a is the amplitude of sine function defining the bump's height, X and Z are the x- and z-coordinate values of the stylus tip position on the virtual canvas defined as an XZ-plane. The (X, Z) values change along with the user's stylus movements on the canvas, and then these Y_x and Y_z values synchronously change with the movements. Finally, Y', the total penetration depth of the stylus tip with bumps, is calculated by adding Y_x and Y_z to Y, the penetration depth without bumps (as shown in Fig. 4). The derived value Y' is used to obtain the reaction force F_v as defined in Eq. 1, and thus, the generated reaction forces finely vibrate the stylus because of the bumps. The texture effect gives the user a feeling as if he/she is writing characters on a real paper by using the brush.

In addition to the surface texture, the system adds a frictional force effect for presenting the roughness of the canvas surface as shown in Fig. 5. The frictional force f is calculated by using the following equation:

$$f = \mu \cdot (-v) \cdot F_v \tag{3}$$

where μ is the constant value defining the strength of the generated friction, v is the unit velocity vector of the stylus on the canvas (XZ-plane), F_v is the reaction force from the canvas calculated by Eq. 1. The frictional force f is proportional to the force F_v and is generated in the opposite direction of the vector v (stylus moving direction). Finally, the reaction force F is calculated as a composite force of F_v and f as shown in Fig. 5 and is exerted via the PHANTOM device.

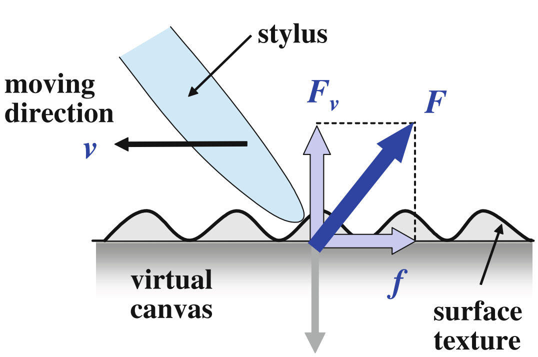

Fig. 5 Surface texture effect and friction force added to the reaction force

4 3D brush model for calligraphy

In this section, we describe the virtual 3D brush model designed for simulating and visualizing realistic calligraphy based on the user's brush-strokes.

A VR system with haptic modality should manage at least two very different update frequencies for graphics and haptic outputs independently. While the graphics updates are typically done in 30 Hz, the haptic channel needs to be updated in 1 kHz (Takekata et al. 2005). The system, therefore, requires a simple model for preserving the very high frequency haptic updates with minimum degradations on the graphics quality. Figure 6 shows the proposed 3D brush model providing the well-balanced performance and quality tradeoff. The model consists of two parts, a handle and a tuft, and each part is represented by using a simple geometrical shape such as a cylinder and a cone, respectively. Figure 7 shows how this simple brush model can visualize realistic brush-strokes. Because appropriately tilting the brush is an important skill for neatly writing characters, visualizing the titling angle is an important function. The PHANTOM device senses the stylus location in 6DOF (degree of freedom) with its position (x, y, and z values) and orientation (roll, pitch, and yaw values). Accordingly, the system renders the brush handle according to the orientation information of the stylus. The rendered handle clearly visualizes the degree of brush tilting as well as the movements in the virtual task space. The user can intuitively control the stylus movements by following the visualized handle motions.

Modeling the brush tuft is a crucial part for generating realistic calligraphy. There is an approach to model it as a geometrical element constructed by NURBS free-form surface (Xu et al. 2005). Although it can realistically visualize the written objects, it is too expensive to maintain the 1 kHz haptic control loop. Consequently, we devised a

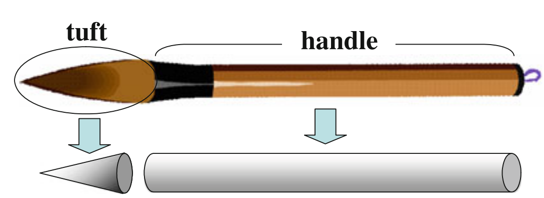

Fig. 6 3D brush model

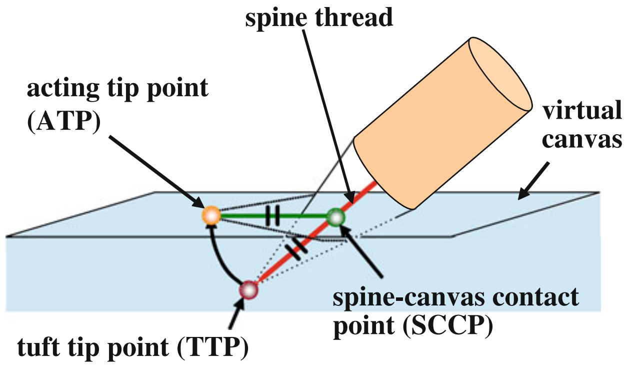

Fig. 7 Brush tuft deformation method

computationally lighter method as shown in Fig. 7. The proposed approach only simulates a single thread in the center of the brush hair called "spine thread." Then, the method recreates the user's brush-strokes on the basis of the spine thread. The spine thread is created on the center line of the brush handle as shown in Fig. 7. If the tuft tip point (TTP) penetrates into the virtual canvas, the system detects a collision between the brush tuft and the canvas, and then activates the calligraphy rendering algorithm. Firstly, it finds the spine-canvas contact point (SCCP), an intersection point between the canvas surface and the spine thread. Next, it rotates the TTP around the SCCP as a center of rotation until the TTP reaches to the canvas surface. Then, it regards the rotated TTP as the acting tip point (ATP). This simple algorithm can efficiently simulate the brush tuft deformation for visualizing the realistic strokes.

Figure 8 illustrates the method for rendering a footprint of the brush tuft contacting with the canvas surface. Firstly, it renders a circle around the SCCP with radius r calculated by the following equation:

$$r = R \cdot l/h \tag{4}$$

where R is the radius of the thickest part in the brush tuft (the model assumes it is equal to the radius of the brush handle), l is the distance between the ATP and the SCCP, h is the length of the spine thread. The user can adjust the brush tuft thickness by changing the value R as described in Sect. 6. Next, the rendering method calculates the two lateral points LP_a and LP_b on the circle and draws a triangle formed by the ATP, LP_a, and LP_b as shown in Fig. 8. Finally, the footprint is rendered as a summation of the circle and the triangle. The shape becomes like a trickle as shown in the figure.

As evidenced by Eq. 4, the circle size (thickness of the rendered footprint) is proportional to the value l, and l is equal to the distance between the TTP and the SCCP (a part of the spine thread penetrated into the canvas) as shown in Fig. 7. Accordingly, the thickness of rendered image is proportional to the pressure given by the user through the PHANTOM stylus. The user's stronger pressure produces the thicker strokes on the display just as real calligraphy.

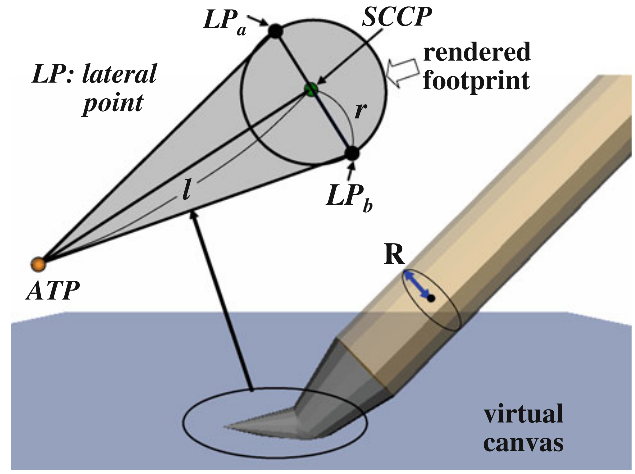

Fig. 8 Footprint rendering method based on the brush model

Figure 9 shows a series of snapshots taken when the user is writing a stroke on the virtual canvas. Each snapshot makes the brush tuft invisible for clearly showing the positional relationships between the brush handle, the spine thread, and the virtual canvas. Figure 9a shows a scene captured before the brush tuft contacts with the virtual canvas. As shown in Fig. 9b, the system starts calculating three points, SCCP, TTP, and ATP, as soon as the brush tuft intersects with and penetrates into the virtual canvas. The footprint is rendered based on the above mentioned algorithm. In Fig. 9c, the stroke image is formed in a succession of footprints traveling with the user's brush movements. Finally, a complete stroke is rendered as shown in Fig. 9d. Although the proposed brush model can visualize the realistic strokes, it only requires a small amount of computations using the positional relationships between the three points (SCCP, TTP, and ATP) and the canvas. Consequently, the proposed model realizes a light-weight yet powerful and flexible stroke rendering.

5 Training support functions with haptic modality

5.1 Record and replay functions

The system provides a function for recording the instructor's fine motor skills of handwriting and replaying them whenever the learner wants to practice. The function is implemented by sampling a sequence of the instructor's hand motions and afterward reproducing it by using the PHANTOM device.

Figure 10 shows an example process for recording a brush-stroke written by the instructor. When he/she presses

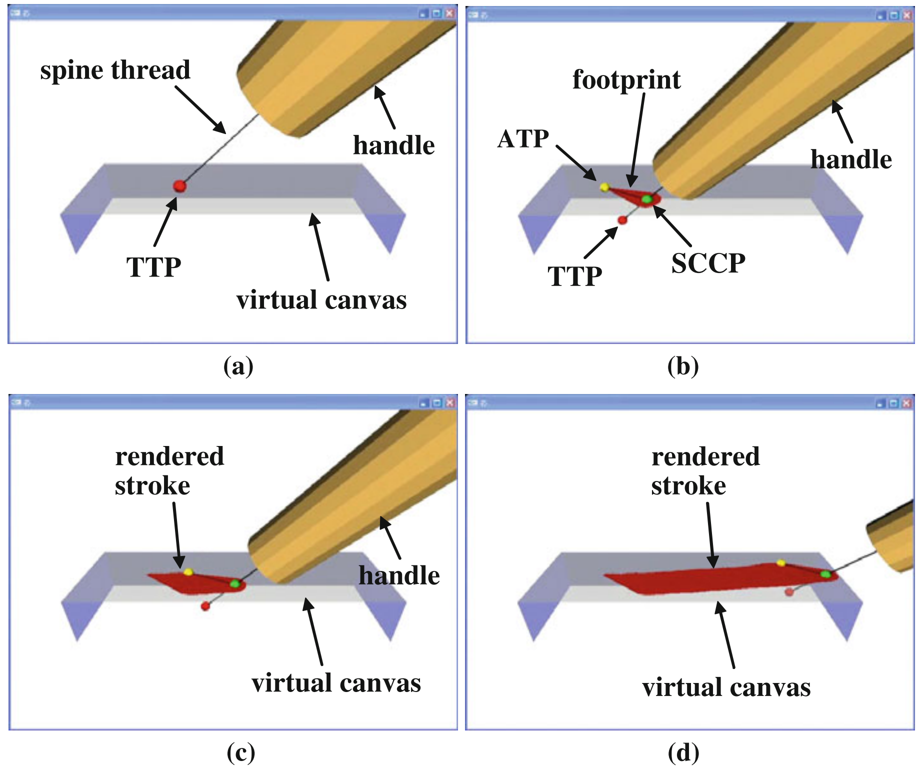

Fig. 9 A series of snapshots taken when the user is writing a stroke on the virtual canvas: **a** a scene captured before the spine thread contacts with the virtual canvas, **b** a scene captured right after the spine thread contacts with the virtual canvas, **c** a scene captured when the user starts moving the brush, **d** a scene captured when the user ends the movement of the brush

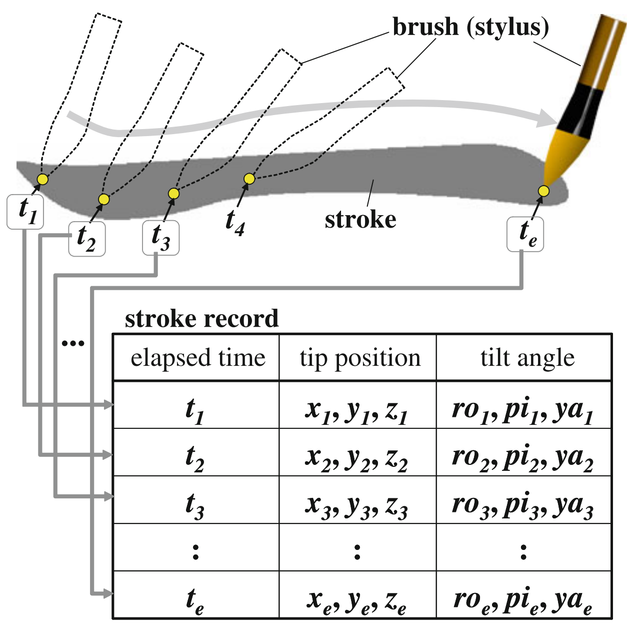

Fig. 10 An example process for recording a user's brush-stroke. The brush tilt angle (*orientation*) is recorded as a tuple of roll (*ro*), pitch (*pi*), and yaw (*ya*)

the "record" button in the training mode selection buttons described in Sect. 6, the system activates the record mode. Firstly, it moves the stylus to the predefined initial point in the task space. Then, the system continuously samples the tip position and tilt (orientation) angle of the stylus along with the instructor's brush-stroke as shown in Fig. 10. Because the PHANTOM device provides a 6DOF sensing function as mentioned in Sect. 4, the tip position and tilt angle are recorded as a set of 3D coordinate values (x, y, and z) and a type of Euler angles (roll, pitch, and yaw) of the stylus, respectively. A sampling interval (an elapsed time between nearby sample points) is an important factor for accurately reproducing the motions at replay time. As mentioned in Sect. 4, haptic interactions should be controlled in a very high frequency update loop that normally is 1 kHz for stable operations. Accordingly, the system senses and records the data in every 1 ms to preserve the reproduction of the instructor's natural motions at replay time. The sampling continues until the instructor presses the record button again.

The recorded motion is replayed when the learner presses the "replay" button just below the record button as described in Sect. 6. Figure 11 shows an example process for replaying a brush-stroke recorded by the above mentioned procedure. The system firstly moves the stylus to the initial position just like the record option, and then starts reproducing the motion from there. Then, it continuously presents an attractive force helping the learner for tracing the recorded strokes. As shown in Fig. 11, the system calculates the attractive force based on the distance between the current stylus tip position and its corresponding position recorded at the same elapsed time (shown as time t_k in Fig. 11). The attractive force is

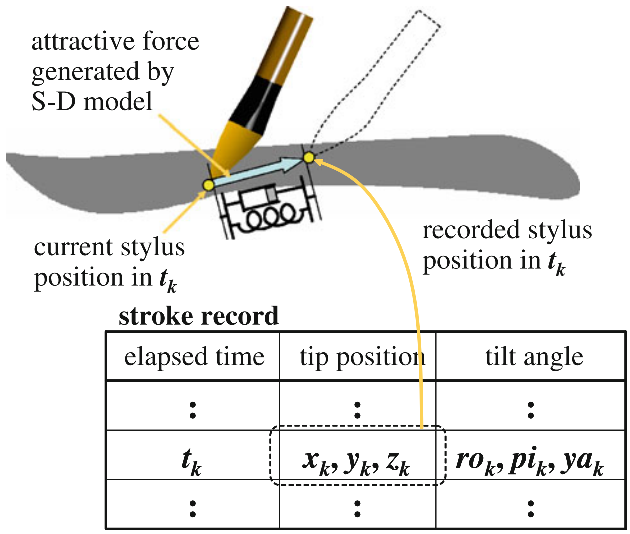

Fig. 11 An example process for replaying a recorded brush-stroke

calculated by using S-D model in the same manner as the calculation of the reaction force F_v defined in Eq. 1. The attractive force F_a is calculated as follows:

$$F_a = k_t \cdot |P_i^k - P_l^k| - d \cdot V \quad (5)$$

where k_t is the stiffness parameter in the spring term for controlling the strength of the attractive force, P_i^k and P_l^k are the recorded instructor's and the captured learner's stylus tip positions, and $d \cdot V$ is the damper term.

Whereas the PHANTOM OMNI™ model provides the 6DOF input function, it can only exert a force without orientation (3DOF output). Accordingly, the system replays the tilting angle of the stylus by graphics animation. As shown in Fig. 12, both the instructor's and learner's brush movements with their positions and tilts are simultaneously rendered during the replay mode. The learner can visually check how he/she is good at following the instructor's brush movements. Additionally, the system renders both the instructor's and learner's strokes in different colors (instructor's strokes in red and learner's in black as default colors). The learner, therefore, can easily compare the difference among them and find some largely different parts for further improvements.

5.2 Training support functions: coaching and assist modes

The motion replay function described in Sect. 5.1 accurately reproduces the instructor's hand motions by strictly following the recorded brush-strokes in synchronization with their elapsed time. This function effectively corrects the gap between the instructor's and learner's motions by generating the attractive force F_a^i (the attractive force F_a generated at elapsed time t_i) as shown in Fig. 13. The learner can intuitively catch the instructor's writing skills by going through the motions by lightly grasping the PHANTOM stylus. This is called *coaching mode* because it makes the learner to forcibly follow the replayed motions. It can positively instruct novices on basic writing skills as with a case when an athletic coach teaches first-timers on basic physical motions.

Although the proposed method also is useful for experienced writers for learning new characters, they may prefer guidance with less supervision than the coaching mode exercise. We, therefore, implemented another training option called *assist mode* providing a more self-motivating training environment as shown in Fig. 14. When the learner's position departs from the instructor's motion path, the system gently gets the learner's position back to the instructor's. After the system reads the learner's current stylus tip position (point p_l^n in Fig. 14), it detects the nearest sample point (point p_i^m in Fig. 14) and its consecutive sample point in the stylus traveling direction (point p_i^{m+1} in Fig. 14). Then, the system calculates an attractive force F_{as} as follows:

$$F_{as} = F_m + F_{m+1} \quad (6)$$

where F_m is the force acting from point p_l^n to point p_i^m and F_{m+1} is a portion of the force acting from point p_l^n to point

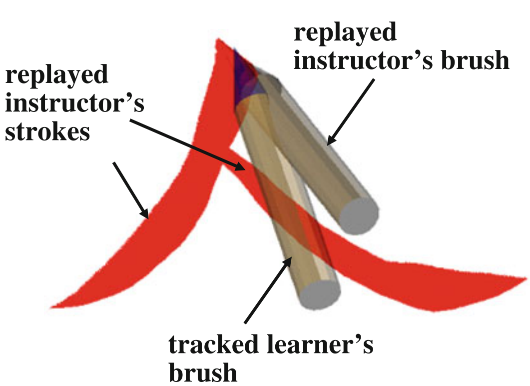

Fig. 12 A captured screen image in replay mode

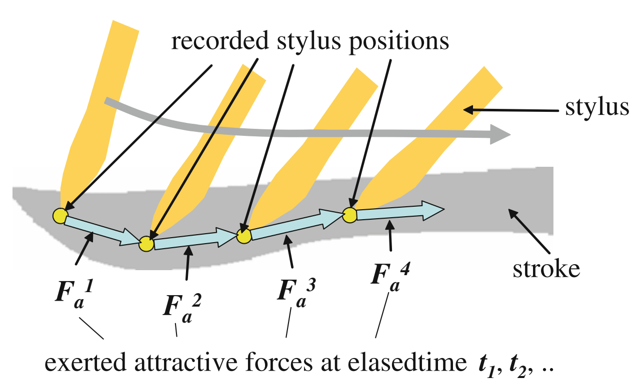

Fig. 13 Presentation of a series of attractive forces in coaching mode

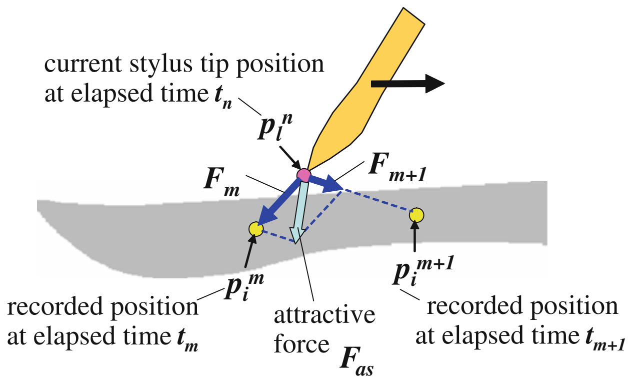

Fig. 14 Calculation and exertion of an attractive force in assist mode

p_i^{m+1}. Both F_m and F_{m+1} are calculated by using S-D model defined in Eq. 5. If the system simply attracts the learner's stylus to the nearest point, it may guide the learner in the reverse direction. Consequently, we devise a method for gradually leading the learner to the recorded motion path by adding the partial force F_{m+1} in the stylus traveling direction. This mode enables the learner to proactively master the instructor's writing technique with lightly supervised haptic guidance.

5.3 System configuration for efficient training

The hand-eye coordination in a virtual task space is a crucial factor for creating an easy-to-use virtual environment. It needs to be identical to the real-world task environment for effectively learning skills and know-how of writing handwritten characters. Consequently, we designed and set the system configuration as shown in Fig. 2. It places the PHANTOM task space just above a tablet display for providing a realistic hand-eye coordinated writing environment. The system supports a function to manually adjust the height of the virtual canvas in the virtual work space. It, therefore, enables the user to match the stylus tip position with the virtual brush tip in the space during the handwriting operation.

Time-series sequential images shown in Fig. 15 present that the user is stably writing two characters standing for "calligraphy" in the hand-eye coordinated environment. In our former study in comparing two different configurations such as a common desktop setup and the hand-eye coordinated style as shown in Fig. 15, a noticeable superiority was observed on the later setup (Nishino et al. 2009). The natural hand-eye coordination supported by the system configuration as shown in Fig. 15 is considered to be an

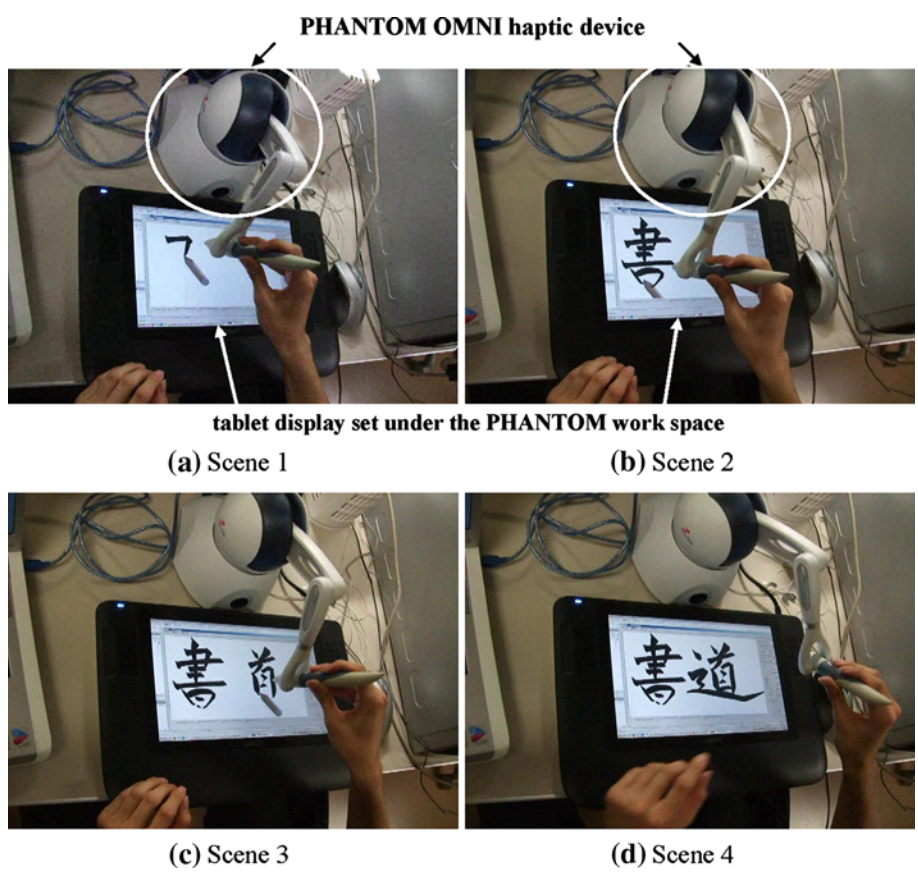

Fig. 15 Time-series sequential images captured in a handwriting task in the hand-eye coordinated environment

effective way for seamlessly connecting the virtual writing space to the real environment.

As shown in Fig. 1, the instructor needs to write characters with unusual stance and viewpoint by standing behind the learner when teaching. The proposed system allows him/her to record the characters written with natural stance and viewpoint, and replay them to the learner with the same stance and viewpoint. Additionally, the learner can use the system to check his/her level of proficiency by recording and replaying his/her motions and objectively find insufficient parts in the recorded motions for further improvements.

6 User interface

Figure 16 shows a captured image of the operational screen. Functions of the GUI components labeled as 1 through 10 in the figure are as follows:

1. Task space

This is a virtual task space where writing exercises are performed and visualized based on the algorithm as explained in Sect. 3, 4, and 5.

2. Virtual brush

The virtual brush explained in Sect. 4 is translucently rendered in a virtual task space. Because it is rendered along with the user's hand movements, he/she can visually check his/her brush-strokes and easily adjust the motions in the virtual task space.

3. Mode selection radio buttons

The user can exclusively select a mode among "brush" and "pen" modes by using the buttons. The brush mode visualizes the calligraphy based on the 3D brush model as described in Sect. 4. The pen mode simulates a penmanship environment and just draws the strokes with a fixed size dot.

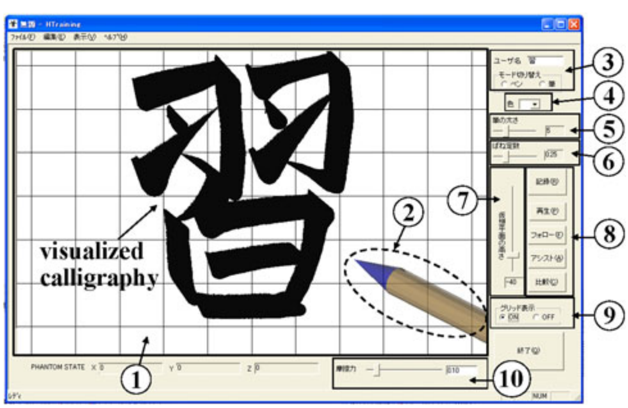

Fig. 16 Graphical user interface of Japanese calligraphy training system. *1* task space, *2* virtual brush, *3* mode selection radio buttons, *4* color selection pull-down menu, *5* brush size selection slide bar, *6* brush tuft hardness selection slide bar, *7* canvas height adjustment slide bar, *8* training mode selection buttons, *9* grid on/off radio buttons, *10* friction strength adjustment slide bar

4. Color selection pull-down menu

The user can select the color of the rendered strokes. The default value is "black."

5. Brush size selection slide bar

The user can select the thickness of the brush tuft. The thicker brush tuft produces the thicker strokes.

6. Brush tuft hardness selection slide bar

The user can change the brush tuft hardness defined as the constant value k_b in Eq. 1.

7. Canvas height adjustment slide bar

The user can adjust the height of the virtual canvas as he/she feels comfortable in the writing task by changing the variable P defined in Eq. 1.

8. Training mode selection buttons

The user can select a specific training mode according to his/her learning purpose as described in Sect. 5.

9. Grid on/off radio buttons

The user can turning on and off the grid display mode in the task space (Fig. 16 shows the grid mode is on).

10. Friction strength adjustment slide bar

The user can adjust the strength of the frictional force by changing the variable μ defined in Eq. 3.
The system is written in C++ targeted at running on Windows computers. It uses OpenGL library for graphics rendering and OpenHaptics Toolkit for controlling the PHANTOM device.

7 Experiments

In this section, we elaborate two experiments conducted for verifying the effectiveness of the proposed system.

7.1 Experiment 1

7.1.1 Experimental procedure

In the first experiment, we aim at verifying how realistically the system can reproduce a calligraphy training environment in a virtual task space. We set up an experimental environment as shown in Fig. 2. We asked subjects to perform the calligraphy both in the real and virtual task spaces and assess the reality of the system through comparing two exercises. Presenting the realistic texture of a calligraphy paper is a significant factor for reproducing exquisite handwriting in a virtual task space. The system implements the paper texture based on the rubbing movement of the brush as described in Sect. 3. We, therefore, included two writing tasks by using the system with and without frictional forces.

We employed twenty subjects, all CS major students with one exception (a CS faculty staff). Firstly, we asked the subjects for writing a letter by using the real brush, ink, and paper. We chose the letter "eternity" as the target character for the writing task as shown in Fig. 17 because it is one of the most difficult characters to learn. In spite of its simplicity as it looks, it requires three important brush-stroke skills such as hold, flick, and sweep as shown in the figure. Next, we asked them for writing the same character by using the system without the friction effect. Finally, the subjects are asked to write the letter again by using the system with the friction effect. We allowed them to rehearse the system for a few minutes before writing the character. After they write the character thrice with the real brush, the virtual brush without friction, and the virtual one with friction, we asked them the following questions:

- Q1: Which system do you feel more realistic, the virtual brush with or without friction?
- Q2: Which system do you feel easier to write?
- Q3: Which system do you feel better for practicing and mastering the three skills that are hold, flick, and sweep motions?

7.1.2 *Result and discussions*

As regards the answers to Q1 described in the previous subsection, 11 subjects responded the friction improved the reality and nine answered they prefer the frictionless case. Although the total number of subjects is not enough for statistically assessing the significance of the system efficiency, friction has no clear effect on improving the reality

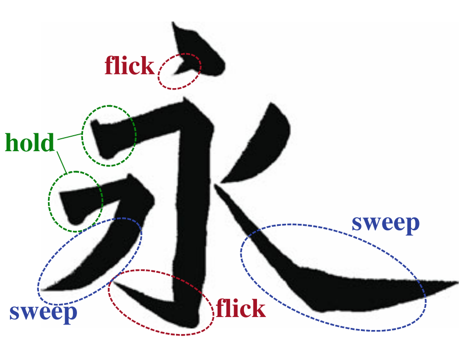

Fig. 17 A character meaning "eternity" used in the experiment 1

of the virtual task space. We queried Q2 and Q3 with four-staged rating from 4 (very easy to write) to 1 (very difficult to write) to the subjects. Figure 18 and Table 1 show the frequency distribution and the average ratings, respectively. In Fig. 18a, we can observe that the task with friction (densely screened bars) gains advantage over the frictionless case (sparsely screened bars). The average rating for the task with friction environment (2.9) is higher than the frictionless case (2.2). Consequently, we found the friction improves the easiness for using the system. As regards the results for Q3, the task with friction case gains higher average ratings for all the three subqueries (hold, flick, and sweep motions) as shown in Table 1. As can be seen in Fig. 18b and c, the task with friction gets higher scores over the frictionless task for learning the holding and flicking motions. We perceived that presenting a moderate resistance on controlling the brush quite is a useful effect on learning these artful motions.

We also asked a highly ranked calligrapher for using the system to assess the effectiveness from the expert's viewpoint. He has 7 years experiences for training calligraphy and holds the seventh degree, a second highest degree from the top. He tried to write several complex characters with many strokes as shown in Fig. 19 and gave us some comments. He argued that he can control the thickness and type face of the characters by changing the pen pressure and such controllability is an important factor for providing a realistic calligraphy task space. He pointed that a finer tuning function on the friction effect is preferable for better simulation of realistic paper texture. He also indicated that other visual effects such as bleeding and scratching are very important for improving the visual reality of calligraphic characters.

7.2 Experiment 2

7.2.1 *Experimental procedure*

We conducted the second experiment to verify the effectiveness of two haptic guidance methods, the coaching and assist mode training functions as described in Sect. 5.2. We employed 18 subjects who are all CS major students. We evenly split them into three groups (six subjects in each group) and assigned different roles to the groups as follows:

- Group A learns a target character without haptic guidance (visual information only),
- Group B learns with haptic guidance in coaching mode, and
- Group C learns with haptic guidance in assist mode.

We aim at confirming superiority in using the coaching and assist mode training functions through Group B's and

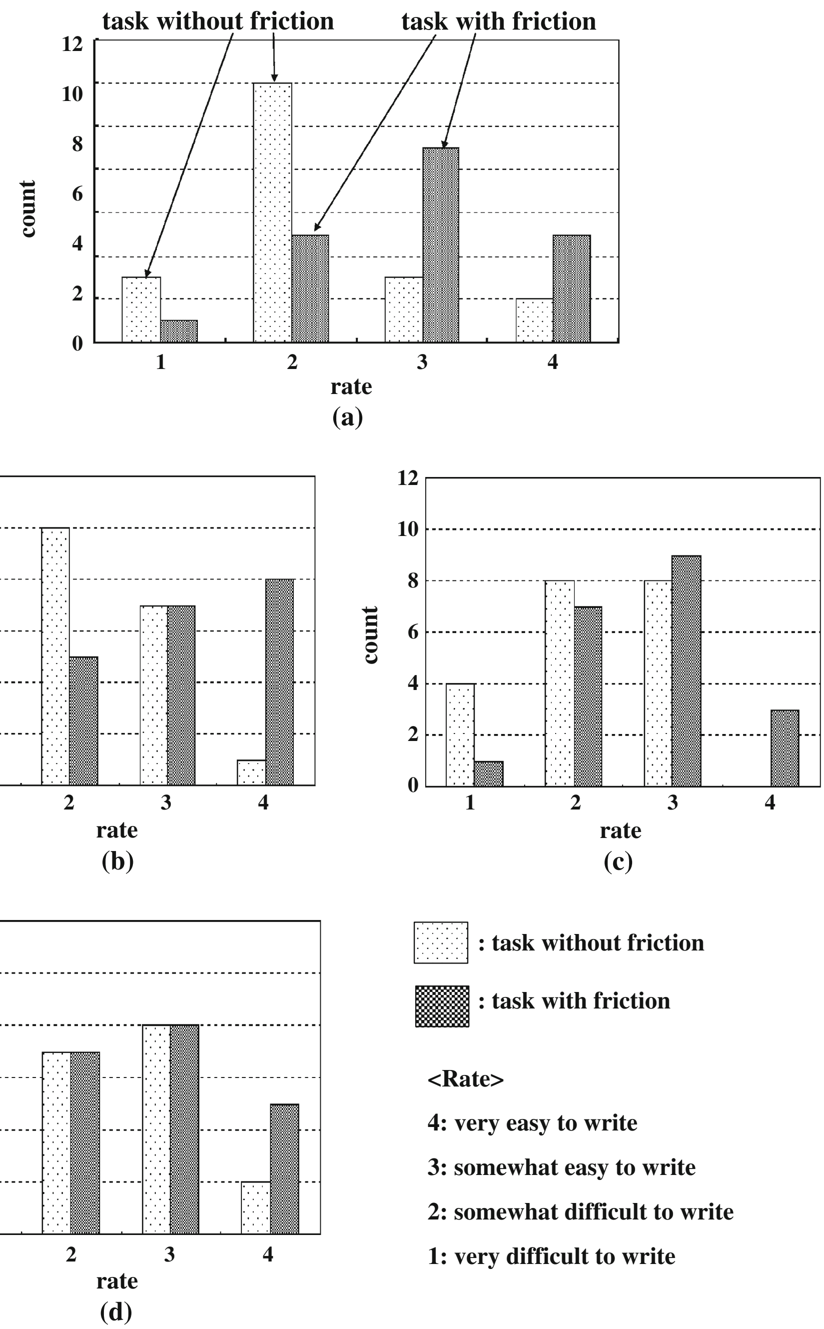

Fig. 18 Results for Q2 and Q3 in histogram form: **a** Result for Q2, **b** Result for Q3 on "hold" motion, **c** Result for Q3 on "flick" motion, **d** Result for Q3 on "sweep" motion

Table 1 Average ratings for queries Q2 and Q3

	Q2	Q3		
		Hold	Flick	Sweep
With friction	2.90	3.15	2.70	2.90
Without friction	2.20	2.50	2.20	2.45

C's exercises, respectively. Group A's role is to see if any efficiency changes are observed with or without haptic guidance in calligraphy training. All subjects learn a character in Chinese language as shown in Fig. 20 with each training method. We tried to rigorously verify the learning effects by setting the exercise on learning an unknown character. The target character shown in Fig. 20 is not included in the standard Japanese character set. Accordingly, learning the character was a first time exercise for all subjects and they need to learn its stroke order in addition to brushwork. We asked a Chinese student to write the character and recorded her brush-strokes as an instructor's guidance data by using the system. We gave the printed model character to all subjects.

Fig. 19 Complex characters with many strokes written by an experienced user

Fig. 20 Target Chinese character used in experiment 2

The experimental procedure is as follows:

1. All subjects freely use the system in 1 min to become familiar with its operations.
2. They write the character alone by copying the printed model. Their brush-strokes are recorded as pre-training outcomes.
3. They freely exercise the writing in 2 min by using their respective training modes.
4. Their brush-strokes are recorded again as post-training outcomes.

7.2.2 Result and discussions

We used character writing speed for quantitatively evaluate the learning effect of the system. In Japanese calligraphy, appropriately controlling the writing speed is an important skill for producing aesthetically pleasing characters. Whereas a writer needs to tie up his/her brush on the hold part, he/she should quickly move the brush for drawing the flick and sweep parts. Rapidly and smoothly linking these movements is a fundamental skill for writing the calligraphic characters. We, therefore, checked the writing speed measured before and after the training and verified if any improvements on the writing performance can be observed and any differences between the groups.

The three radar charts shown in Fig. 21 illustrates all subjects' writing speeds measured before and after the training. We extracted them from the recorded data in step (2) and (4) in the experimental procedure as mentioned in Sect. 7.2.1. Figure 21a shows the performance results of the subjects in Group A. The dotted and solid lines shown in the figure indicate the writing speeds measured before and after the vision only training, respectively. Whereas the post-training writing speeds of two subjects (subject 1 and 5) become faster than their pre-training speeds, the four subjects' performance remains unchanged. In contrast, all subjects' performance in Group B improved after they trained by using the coaching mode haptic guidance function. In Group C, four subjects' performance improved after they trained by using the assist mode haptic guidance function. In this group, one subject's performance degraded after the training (subject 3), but it is the only subject whose performance degraded among the whole 18 subjects.

We can observe that the guidance with haptic modality contributes to improve the writing performance and the improvement is a noticeable trend especially in Group B. The coaching function used in Group B forces the learner to follow on the instructor's motion in time with the recorded brush-stroke speed. In contrast, the assist mode function used in Group C gently presents the recorded motion in concert with the learner's movements. Because the coaching function closely recreates the real teaching method shown in Fig. 1 that is usable for teaching novices and new model characters, it is considered to achieve a best effect among three methods on the experiment targeting at learning the unknown character. We also asked subjects in Group B and C for subjectively rating the effectiveness of the haptic guidance on the calligraphy training in five ranks. Table 2 shows the average rating value for each group. Whereas the rate in Group B is 3.67 being close to rate 4 (rather effective), Group C's rate is 2.17 approaching the rate 2 (rather ineffective). This result also indicates the coaching mode function gave a better effect on the training in this experiment.

Figure 22 shows example characters recorded before and after the training. They are written by two subjects in Group C. Figure 22a shows an example case that the visual quality such as the balance and sharpness of the character is significantly improved after the training. Figure 22b shows as a counter example that the visual quality is not so different after the training for comparison.

In this experiment, we observed a haptic guidance, especially the coaching mode function, has an effect on improving the writing smoothness (speed). The coaching

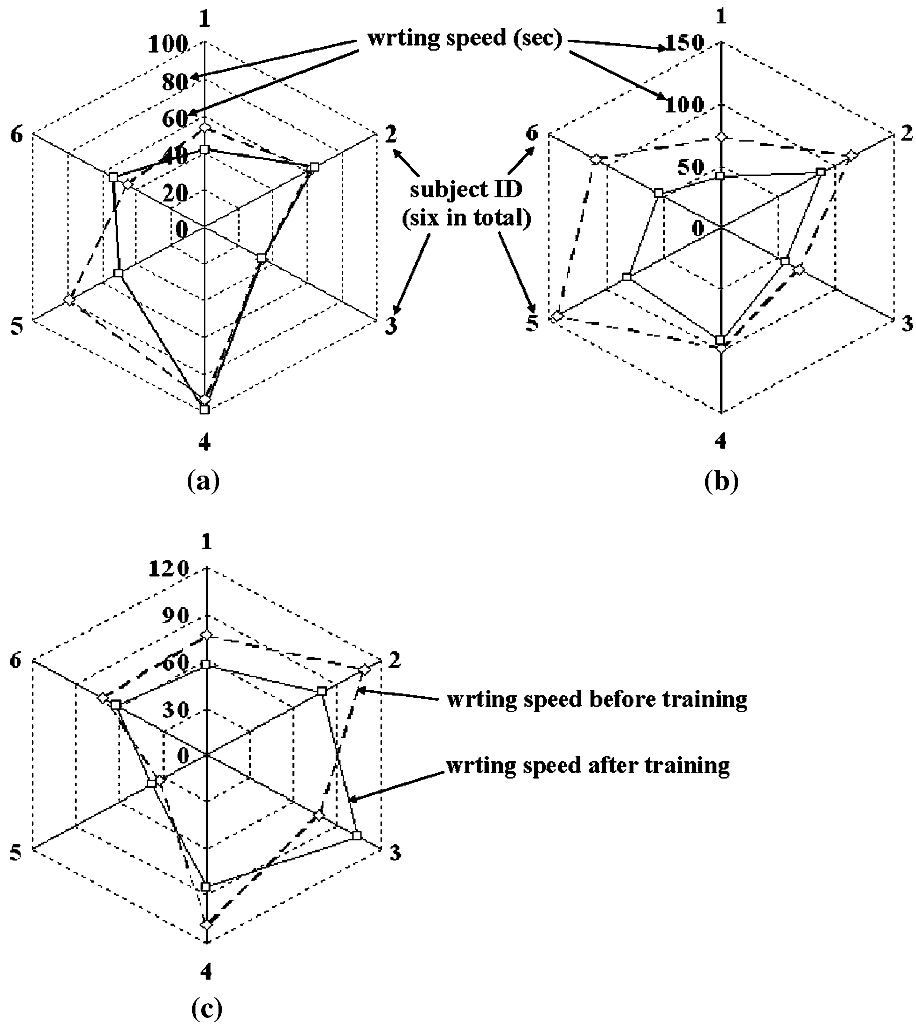

Fig. 21 Writing speeds measured before and after the training: **a** results for Group A, **b** results for Group B, **c** results for Group C

Table 2 Average ratings for the effect of haptic guidance: 5 for very effective, 4 for rather effective, 3 for neutral, 2 for rather ineffective, 1 for almost ineffective

Training mode	Average rating
Coaching (Group B)	3.67
Assist (Group C)	2.17

mode also receives a higher rate about the query on the effectiveness of the haptic guidance for calligraphy training than the assist mode. We would like to further evaluate the assist mode function by conducting an experiment employing experienced writers.

8 Conclusions

We described an approach to intuitively learn how to handwrite characters and developed a virtual training system with integrated haptic and visual modalities. We

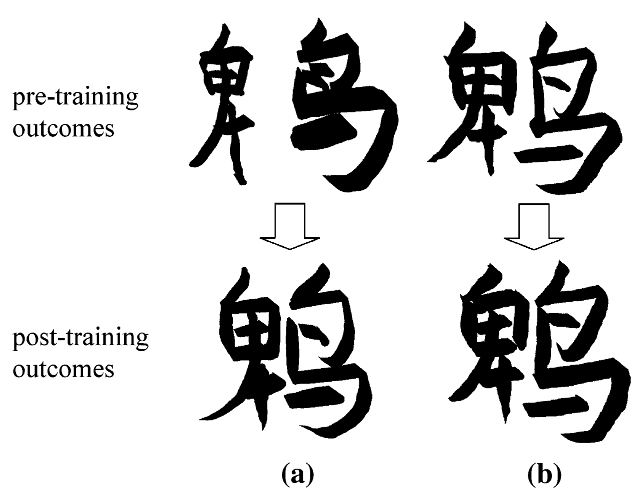

Fig. 22 Example characters written by subjects in Group C: **a** an example case that the visual quality such as the balance and sharpness of the character is significantly improved after the training, **b** an example case that the visual quality is not so different between pre- and post-training outcomes

designed and implemented two different training styles with haptic modality, the coaching and assist mode training functions. We also designed a simple 3D brush model enabling the efficient simulations of brush tuft deformations and force generations without compromising visual quality. The users can learn and acquire some important skills to become a good calligrapher such as appropriately tilting the brush and giving pen pressures when writing. We conducted two experiments to verify the effectiveness of the system. We confirmed that the proposed method improved the reality and usability of calligraphy training environment in the first experiment. We also verified that a proposed training function with haptic modality has a beneficial effect on training unknown model characters in the second experiment.

Japanese “relaxed education (Yutori education)” policy in elementary and secondary schools significantly reduces the lesson time required for cultivation of aesthetic sentiments. The proposed system may be useful for remedying the situation. We, therefore, would like to further evaluate the system by applying it in elementary and secondary education as future work. As functional enhancements, a remote learning function via the Internet (Nishino et al. 2008) and the provision of a task space with two-handed-operation and dominant/non-dominant hands collaboration (Keefe and Laidlaw 2005) are functions for further advancing the value of the proposed system.

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