A STUDY ON CHAIR DESIGN BY INTERACTIVE THREE-DIMENSIONAL MODELING USING SKETCHING INTERFACE

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Abstract. This paper discusses the potential derived by developing a sketching interface to achieve an intuition-oriented design process for beginners, focusing on fabrication. Using experiments and a questionnaire, we evaluate both the method developed and the change in the consciousness of participation in full-scale 3D (Three Dimensional) design. A specific feature of the developed sketching interface is that it is not fully packaged; it means designers can modify and customize a tool to their needs. However, there was no difference between the sketching interface and ordinary 3D CAD (Computer-Aided Design) in increasing the motivation to use computers to fabricate; including a customizable feature (not fully packaged) could open up the possibilities of increasing motivation for the subjects to participate in the fabrication. The experiment results demonstrated that the sketching interface input system has equivalent reproducibility to existing 3D CAD, and even beginners can intuitively and immediately realize fabrication.

Keywords. 3D CAD; sketching interface; fabrication support; digital fabrication.

1. Background

Fab Lab, which began as an outreach activity for research conducted at the Center for Bits and Atoms of the Massachusetts Institute of Technology Media Lab, has rapidly expanded its network worldwide (Gershenfeld 2005). Participation in fabrication using computers is becoming more comfortable and familiar for people year by year due to the spread of related educational opportunities and teaching materials. High-usability input devices, such as the computer mouse, have been developed with the widespread use of computers. In recent years, LCD (Liquid Crystal Display) pen tablets and touchscreen tablets have become popular because they allow users to input data via simple operations. Moreover, around 2000, the research and development of sketching interfaces began flourishing. As in this research, software development that enables modeling chairs from sketches is being carried out. For these reasons, the hurdle to participation is lower than ever before. However, although facilities that can perform digital fabrication, such

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as Fab Lab, are becoming more common and a personal fabrication revolution is taking place, such fabrication remains far from easy for those not associated with it. In the general participation process of (1) training to use software such as CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) and (2) designing and processing one's work, the education conducted for skill acquisition is by no means "fun." Information on design input using LCD pen tablets and touchscreens has not been fully clarified yet. Moreover, currently, the use of digital tools to reach a user's sound design is not well understood.

2. Research objectives

This study aims to confirm whether the following two objectives could be achieved: (1) developing a straightforward design input method to aid beginners who do not possess specialized knowledge and skills to easily operate, design, process, and fabricate by their intuition and (2) opening up fabrication to society using digital carving technology by eliminating the requirement to learn three-dimensional (3D) CAD, which is a prerequisite for participation and is influencing the field of architecture and furniture design. First, we developed a method that enables beginners' participation in fabrication using digital design and digital processing technology without having to learn 3D CAD. Specifically, we created a system that allows beginners to design chairs. We focused on the following operations from 3D CAD in ordinary digital fabrication: (1) make design input/editing possible as if sketching with paper and pen, (2) automate detail generation for component mounting, and (3) semiautomate data generation required to operate the processing machine.

3. Introduction of interactive 3D modeling by sketching interface

3.1. RELATED WORK

In a previous study (Mizutani et al. 2019) that focused on CNC (Computer Numerical Control) chair fabrication, the authors devised a system that enabled people unfamiliar with CAD operations to design. However, research on design input methods, specifically device studies, had not yet been conducted. An interactive tool called SILK (Sketching Interfaces Like Krazy) (Landay and Myers 2001) is one of the pioneering technologies classified as sketching interfaces; its system replaces designing through traditional CAD graphical user interfaces with just sketching. Research on two-dimensional (2D) graphics, such as screen and website design, as well as on sketching interfaces for 3D graphics has been conducted in the same manner. As the first example of incorporating interactivity, SKETCH (Zeleznik et al. 2006) was remarked upon as being different from the earlier batch-processing approach of outputting the line drawing input to the computer as a 3D shape. These studies clarified that even beginners and children with no experience in 3D graphics can easily create 3D models using a sketching interface. Research on and development of such methods have been actively conducted since around 2000, and a review of those studies was conducted by Igarashi (2006).

The most similar study to our research was on SketchChair (Greg Saul et al.

2011), a system that allows users to design a chair by merely inputting a side view (2D) of the chair from the user interface. The system's primary feature is that it allows a human being to sit on the generated chair model within a physics engine, which then performs a stability analysis. The chair's stability and the person's sitting posture when sitting can be visually confirmed, enabling users to envision the size, scale, and sitting comfort with ease. In other words, the system is equipped with functions that support novices who do not possess such a skill set or knowledge to design original chairs. In ordinary furniture design, 3D CAD is used not only to design shapes but also to create design drawings and processing data. One of the features of such a system that can be considered as both an advantage and disadvantage is that the design drawings for processing chair parts are automatically generated by the software. At about the same time as the release of SketchChair, Kostas Terzidis pointed out in his book (2006) that, currently, designers cannot demonstrate their creativity because toolmakers such as software vendors have prepared essential parts of the design process in advance so that the designers are mere "tool users" who tweak the form within a range of prearranged operability. So it cannot be said that SketchChair is out of the category of "tool maker" and "tool user" defined by Kostas Terzidis and that users cannot be more creative than they are supposed to. Additionally, it cannot be said that we should expect to see an effect of increasing the willingness to participate in full-scale 3D design and encouraging opportunities for participation beyond that. Nearly a decade has passed since the release of SketchChair, but to date, the input and design methods of other sketching interfaces have not been generalized. The reasons for this are (1) the emergence of easy-to-learn software such as SketchUp, which has made 3D design itself more effortless, and (2) the emergence of visual programming interfaces, which make it possible for designers to write their own algorithms and develop original tools.

3.2. SYSTEM OVERVIEW

In this research, we mainly aim to get users actively involved in full-scale 3D design after making chairs using the developed system. Therefore, the design process was conducted by leaving a *yohaku* (i.e., a design mechanism with flexibility to adapt to the user's skill level) in the support system so that the designers could modify and customize the tools to their needs. The base system for development was powered by Rhinoceros and Grasshopper (Robert McNeel & Associates; developed by the Rhinoceros plug-in graphical algorithm editor), which are design platforms providing user-friendly programming environments and compatibility with open-source plugins. The specific system configurations were (1) creating a web application-based sketching interface, (2) enabling the user to customize, on Rhinoceros and Grasshopper, dimensions of chair part and details of joints for assembling. This system is intended for people who have no experience with 3D CAD that includes up to inexperienced architects in 3D from people who are not professional. How to use the system differs depending on the user's skill level in 3D design. Although some design restrictions are set as the initial stage, it is assumed that the tools will be modified later according to the user's wishes. This statement is the true meaning of *yohaku*.

3.3. SUPPORT SYSTEM FEATURES

To realize the paper-and-pen operation, the sketching interface was developed via JavaScript as a web application that could be used with a stylus from a tablet device such as an iPad (Fig. 1-1). When operating the pen tool, the stylus trajectory was drawn as a dot group, and when operating the eraser tool, the points were erased. By making the design input method similar to the experience of using a pen and paper, we assumed that even those who had never used 3D CAD could easily participate in this computer-based design.

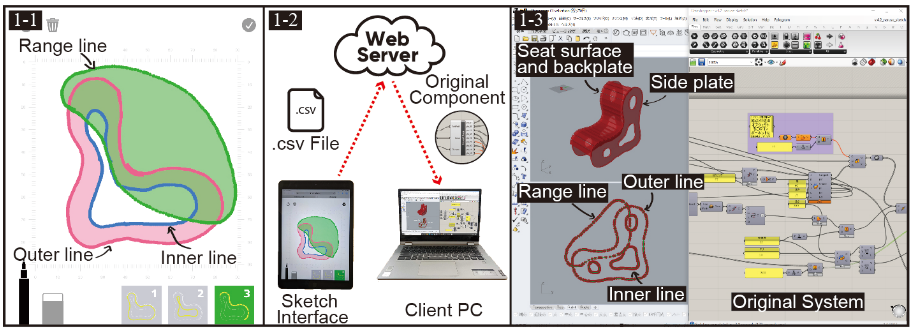

Figure 1. System overview. 1-1: Sketching interface UI screen. 1-2: Data transfer from iPad to PC. 1-3: Process up to 3D model generation by Rhinoceros + Grasshopper.

As shown in Figure 1-3, the chair to be designed comprised two side plates and a plate connecting them in a ladder shape: the seat surface and the backplate. To design the chair, the user had to input a side view of the chair through the sketching interface in Figure 1-1. To design this side view, the information required the (1) outer line, (2) inner line, and (3) range line where the seat and backplate were attached. While switching the information to be input from the icon on the web application, each shape had to be input from (1) to (3). When the user pressed the save confirmation button after the shape was satisfactory, the contour coordinate data of each point cloud (1)-(3) drawn on the sketching interface and acquired by the concave hull was saved as a CSV (Comma-Separated Values) file on the server. Then, the contour coordinate data of the point group in the CSV were downloaded to a web server connected to a local PC (Personal Computer) for processing as shown in Figure 1-2. This PC, on which Rhinoceros and Grasshopper were installed, ran components developed on Grasshopper, as shown in Figure 1-3. A point cloud was generated on Grasshopper from the contour coordinate data, generating a spline. When shapes (1)-(3) input in the sketching interface were splined by the components in Figure 1-3, a 3D model of a chair was automatically generated. The member dimensions of the seat surface and backplate, e.g., the distance between the seat surface and backplate, could be altered and input by the user as parameters from the system shown in Figure 1-3. In some cases, the algorithm could be partially rewritten, and the user could customize the chair configuration method, e.g., for assembling the members and shape for the generated details.

This process summarized above was repeated until the user was satisfied. When the user reached their ideal chair design, the operation data for the digital processing machine, such as a CNC router, were generated. Since the system shown in Figure 1-3 could automatically output the spline data required for generating the operation data, easily performing the series of CAD operations required for generating the G-code was possible. Thus, via the above procedure, we built a mechanism that allows users to participate in computer-based design immediately and without learning 3D CAD.

4. Method

In this study, we experimented with 20 undergraduate and graduate students who had no experience with 3D CAD to discover the effects of using the support system developed in this study and determine possible improvements. The participants were divided into Group A (G-A), which used the developed sketching interface input system (iPad + stylus), and Group B (G-B), which used a ready-made 3D CAD interface (PC + mouse). The experiment was conducted according to the following procedure (Figure 2):

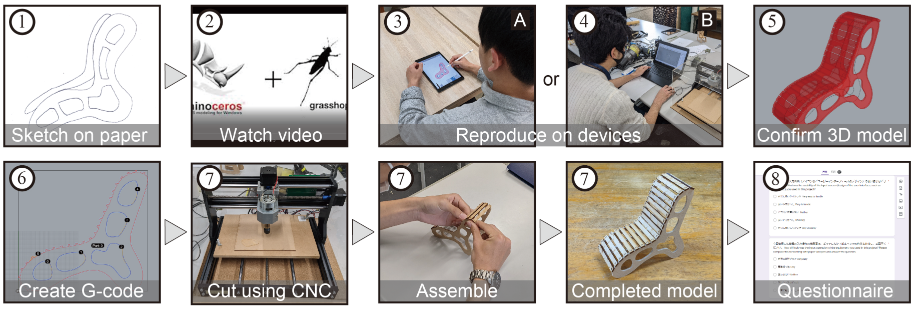

Figure 2. Experimental method: On procedure 3, we measured the input time. The experimenter performed the operations up to experimental steps 4–7.

1. Each subject created a side view of the chair from a sketch using paper and a pen.
2. Each subject received an explanation of the operation method via a video (about 1 minute 30 seconds) about the input operation to be performed by each group.
3. To reproduce the side view drawn in the first step, the subjects in G-A used the stylus to input from the sketching interface, while the subjects in G-B used the mouse to input from the ready-made 3D CAD interface.
4. After confirming the 3D shape of the chair that was three-dimensionalized from the side view by the developed support system, the subjects corrected the shape until they thought that the shape from the first step had been reproduced.
5. The subjects generated a side view of a model (1/5 scale) on the Rhinoceros model space from the developed support system.
6. The subjects generated G-code to process the side plate members using LinCAM3, a CAM software that can be plugged into Rhinoceros.
7. The subjects cut out the side plates for the model from the G-code generated in previous procedure 6 using a desktop CNC router and assembled the model using

the precut seat surface and backplate parts.

8. The subjects responded to a questionnaire survey on the system's use as developed for the participants and their own changes in consciousness regarding fabrication using computers.

5. Results from user experiment and Discussion

5.1. QUESTIONNAIRE RESULT AND DISCUSSION

The questionnaire was answered by all people in each group. Q1-Q7 referred to the system's usability, and Q8-Q11 asked if the participants had gained an interest in fabrication after using the system. Table 1 shows the results of Q1-Q7, Table 2 shows the results of Q8-Q10, and Q11 (multiple choice question).

Table 1. Questionnaire results for questions Q1 to Q7.

Question 1 How was the usability of the input screen (user interface design such as icons) used this time?					
Experimant Group	1.Very easy to handle	2.Easy to handle	3.Neither	4.Difficult to handle	5. Very difficult to handle
A (iPad+stylus) n=10	50.0%	40.0%	10.0%	0.0%	0.0%
B (PC+mouse) n=10	30.0%	50.0%	0.0%	20.0%	0.0%
Question 2 How difficult was the input operation of the device used this time? Please compare the work with paper and pen and answer.					
Experimant Group	1.Very easy	2.Easy	3.Same	4.Difficult	5.Very difficult
A (iPad+stylus) n=10	40.0%	60.0%	0.0%	0.0%	0.0%
B (PC+mouse) n=10	10.0%	50.0%	10.0%	30.0%	0.0%
Question 3 Did you get the shape you envisioned? Please compare the work with paper and pen and answer.					
Experimant Group	1.Agree	2.Agree a little	3.Same	4.Disagree a little	5.Disagree
A (iPad+stylus) n=10	80.0%	20.0%	0.0%	0.0%	0.0%
B (PC+mouse) n=10	50.0%	40.0%	0.0%	10.0%	0.0%
Question 4 How was the shape adjustment / correction work? Please compare the work with paper and pen and answer.					
Experimant Group	1.Very easy	2.Easy	3.Same	4.Difficult	5.Very difficult
A (iPad+stylus) n=10	50.0%	20.0%	20.0%	10.0%	0.0%
B (PC+mouse) n=10	30.0%	50.0%	0.0%	20.0%	0.0%
Question 5 How many shape corrections did you make compared with working with paper and pen?					
Experimant Group	1.Significantly more	2.More	3.Same	4.Less	5.Significantly less
A (iPad+stylus) n=10	10.0%	40.0%	40.0%	10.0%	0.0%
B (PC+mouse) n=10	10.0%	50.0%	20.0%	20.0%	0.0%
Question 6 Do you think you were able to design the chair you wanted this time?					
Experimant Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A (iPad+stylus) n=10	80.0%	20.0%	0.0%	0.0%	0.0%
B (PC+mouse) n=10	60.0%	40.0%	0.0%	0.0%	0.0%
Question 7 How did you feel about the difficulty of this series of work including model making?					
Experimant Group	1.Very easy	2.Easy	3.Neither	4.Difficult	5.Very difficult
A (iPad+stylus) n=10	80.0%	20.0%	0.0%	0.0%	0.0%
B (PC+mouse) n=10	30.0%	60.0%	10.0%	0.0%	0.0%

Regarding Q1 from Table 1, over 80% of the subjects answered that the input screen was "Very easy to handle" or "Easy to handle," and there was no significant difference in the overall average. However, the number of subjects who answered "Difficult to handle" was 0% in G-A but 20% in G-B, suggesting that G-A was more comfortable with operating the device. Q2-Q5 compared each device's input operation to paper and pen. Regarding Q2 and Q3, we can say that the design input operation was remarkably simple and the shape was highly reproducible because 100% of the answers were selected from among "Very easy," "Easy," "Agree," and "Agree a little" in G-A. Regarding Q4 (on the shape adjustment work), 70% of the answers in both G-A and G-B were "Very easy" or "Easy." In particular, 50% of G-A answered "Very easy," and it was found that many subjects felt that the device's input operation was more manageable than designing with paper and pen. In response to Q5 (regarding the number of shape corrections), 50% of the subjects in G-A answered "Significantly more" and "More," and 60% of the subjects in G-B answered "Significantly more" and "More". Although the points with high response rates of “Significantly more” and “More” were nearly the same in both G-A and B, it can be inferred that the factors are different. Considering the answers of the subjects in G-A to Q2, Q3, and Q4, this might have been related to the device’s straightforwardness compared with using paper and pen, suggesting that corrections were easily repeatable. However, G-B used a ready-made software wherein the spline’s control points could be controlled by free mouse operation. More slight adjustments could be made than with paper and pen, which was cited as a factor that increased the number of corrections. Besides regarding Q5, even 40% of subjects in G-A answered “Same,” it can be inferred the developed sketch input system is closer to the operation of pen and paper. Regarding Q6 and Q7, 100% of the respondents in both groups answered “Agree” or “Agree a little.” For Q7 (concerning the difficulty of the work), 80% of the subjects in G-A answered “Very easy.” Therefore, it was found that the developed sketching interface achieved immediate and highly satisfying design input.

Table 2. Questionnaire results for questions Q8 to Q10 and Q11.

Question 8 Do you want to make a chair that you designed yourself in this experiment in full size?

Experimant Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	40.0%	40.0%	10.0%	10.0%	0.0%
B（PC＋mouse）n=10	30.0%	40.0%	20.0%	10.0%	0.0%

Question 9 Do you want to try manufacturing like this again?

Experimant Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	70.0%	30.0%	0.0%	0.0%	0.0%
B（PC＋mouse）n=10	90.0%	10.0%	0.0%	0.0%	0.0%

Question 10 Do you want to learn more advanced 3D design (design using a computer) in the future?

Experimant Group	1.Agree	2.Agree a little	3.Neither	4.Disagree a little	5.Disagree
A（iPad+stylus）n=10	50.0%	20.0%	20.0%	10.0%	0.0%
B（PC＋mouse）n=10	50.0%	50.0%	0.0%	0.0%	0.0%

Question 11 What do you want to learn in the future to learn 3D design? (Multiple selections are possible)

Experimant Group	Operation of 2DCAD	Operation of 3DCAD	Operation of CAM	Operation a digital processing machine	Programming
A（iPad+stylus）n=10	0	4	1	2	5
B（PC＋mouse）n=10	7	7	5	4	4

Regarding Q8 (on the subjects’ desire to create a full-size chair), there was no large difference between the groups, and over 70% of the subjects were enthusiastic about making a real product. For Q9, regarding whether they wanted to try this fabrication again, all subjects responded ”Agree” or ”Agree a little” and were highly motivated to participate in future fabrication. Although it seemed as if there was no significant difference, G-B seemed to have more motivation for future fabrication, which was suggested when 90% of the subjects answered ”Agree” to Q10 and 100% chose ”Agree” or ”Agree a little.” Regarding the consciousness toward technology as answered in Q11, the subjects of G-B were more positive toward improving their motivation to participate in 3D design. This unexpected result was thought to be because the only difference between the operation processes of G-A and G-B was the input method, as the implementation of *yohaku* to involve the users in the modification of the developed support system, i.e., its operation and processing, was the same. This is because it was predicted that G-B would spend more time in contact with the support system than G-A and have a higher understanding of *yohaku*. G-B performed design input on a local PC, wherein the developed support system’s processing results were drawn. The experiment in this study was not appropriate as a method for analyzing the hypothesis that implementing *yohaku* would lead to subsequent participation in full-scale 3D design and improvement in learning motivation. However, both groups showed a high level of motivation to participate in fabrication in the future, indicating the usefulness of a design system that leaves in a mechanism that is not fully packaged.

5.2. ANALYSIS AND CONSIDERATION OF THE MATCH RATE OF FIGURES

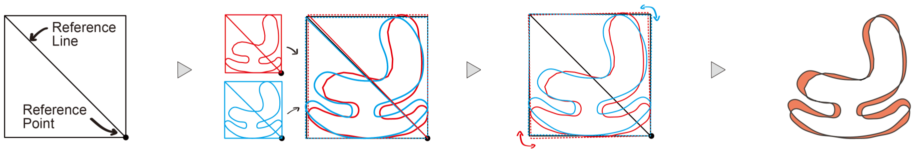

Figure 3. Determination of the difference area.

Next, the chair's side view designed by the subjects in the experiment was analyzed and discussed. The area match rates of the figures drawn on paper and each device were calculated and compared. The method (Figure 3) was as follows: (1) The reference point and reference line were determined to adjust the scale. The diagonal line of a 900 × 900(mm) square was used as the reference line according to the CNC router's acceptable plywood size when determining the actual size. The reference point was set on a corner point of the bounding box, which is the bottom of the chair's backplate. (2) The diagonal from the bounding box of the shape drawn on paper and each device was obtained, then we matched the scale's reference (3) To correct the figure's inclination, the angle of the reference line was matched with the reference point as the axis and the diagonal angle obtained from the bounding box of the figures drawn on paper and each device. (4) The total difference area of the two figures was calculated. The difference area here was the total area of both the inside (minus) and outside (plus) deviations. The different surface areas obtained for each design were divided by the sum of the surface area of the figure used for calculating the different surface areas (the figure drawn on paper and the figures drawn via the input method for each group), and the rate of change was calculated and compared. When using sketches on nonscale paper as a comparison standard, a way to unify each design for the multiple inner diameter lines entered at the discretion of the subjects was not found, so we excluded them from the analysis. It was found that, to obtain the coincidence rate of the figures, including the inner diameter lines, unifying the scale standard and the number of inner diameter lines was necessary. Table 3 shows the area match rate of the outer lines and input time in each input device and Figure 4-1 shows mean match rate of outer line figures (G-; A and G-B) with standard deviation (SD) error bars.

From Table 3, the average value of the match rate was 79.2% in G-A, 77.7% in G-B, suggesting the match rate was slightly higher in G-A. As an analysis of the match rate, Figure 4-1 shows the data with mean value and SD. In comparing the mean values of each group, the null hypothesis H0 was assumed that there is no significant difference between G-A and G-B; where the alternative hypothesis H1 was assumed that there may be a significant difference. After confirming the presence or absence of homoscedasticity by the F-test, the significance level was set to 5% and an unpaired t-test was performed. As a result, the null hypothesis was accepted because the p-value was greater than the significance level of 5%, and no significant difference could be confirmed [t (18) = 0.36, p = 0.7233]. Since no significant difference could be confirmed and the difference in the matching rate of each group was small, it can be said that each input device has the same degree of graphic reproducibility. Next, the analysis was performed against the input time. From Table 3, the average input time was 469 (s) for G-A, and 873 (s) for G-B which was shorter for G-A. Figure 4-2 shows the data with mean value and SD. In comparing the mean values of each group, the null hypothesis H0 was assumed that there is no significant difference between groups; where the alternative hypothesis H1 was assumed that there may be a significant difference. After confirming the presence or absence of homoscedasticity by F-test, the significance level was set to 5% and an unpaired t-test was performed. As a result, it was found that the null hypothesis was rejected because the p value was smaller than the significance level of 5%, and there was a significant difference[t (14) = 3.33, p = 0.0049]. Since a significant difference was confirmed, the confidence interval (CI) was calculated and found to be 95%, CI = (358, 580) in G-A; 95%, CI = (663, 1084) in G-B.

Table 3. Match rate of outer line figures. The terms represented in the table are Paper Input Area (PIA), Device Input Area (DIA), Difference Area (DA). Match Rate is calculated by subtracting the differential rate (DA/PIA + DIA) from 100%. .

Group A (iPad+stylus)						Group B (PC+mouse)					
Subjects	PIA (mm²)	DIA (mm²)	DA (mm²)	DA/PIA+DIA	Match Rate	Subjects	PIA (mm²)	DIA (mm²)	DA (mm²)	DA/PIA+DIA	Match Rate
A	429,859	382,226	88,481	10.9%	89.1%	K	345,495	283,895	167,961	26.7%	73.3%
B	383,013	372,662	123,378	16.3%	83.7%	L	270,320	283,754	184,463	33.3%	66.7%
C	293,564	291,932	248,232	42.4%	57.6%	M	421,523	424,973	129,550	15.3%	84.7%
D	273,593	228,355	117,959	23.5%	76.5%	N	342,686	373,085	144,563	20.2%	79.8%
E	343,646	318,877	87,505	13.2%	86.8%	O	318,470	331,081	102,578	15.8%	84.2%
F	269,124	310,140	131,260	22.7%	77.3%	P	248,212	252,002	205,883	41.2%	58.8%
G	285,884	339,816	213,525	34.1%	65.9%	Q	363,055	392,942	99,971	13.2%	86.8%
H	390,529	364,414	112,710	14.9%	85.1%	R	225,386	283,148	109,252	21.5%	78.5%
I	334,782	344,714	86,949	12.8%	87.2%	S	347,406	330,189	166,190	24.5%	75.5%
J	317,320	362,472	114,147	16.8%	83.2%	T	453,717	433,309	104,292	11.8%	88.2%
			Average	20.8%	**79.2%**				Average	22.3%	**77.7%**

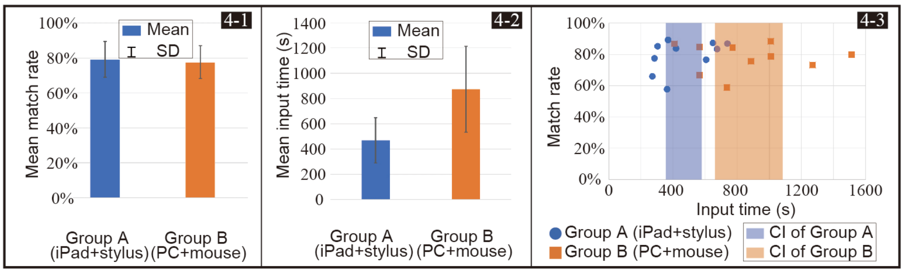

Figure 4. 4-1: Mean match rate of outer line figures (G-A and G-B) with SD error bars. 4-2: Mean input time with SD error bars. 4-3: Relationship between input time to each device and figure match rate and CI of input time. .

From the above, Figure 4-3 shows the relationship between the figure match rate and the input time for each device, and the result of the CI of the input time. From Figure 4-3, it can be said that the input time of G-A is significantly shorter than that of G-B due to the CI in the input times of G-A and G-B do not overlap. From this, it can be considered that since G-A can input intuitively, the variance of the input time by the subject is small and the figure can be reproduced in a shorter time than G-B. By contrast, in G-B, it can be considered that the variance of the input time among the subjects became large due to the skill level of the subject's PC operation. From the above, it can be said that the developed sketch input system has immediate reproducibility equivalent to that of existing 3D CAD, and even people without specialized knowledge can intuitively realize fabrication using a computer.

6. Conclusion and Future Work

Using the developed sketching interface, even beginners without specialized knowledge could reproduce designs as if sketching with paper and pen. Moreover, it was found that design input could be performed more easily and immediately than with ordinary 3D CAD. Herein, analyzing and considering the effect of improving people's motivation to participate in fabrication using computers solely by comparing the differences in design input methods were impossible. However, it has been shown that *yohaku* in a design system may increase people's willingness to participate, although comparing our developed system with other fully packaged systems to determine whether this is accurate is necessary. In future research, if a method to confirm the effect of implementing *yohaku* is developed, studies on how to construct such a system should be conducted. This could include researching how to determine the right amount of *yohaku* and developing a system that could further open up fabrication using computers to society. By achieving this, the developed tool will become more flexible to accommodate the user's proficiency in 3D design, and will contribute to raising the level of understanding of 3D design in the architecture industry in the future.

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