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Evaluation of Ergonomic Design Based on Dynamic Model of Scissor

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ABSTRACT Unlike general scissors, many commercial hairdressing scissors reflect ergonomic design with handles that provide users with comfort, minimizing fatigue and the risk of injury. However, there has not been a lot of prior research on quantitatively evaluating the merits of ergonomic design. This paper proposes a quantitative criterion to evaluate the performance of commercial hairdressing scissors. An experiment was conducted using several hairdressing scissors to establish the quantitative evaluation criterion. It was discovered that more fingers were involved than required to create a scissoring, and these fingers exerted antagonistic forces during the scissoring. Incorporating this property, a dynamic model of scissor mechanics was developed to analyze the characteristics of redundant finger forces, and a corresponding load distribution algorithm was derived. Three different types of scissor designs were compared through simulation. It was observed that the more ergonomic design was applied to the scissor, the less rotational kinetic energy was consumed. As a result, we propose rotational kinetic energy consumption as the quantitative evaluation criterion. The results of this research will be useful in designing specific scissor designs.

INDEX TERMS Antagonistic, dynamic model, ergonomic design, force redundancy, quantitative evaluation criterion, Robot, Scissor.

I. INTRODUCTION

A. SCISSORING

A scissor is a tool that cuts cloth, paper, leather, hair, etc., by crossing two blades. It is operated on the principle of a lever, where each finger holds on the two crossed blades and opens and closes them to cut. Scissoring refers to cutting an object with scissors. This skill is subjective, but the structure of scissor has evolved to provide comfort to the user. For this reason, an ergonomic design is reflected in many scissors.

If the scissors are not properly sized, especially the handle, the user will have difficulty grasping the scissors and will not be able to perform accurate scissoring. The most efficient way to grasp the scissors is to place the thumb on the bottom ring of the scissor handle and the index, middle, and ring fingers on the top ring. When grasping the scissors, placing the handles at the medial phalanges of the fingers provides better scissoring [1].

In this research, we specifically study the mechanics and analysis of hairdressing scissors because they are the most used scissors in our daily life. Scissoring involves the overall movement of the arm, including not only the fingers but also the wrist, elbow, and shoulder. However, in hairdressing, most of the motion involves cutting along a straight line, which can be performed without substantial motion of wrist, elbow, and shoulder [2]. Thus, we limit our focus to hand motions.

B. ERGONOMIC DESIGN HANDLE

When evaluating the usability of a tool, an ergonomic design is an important factor to be considered since the goal of ergonomic design is to make tools more comfortable for users during prolonged use and prevent injuries caused by repetitive motion [3], [4], [5]. When evaluating the ergonomic characteristics of scissors, the most important characteristic is the design of the handle. Table I describes

TABLE I
THREE TYPES OF HAIRDRESSING SCISSORS AND THEIR CHARACTERISTICS

Type	Appearance	Characteristic
Classic handle		Both handles line up Minimal ergonomics
Offset handle		Handles do not align Popular ergonomics
Crane handle		Thumb handle is angled downwards Best ergonomics

the three most common types of hairdressing scissors, their appearance and characteristic.

The basic characteristic of the classic handle is that handles are placed in opposite directions with respect to the center line of the pivot and are symmetrical. Compared to the other handles, the distance from the pivot to the thumb handle is the farthest, resulting in the longest and most powerful movement of the upper blade. On the other hand, it also tends to strain the thumb and causes unnecessary tension in the shoulder muscles due to the elevated elbow. For these reasons, the classic handle is evaluated as the least ergonomic [3].

The offset handle scissor is the most popular hairdressing scissor that reflects the ergonomic design. The distance from the pivot to the thumb handle is shorter compared to the classic handle. Therefore, the thumb handle is not aligned with another handle. The offset handle is evaluated as providing a relaxed and natural handling experience because it allows the thumb to move more in an orbital motion [4], [5].

The crane handle scissor is an exaggerated version of the offset handle scissor. The distance from the pivot to the thumb handle is shorter than that of the offset handle. Therefore, the thumb handle is moved further inward toward the pivot. This handle design was evaluated to relieve the burden on the hand, wrist, arm, and shoulder [5], [6], [7].

Overall, the contact point between the finger and the handle when grasping scissors differs for each type of handle. Specifically, the displacement from the pivot to the contact point for the thumb becomes shorter from the classic handle to the crane handle. Different contact points result in different finger force distribution and different rotational kinetic energy consumption for the same scissoring. As a results, the contact point can be used an important factor in the ergonomic design and analysis of scissor handles.

Since there is no significant movement of the arm from the wrist to shoulder, it is noteworthy that the ergonomic design for hairdressing scissors is mostly reflected in the handle. Therefore, the tendency of finger forces can vary depending on the type of design.

II. ANALYSIS OF FINGER FORCE IN SCISSORING

In this section, the finger forces generated at the contact points are interpreted when performing natural scissoring. The purpose of this interpretation is to analyze the tendency of the finger forces during scissoring.

As mentioned before, our focus is on the motion of hands during scissoring. Specifically, we will consider the finger forces acting on the scissors and study how they can be used to quantitatively evaluate the degree of ergonomic design for each type of scissors. Thus, the degrees of freedom (DOF) of the scissor can be considered as two. However, in general, there are four fingers in contact with the scissor during scissoring, resulting in force redundancy. Therefore, without any additional conditions, the required finger force cannot be found determined based solely on finger motion for scissoring. In the next section, we will attempt to identify the additional constraints through the measurement of the finger forces during the actual performance of individuals while scissoring.

In order to analyze the scissoring, we conducted an experiment. The scissoring can be divided into two distinct stages of action: opening and closing, according to the movement of the fingers shown in Fig. 1. During the opening action, the thumb pushes the bottom ring outward, and the contact point is located on the underside of the bottom ring. During the closing action, the thumb pushes the bottom ring inward, and the contact point is located on the topside of the bottom ring. Therefore, depending on the action, the contact point changes, as does the direction of thumb force. In case of the top ring, the three fingers – index, middle, and ring fingers – contact the handle, and unlike the thumb, the contact points and directions of each finger force do not change depending on the action. Specifically, index finger pushes the top ring outward, and the ring and index fingers push the handle inward.

Based on these observations, we attached force-sensitive resistors [8] to the surfaces of the contact positions as shown in Fig. 2. It was also observed from the experiment that there are peculiarities in finger behavior. First, there is an antagonistic finger force between the index, middle, and ring fingers. When the opening action is performed, intuitively, the middle finger force is required to rotate the lower blade,

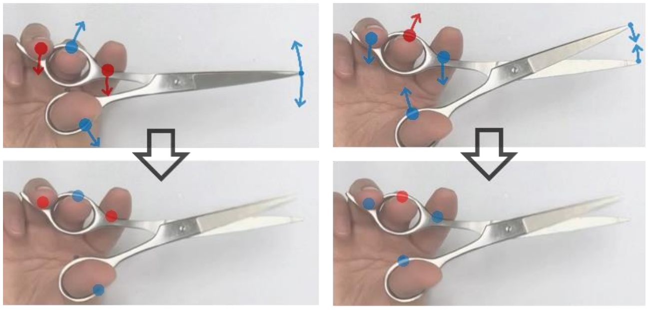

FIGURE 1 (left) opening action, (right) closing action. The contact points are marked in circles. The blue arrow indicates the direction of movement according to each action and the red arrow indicates the direction of the antagonistic movement contrary to the actions.

FIGURE 2 The force sensitive resistors are attached to the contact points on the scissor handle.

as indicated by the blue arrow. However, the index and ring fingers continue to make contact and exert forces on the handle. At this time, the forces exerted by the index and ring fingers expressed as the red arrow, act as a kind of antagonistic finger force contrary to the opening action. Similarly, when the closing action is performed, the index and ring fingers forces are required to rotate the lower blade, as indicated by the blue arrow. However, the middle finger continues to contact and exerts force on the handle. The force exerted by the middle finger, expressed as the red arrow, acts as antagonistic finger force contrary to the closing action.

Next, it was also observed from the experiment that the gravity compensation for scissoring is mostly contributed by the middle finger. This is because the thumb cannot exert a force opposite to the gravity field during the opening action. Similarly, the index and ring fingers also cannot contribute to gravity compensation because they can only exert downward force.

Based on the tendencies observed in scissoring, the total of forces in the y-axis direction for index, middle, and ring fingers involved in the actions of the lower blade are considered in the equation as follows:

$$\sum f_{iy} = 0, \quad i = 2, 3, 4 \tag{1}$$

where, f_{iy} are expressed as the y-component of the force for the i-th finger (index, middle, and ring fingers are indicated as 2, 3, and 4). When performing scissoring, only the middle finger plays the role of supporting the lower blade against gravity. Thus, the respective equations of motion can be presented as follows:

$$\mathbf{F}_3 = -\mathbf{F}_\mathrm{g} \tag{2}$$

where, $\mathbf{F}_3$ is the middle finger force and $\mathbf{F}_\mathrm{g}$ is the gravity force. Equations (1) and (2) are utilized to calculate the finger force required for scissoring.

III. SCISSOR MECHANICS

In this section, the equations of motion for the scissor are presented. These equations of motion cannot be solved without additional constraints due to the aforementioned force redundancy. As additional constraints, first, a load distribution scheme is proposed based on the observations made through the above-mentioned experiment. Secondly, we assume that the energy consumption is minimized during scissoring. Since we ignore the translational motion of the scissor, we propose that the rotational kinetic energy of the scissor (i.e., both blades) should be minimized during the scissoring.

A. DYNAMICS MODEL OF SCISSOR

As mentioned above, we largely ignore the translational motion of the scissor; thus, we assume that the pivot of the scissor remains fixed and both blades rotate about the pivot. The coordinate system used in the model is shown in Fig. 3. The origin is located at pivot, and the x-axis is along the common centerline of the blades when the scissor is closed. For simplicity, we assume that the scissor remains roughly horizontal during scissoring, so the x-axis is perpendicular to gravity, and the y-axis is in the opposite direction of gravity.

Fig. 4(a) shows the forces acting on the upper blade. ${}^\mathrm{u}\mathbf{F}_\mathrm{r}$ is the force from the pivot, ${}^\mathrm{u}\mathbf{F}_\mathrm{g}$ is the gravity, $\mathbf{F}_1$ is the force from thumb. Therefore, the equation of motion for the upper blade is as follows:

$${}^\mathrm{u}\mathbf{F}_\mathrm{r} + \mathbf{F}_1 + {}^\mathrm{u}\mathbf{F}_\mathrm{g} = \mathrm{m_u}\mathbf{a}_\mathrm{u} \tag{3}$$

or in components:

$$\begin{aligned} {}^\mathrm{u}f_\mathrm{rx} + f_\mathrm{1x} &= \mathrm{m_u} g \sin\theta_\mathrm{u} \\ &\quad + \mathrm{m_u}\, {}^\mathrm{u}r_\mathrm{g}(\alpha_\mathrm{u} \sin {}^\mathrm{u}\theta_\mathrm{g} + \omega_\mathrm{u}^2 \cos {}^\mathrm{u}\theta_\mathrm{g}) \end{aligned} \tag{4}$$

$$\begin{aligned} {}^\mathrm{u}f_\mathrm{ry} + f_\mathrm{1y} &= \mathrm{m_u} g \cos\theta_\mathrm{u} \\ &\quad + m_\mathrm{u}\, {}^\mathrm{u}r_\mathrm{g}(-\alpha_\mathrm{u} \cos {}^\mathrm{u}\theta_\mathrm{g} + \omega_\mathrm{u}^2 \sin {}^\mathrm{u}\theta_\mathrm{g}). \end{aligned} \tag{5}$$

The moment equation is:

$$\mathbf{r}_1 \times \mathbf{F}_1 + {}^u\mathbf{r}_\mathrm{g} \times {}^u\mathbf{F}_\mathrm{g} + {}^u\boldsymbol{\tau}_\mathrm{f} = \mathbf{I}_\mathrm{u}\boldsymbol{\alpha}_\mathrm{u} \tag{6}$$

or in components:

$$\begin{aligned} f_\mathrm{1y} r_\mathrm{1x} - f_\mathrm{1x} r_\mathrm{1y} &= \mathrm{m_u} g \cos\theta_\mathrm{u}\, {}^\mathrm{u}r_\mathrm{gx} \\ &\quad - \mathrm{m_u} g \sin\theta_\mathrm{u}\, {}^\mathrm{u}r_\mathrm{gy} \\ &\quad - {}^\mathrm{u}\tau_\mathrm{f} + I_\mathrm{u}\alpha_\mathrm{u} \end{aligned} \tag{7}$$

where, $\mathbf{r}_1$ and ${}^\mathrm{u}\mathbf{r}_\mathrm{g}$ are the positions of the thumb and the center of mass from the pivot, respectively. Table II describes the detailed nomenclature of variables.

Fig. 4(b) shows forces acting on the lower blade. ${}^\mathrm{l}\mathbf{F}_\mathrm{r}$ is the force from the pivot, ${}^\mathrm{l}\mathbf{F}_\mathrm{g}$ is the gravity, $\mathbf{F}_2$, $\mathbf{F}_3$, and $\mathbf{F}_4$ are the forces from the index, middle and ring fingers,

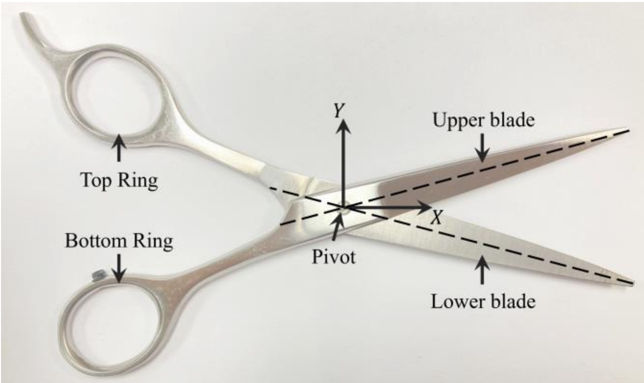

FIGURE 3 Coordinate system used for modeling the scissor.

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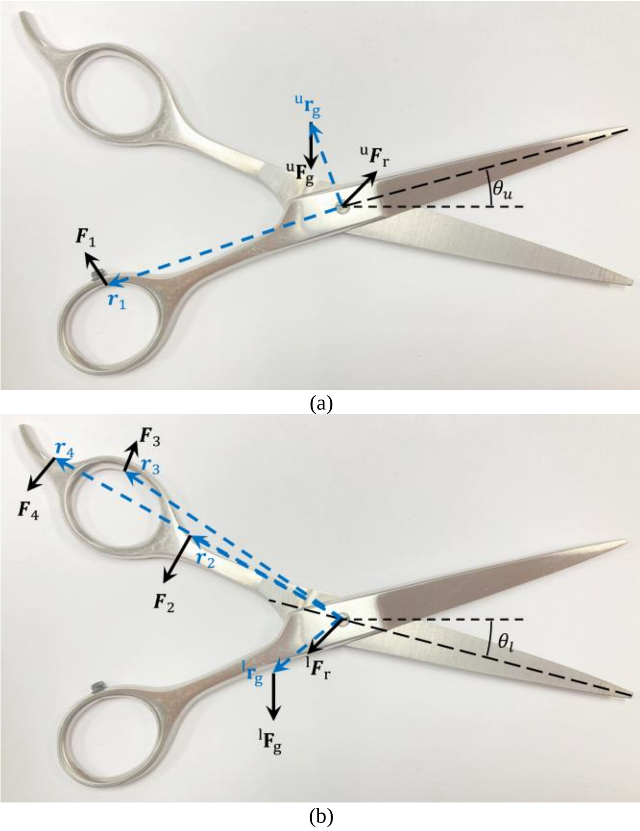

FIGURE 4 (a) Forces acting on the upper blade and (b) Forces acting on the lower blade.

respectively. The equation of motion of the lower blade is as follows:

$$ {}^{1}\mathbf{F}_r+\mathbf{F}_2+\mathbf{F}_3+\mathbf{F}_4+{}^{1}\mathbf{F}_g=m_l\mathbf{a}_l \tag{8}$$

or in components:

$$\begin{aligned}&-{}^{1}f_{rx}\cos(\theta_u-\theta_l)+{}^{1}f_{ry}\sin(\theta_u-\theta_l)\\&+f_{2x}+f_{3x}+f_{4x}=m_l g\sin\theta_l\\&+m_l\,{}^{1}r_g(-\alpha_l\sin{}^{1}\theta_g+\omega_l^2\cos{}^{1}\theta_g)\end{aligned} \tag{9}$$

$$\begin{aligned}&-{}^{1}f_{rx}\sin(\theta_u-\theta_l)-{}^{1}f_{ry}\cos(\theta_u-\theta_l)\\&+f_{2y}+f_{3y}+f_{4y}=m_l g\cos\theta_l\\&+m_l\,{}^{1}r_g(-\alpha_l\cos{}^{1}\theta_g-\omega_l^2\sin{}^{1}\theta_g).\end{aligned} \tag{10}$$

The moment equation is:

$$\mathbf{r}_2\times\mathbf{F}_2+\mathbf{r}_3\times\mathbf{F}_3+\mathbf{r}_4\times\mathbf{F}_4+{}^{1}\mathbf{r}_g\times{}^{1}\mathbf{F}_g+{}^{l}\boldsymbol{\tau}_f=\mathbf{I}_l\boldsymbol{\alpha}_l \tag{11}$$

or in components:

$$\begin{aligned}&f_{2y}r_{2x}-f_{2x}r_{2y}+f_{3y}r_{3x}-f_{3x}r_{3y}+f_{4y}r_{4x}-f_{4x}r_{4y}\\&=-m_l g\cos\theta_l\,{}^{1}r_{gx}-m_l g\sin\theta_l\,{}^{1}r_{gy}-{}^{1}\tau_f+I_l\alpha_l\end{aligned} \tag{12}$$

where, $\mathbf{r}_2$, $\mathbf{r}_3$, and $\mathbf{r}_4$ are the positions of the index, middle and ring fingers, respectively. ${}^{1}\mathbf{r}_g$ is the position of the center of mass.

Looking at the overall equations of the total force and moment of scissoring, the number of force variables is ten, including the two components of the pivot force and the eight components of the four finger forces, while the number of force and moment equations is six (4), (5), (7), (9), (10), and (12). Therefore, there is force redundancy as mentioned above, and to solve this redundancy, we need additional constraints. In the following subsection, we present a way to resolve the force redundancy.

B. RESOLVING THE FORCE REDUNDANCY

To resolve the force redundancy, we should incorporate equations (1) and (2) observed from Section II. (1) implies the antagonistic tendency between the forces from index, middle, and ring fingers and (2) implies that the middle finger supporting the gravity (2). These additional constraints provide us with three more equations, which can be organized as a linear equation as follows:

$$\mathbf{AF}=\mathbf{B} \tag{13}$$

where $\mathbf{F}$ denotes the force exerted on the scissors. The components of $\mathbf{A}$, $\mathbf{F}$ and $\mathbf{B}$ can be referenced in the appendix. Therefore, we have nine equations and ten variables (refer to Appendix), meaning we still need additional condition to obtain a unique solution. This is a typical force redundant system [9-13]. One way to solve this problem is pseudoinverse solution. However, it does not guarantee the signs of the finger forces. To resolve this, we assume that the users tend to minimize the finger forces during scissoring.

Additionally, as observed in Section II, the directions of the forces from the index, middle, and ring fingers point in (roughly) opposite directions during the opening and closing actions. These can be presented as inequality constraints and thus cannot be solved by referencing the pseudoinverse. Therefore, we formulate this as a constrained optimization problem as follows:

$$\begin{aligned}&\text{minimize}\quad \mathbf{F}^{T}\mathbf{F},\\&\text{subject to}\quad f_{2y}<0,\quad f_{3y}>0,\quad f_{4y}<0,\quad \mathbf{AF}=\mathbf{B}\end{aligned}$$

TABLE II
NOMENCLATURE OF VARIABLES

Variable	Description
m_u, m_l	Mass of the upper and lower blade
$\mathbf{a}_u$, $\mathbf{a}_l$	Linear acceleration of the upper and lower blade
θ_u, θ_l	Orientation of the upper and lower blade
α_u, α_l	Angular acceleration of the upper and lower blade
${}^{u}\theta_g$, ${}^{1}\theta_g$	Angle between position of the center of mass and the *x*-axis
ω_u, ω_l	Angular velocity of the upper and lower blade
${}^{u}\tau_f$, ${}^{1}\tau_f$	Friction torque acting on the upper blade and lower blade
$\mathbf{I}_u$, $\mathbf{I}_l$	Moment of inertia of the upper and lower blade

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where, $\mathbf{F}^{\mathrm{T}}\mathbf{F}$ is the objective function to be minimized.

C. QUANTITATIVE EVALUATION CRITERION

The power generated by the finger can be calculated as:

$$\mathbf{P}_{\mathrm{i}} = \boldsymbol{\tau}_{\mathrm{i}} \cdot \omega = (\mathbf{r}_{\mathrm{i}} \times \mathbf{F}_{\mathrm{i}}) \cdot \omega \quad (14)$$

where $\mathbf{P}_i$ and $\boldsymbol{\tau}_{\mathbf{i}}$ are the power and torque generated by the *i*-th finger, respectively and ω is the angular velocity of the blade. During the overall scissoring, the rotational kinetic energy consumption by the blade is equal to the integral of the instantaneous power generated by the finger force. Referring to (14), the rotational kinetic energy consumption of the three type scissors – classic, offset, and crane – introduced in Table I, will be calculated in the following simulation section. The results of the energy consumption with and without the ergonomic design will be presented.

IV. ANALYSIS OF SCISSOR DESIGN BASED ON QUANTITATIVE CRITERION

In this section, the rotational kinetic energy required to perform the overall scissoring is computed and compared for the three types of scissors utilizing a dynamic simulation. The qualitative evaluation result, commonly known as comfort, will be verified by comparing the energy, which is proposed as the quantitative evaluation criterion for the ergonomically designed scissors.

Fig. 5 shows the velocity profiles of the upper and lower blades. Based on experimental observations of scissoring, a single scissoring cycle is set to take 2 seconds. The opening action is set from 0 to 1 seconds, and the closing action is set from 1 to 2 seconds. During scissoring, the three fingers try to grip and maintain the scissor, while the thumb tries to mobilize the scissor in abduction and adduction [2], [14]. To reflect this, the upper blade, where the thumb is located, undergoes relatively larger motion compared to the lower blade.

The velocity profiles of the blades are utilized as input to the optimization problem. Then, the finger force calculated in the dynamic simulation environment is obtained as the output from the optimization problem, as derived in Sec III.

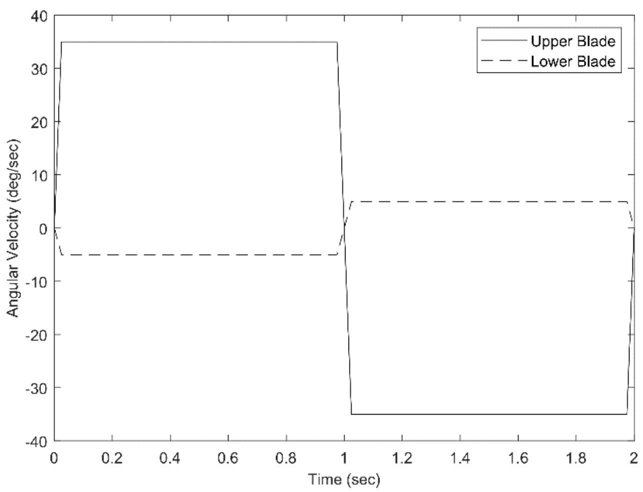

FIGURE 5 Velocity profile of the upper and lower blades. During the opening action, the upper blade and lower blade move at the speed of 35°/s and -5°/s, respectively. During the closing action, the blades are set to move in the opposite direction of the opening action.

TABLE III
PHYSICAL PROPERTIES FOR EACH SCISSOR

Physical Property			Classic	Offset	Crane
			Handle type		
Mass, m (g)		Upper blade	22.3	24.4	24.7
		Lower blade	23.4	30.0	30.2
Distance to center of mass, r_g (mm)		Upper blade	3.2	8.6	8.6
		Lower blade	3.6	9.5	10.2
Angle to center of mass, θ_g (°)		Upper blade	108	144	135
		Lower blade	-124	-162	-169
Length (mm)		Upper blade	165	145	135
		Lower blade	170	175	165
Contact point (mm)	Thumb, r_1	Opening	70	62	58
		Closing	65	59	54
	Index, r_2		45	47	47
	Middle, r_3		68	71	70
	Ring, r_4		85	84	85

The parameters listed in Table III are the physical properties for the three types of scissors and have been directly measured. The distances and angles are measured relative to the coordinate system. The friction torque exerted on each blade between the upper and lower blades during scissoring is adopted from other research outputs [15]. We ignore the friction between the finger and the handle at the contact point, so we assume that the finger force is perpendicular to the contact point.

A single cycle of scissoring was applied. Table IV summarizes the rotational kinetic energy consumption for each type of scissor handle and action. According to Table IV, when performing the scissoring, the energy consumption was 32.1 % less when using the crane handle scissor compared to using the classic handle scissor. Using ergonomic scissors, such as the offset and crane handle, reduces energy consumption by 10.4 *j* and 16.7 *j*,

TABLE IV
ROTATIONAL KINETIC ENERGY CONSUMPTION FOR EACH TYPE OF SCISSOR

Action	Handle type: Classic	Offset	Crane
Opening	24.27 (*j*)	20.60 (*j*)	17.44 (*j*)
Closing	27.70 (*j*)	20.98 (*j*)	17.84 (*j*)
Total	51.97 (*j*)	41.58 (*j*)	35.28 (*j*)

respectively, compared to using the classic handle. Based on the comparison of energy consumption, we can conclude that the qualitative evaluation for the ergonomic design is validated.

Although we validate the ergonomic design using the consumption of rotational kinetic energy, there are other factors to consider regarding ergonomics, including shoulder width, arm pose, etc. However, it is important to note that our application is confined to the hairdressing context, in which the contribution of human posture including the shoulder and elbow is negligible.

V. CONCLUSION

Types of hairdressing scissors have evolved. This paper aims to validate the effectiveness of ergonomically designed scissors in a quantitative manner, in contrast to previous qualitative analyses.

Three different types of hairdressing scissors with different ergonomic designs are employed for comparison. The major contributions of this paper are as allows:

1) Proposition of scissor mechanics for the first time.

2) Discovery of the nature of antagonistic forces among the three fingers (index, middle, and ring fingers).

3) Proposition of a corresponding load distribution scheme.

4) Validation of the effectiveness of ergonomic scissor design through an evaluation index, specifically the rotational kinetic energy consumption.

As for future work, the results of this study can be directly applied to robotic scissoring. Developing mechanics for handling various types of tools with the human hand is another research area.

APPENDIX

A. MATRICES OF THE TOTAL FORCES AND MOMENTS OF THE SCISSORING

$$
\mathbf{A}=\begin{bmatrix}
+1 & 0 & +1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & +1 & 0 & +1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & -r_{1y} & +r_{1x} & 0 & 0 & 0 & 0 & 0 & 0\\
-\cos(\theta_u-\theta_l) & +\sin(\theta_u-\theta_l) & 0 & 0 & +1 & 0 & +1 & 0 & +1 & 0\\
-\sin(\theta_u-\theta_l) & -\cos(\theta_u-\theta_l) & 0 & 0 & 0 & +1 & 0 & +1 & 0 & +1\\
0 & 0 & 0 & 0 & -r_{2y} & +r_{2x} & -r_{3y} & +r_{3x} & -r_{4y} & +r_{4x}\\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1\\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0
\end{bmatrix}
$$

$$
\mathbf{F}=\begin{bmatrix}+f_{rx} & +f_{ry} & +f_{1x} & +f_{1y} & +f_{2x} & +f_{2y} & +f_{3x} & +f_{3y} & +f_{4x} & +f_{4y}\end{bmatrix}^{\mathrm{T}}
$$

$$
\mathbf{B}=\begin{bmatrix}
+\mathrm{m_u} g\sin\theta_{\mathrm{u}} + \mathrm{m_u}\,{}^{\mathrm{u}}r_{\mathrm{g}}(\alpha_{\mathrm{u}}\sin{}^{\mathrm{u}}\theta_{\mathrm{g}} + \omega_{\mathrm{u}}^2\cos{}^{\mathrm{u}}\theta_{\mathrm{g}})\\
+\mathrm{m_u} g\cos\theta_{\mathrm{u}} + \mathrm{m_u}\,{}^{\mathrm{u}}r_{\mathrm{g}}(-\alpha_{\mathrm{u}}\cos{}^{\mathrm{u}}\theta_{\mathrm{g}} + \omega_{\mathrm{u}}^2\sin{}^{\mathrm{u}}\theta_{\mathrm{g}})\\
+\mathrm{m_u} g\cos\theta_{\mathrm{u}}\,{}^{\mathrm{u}}r_{\mathrm{gx}} - \mathrm{m_u} g\sin\theta_{\mathrm{u}}\,{}^{\mathrm{u}}r_{\mathrm{gy}} - {}^{\mathrm{u}}\tau_{\mathrm{f}} + \mathrm{I_u}\alpha_{\mathrm{u}}\\
+\mathrm{m_l}\mathrm{g}\sin\theta_{\mathrm{l}} + \mathrm{m_l}\,{}^{\mathrm{l}}r_{\mathrm{g}}(-\alpha_{\mathrm{l}}\sin{}^{\mathrm{l}}\theta_{\mathrm{g}} + \omega_{\mathrm{l}}^2\cos{}^{\mathrm{l}}\theta_{\mathrm{g}})\\
+\mathrm{m_l}\mathrm{g}\cos\theta_{\mathrm{l}} + \mathrm{m_l}\,{}^{\mathrm{l}}r_{\mathrm{g}}(-\alpha_{\mathrm{l}}\cos{}^{\mathrm{l}}\theta_{\mathrm{g}} - \omega_{\mathrm{l}}^2\sin{}^{\mathrm{l}}\theta_{\mathrm{g}})\\
-\mathrm{m_l} g\cos\theta_{\mathrm{l}}\,{}^{\mathrm{l}}r_{\mathrm{gx}} - \mathrm{m_l} g\sin\theta_{\mathrm{l}}\,{}^{\mathrm{l}}r_{\mathrm{gy}} - {}^{\mathrm{l}}\tau_{\mathrm{f}} + \mathrm{I_l}\alpha_{\mathrm{l}}\\
0\\
\mathrm{m_u} g\sin\theta_{\mathrm{u}} + \mathrm{m_l}\mathrm{g}\sin\theta_{\mathrm{l}}\\
\mathrm{m_u} g\cos\theta_{\mathrm{u}} + \mathrm{m_l}\mathrm{g}\cos\theta_{\mathrm{l}}
\end{bmatrix}
$$

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