Analysis of upper-limb movements to open glass ampoules and training methods in nursing education

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Abstract

An ampoule is a glass cylinder that contains intravenous solutions. Ampoule opening (AO) is performed by nurses on a daily basis, but the procedure involved can cause injuries to the hand as well as contamination of ampoule contents with glass microparticles. As it is currently impossible to completely eliminate the use of glass ampoules, one should learn how to safely perform the AO operation. Herein, we quantitatively analyze the combined seven upper-limb movements of ten experienced participants to clarify the mechanism of AO operations and establish a procedure for safe AO. Unlike current instruction manuals, this study focuses on the joint movements of dominant and nondominant upper limbs rather than on finger positions. A motion-capture system and video cameras are used to analyze the above seven movements of each upper limb. Based on results obtained, the following three guidelines for performing AO operations are derived: (1) supinate the elbow joint to break the ampoule neck; (2) move the dominant hand away from the cutting plane of the ampoule immediately after ampoule breaking without moving the nondominant hand to avoid unnecessary contact of fingers with the cutting plane; (3) synchronize elbow-joint extension with supination in step (1) as the dominant hand is moved away after ampoule breaking. This approach not only ensures safe AO but also helps in learning other skills related to technical nursing education.

Keywords: Ampoule, Ampoule opening, Motion analysis, Upper limb, Nursing skill, Nursing education

1. Introduction

Nurses need to master various skills to provide safe and high-quality healthcare services, and instructing beginners to attain these skills is a necessary part of providing technical nursing education. However, capturing all the actions of a skilled nurse or mimicking them precisely is not easy for beginners. For example, most beginners learning the
Skill of delivering injections tend to focus only on a limited part of the operation, such as how to handle the syringe, which is insufficient to replicate the overall action sequence. In addition, educators often face difficulties in providing verbal explanations for their actions, because their own skills have often been acquired through practice. Therefore, technical nursing education, at present, does not include instructional methods that include rational verbal explanations for implementation of safety techniques. Current techniques for educating beginners may, in the long run, result in learning that is fraught with poor techniques and safety issues, which in turn, may culminate into bad habits. A revival of the present technical nursing education, based on measurement and analysis by scientific means, is, therefore, essential for the training of future nursing staff.

To establish a working model of a certain medical technique, it is appropriate to analyze the motion of individuals using the engineering approach. At present, in the field of nursing, much attention is directed at the study of motions involved in patient moving, provision of transportation assistance to wheelchair patients, blood collection, etc. Although some of the corresponding investigations used a three-dimensional motion-analysis system or an electromyograph (Tamaru et al., 2011; Noto and Muraki, 2014; Maekawa et al., 2014; Aoki et al., 2015), some of them captured the actual situation of motion under different conditions, revealing that simple application to education is not sufficient. Notably, the teaching of safe and rational movement techniques can be incorporated into the education program not only through the analysis of human movement from the viewpoint of engineering but also through the use of quantitative motion analysis for explanatory purposes.

The proposed study focuses on the task of ampoule opening (AO) performed by nurses on a daily basis. An ampoule is a cylindrical glass container for intravenous solutions and comprises three parts—head, neck, and body. Ampoules currently used in medical settings include those of the “one-point cut” type, as depicted in Fig. 1. The head is marked with a dot (point mark) to identify the direction in which the neck of the ampoule is to be pressed. A notch in the neck just below the point mark makes the ampoule easy to open. The neck is to be broken by hand to access the intravenous solution contained inside; this sequence of operations is referred to as ampoule-opening.

Fig. 1 Parts of “one-point cut” ampoule.

AO may cause injuries to fingers and hands of the opener during neck breaking, dispersal of glass microparticles and contamination of ampoule contents. Finger and hand injuries can be painful for medical staff whilst also increasing the risk of secondary infections in patients when bacteria adhering to fingers and hands of medical staff are introduced into ampoule contents (Carraretto et al., 2011; Parker, 1995). Additionally, scattering of glass fragments poses a risk of organ damage in patients if these fragments enter the ampoule contents (Yamaoka et al., 1976; Katz et al., 1973; Pinnock, 1984; Carbone-Traber et al., 1986; Sabon et al., 1989; Giambrone, 1991). Although such injuries and contamination risks have previously been reported, no fundamental solution to the problem has yet been proposed.

Presently, all ampoules need to be opened by hand, and the development and use of instruments for AO (Yokota et al., 2001; Liu et al., 2012) are not widespread owing to issues associated with hygiene control. Although glass poses a higher injury risk compared to plastic, plastic ampoules are costlier and pose difficulties in terms of long-term storage of medicines. Consequently, a majority of ampoules used in Japan are made of glass. As long as this remains the case, it will be difficult to completely eliminate the risks associated with hand injuries and dispersal of glass fragments. Therefore, an understanding of the safe handling and opening becomes all-the-more important.

Quantitative measurements and analysis pertaining to AO have been performed in this study to determine a practical approach toward the development of a solution to the above problem. Instructions to perform ampoule breaking by hand have been included in textbooks related to nursing skills and procedures designed by pharmaceutical companies (e.g.,
Otsuka Pharmaceutical Co., Ltd., 2015). The said instructions mainly focus on describing the direction in which the ampoule neck must be pressed and proper positioning of one’s fingers. The AO operation, however, mainly involves movement of the wrist, elbow, and shoulder joints, rather than fingers, because fingers of the dominant hand holding the ampoule head do not move. Additionally, although some textbooks contain instructions such as “Open so as to draw an arc from the front to the back” and “Apply force and bend backward quickly” (Kajitani and Kadohama, 2015; Uetani et al., 2005), these expressions are perceived as imprecise by many people. Notably, even though the task of ampoule neck opening by hand is seemingly simple and easy, the joints of the upper limb have seven degrees of freedom, and the moving upper limb itself also has numerous degrees of freedom (Rosenbaum, 2010). In other words, the above instructions are difficult to mimic correctly unless precise guidance on joint movements corresponding to the desired motion is provided. As only few studies have analyzed AO in detail, the first step is to clarify the mechanism of AO operations and derive guidance points for ensuring safe AO by focusing on the upper limb movements of a person accustomed to AO, i.e., by indicating what function is associated with AO operations, which joint movements correspond to this function, and which combination of joint movements is the best. Clarification of these aspects allows the important points in AO operation to be compared between beginners and skilled persons and establishes a basis for finding solutions of the original problems in the future. AO features the combined movements of left and right upper limbs and comprises basic actions common to various movements. Therefore, the findings of this study can contribute to not only safe AO but also to the analysis of various other nursing skills.

This study focuses on the joint motion of the dominant and nondominant upper limbs—between the palms and shoulders—with the purpose of clarifying the mechanism of AO operations and determining the procedure for ensuring safe AO by quantitatively analyzing the seven upper-limb-joint movements of experienced participants. Ten participants experienced with AO signed up in this study. The participants were assumed to have mastered safe and efficient AO. Based on this assumption, elements common and different to the actions of these experienced participants were extracted. Participant actions were measured using a real-time optical three-dimensional motion-analysis system (MAC 3D System, Motion Analysis Corporation, Santa Rosa, CA, USA) capable of recording three-dimensional coordinates of markers attached to the upper limbs with sufficient temporal and spatial resolutions. This facilitated the capturing of AO actions, which occur almost instantaneously. Transitions in the seven joint angles representing motions of the dominant and nondominant upper limbs were calculated based on measurements performed by the motion-capture system and corresponding results were used to analyze upper-limb motions.

The remainder of this paper is organized as follows. Section 2 describes joint angles subjected to analysis as well as positions of reflective markers attached to upper limbs. Section 3 describes the experimental environment and methods to process measurement data. Section 4 discusses experimental results, which are subsequently used in Section 5 to discuss common movements and differences between motions of experienced participants. Findings of this study were then used to deduce the procedure for ensuring safe AO. The appendix section presents the method used for analyzing the seven joint-angle types from the reflective-marker positions.

2. Upper-limb joint angles
2.1. Analysis of target motions

Within the normal range of motion, the shoulder joint governs the movement of upper arms back and forth, laterally up and down, and horizontally away from or toward the midline of the body—(i.e., extension/flexion, abduction/adduction, and horizontal extension/flexion). It also facilitates external and internal rotations of the upper arm. The range of motion of the elbow joint allows it to rotate the forearm outward and inward (i.e., supination/pronation) and flex or extend the forearm (i.e., flexion/extension). The wrist joint facilitates back and forth movement of the palm whilst also allowing it to move in the direction of the little finger or thumb (i.e., dorsiflexion/palmar flexion and ulnar deviation/radial deviation).

Although all of the above-mentioned movements have two names, as they are usually distinguished by the direction of motion, they can be represented by a single angle. Additionally, although the extension/flexion and abduction/adduction movements of the shoulder joint can be distinguished anatomically, no generality is lost even if the extension and adduction and flexion and abduction movements are considered identical in our calculations (i.e., extension and abduction/flexion and abduction). The shoulder, elbow, and wrist joints can, therefore, be considered capable of performing seven movements, as depicted in Fig. 2.

Temporal transitions of the seven above-described joint angles representing movements of the dominant and nondominant upper limbs were calculated in terms of the following variables.
Here, $\theta_D$ refers to the dominant hand, while $\theta_N$ refers to the nondominant hand.

### 2.2. Calculation formulae

In this study, reflective markers were attached to the participants at 22 positions—11 each on the left and right shoulders, arms, and hands. Fig. 3 depicts these positions of reflective markers on the left and right hands. Measurements at these positions were performed by means of a motion-capture system. Methods for calculating the seven joint-angle types on the right hand at the said marked positions have been described in the appendix.

![Fig. 2 Seven movements of shoulder, elbow, and wrist joints.](image)

![Fig. 3 Positions of attached reflective markers.](image)
3. Experiment
3.1. Participants and experimental environment

Ten individuals having prior AO experience and over three years of general clinical experience participated in this study, with their physical attributes listed in Table 1.

The participants included 5 males aged \((35 \pm 3.4)\) years, \((175.6 \pm 5.5)\)-cm tall, and weighing \((66.6 \pm 10.0)\) kg (mean ± SD) and 5 females aged \((38.6 \pm 5.0)\) years, \((158 \pm 6.9)\)-cm tall, weighing \((50.2 \pm 5.2)\) kg (mean ± SD). All participants were right-handed. The experimental procedures were approved by the Institutional Ethics Committee of Mukogawa Women’s University, Japan (Reference No. 16-39).

Ampoules of 5-mL capacity were used in this study, and the ampoules were customized to record—the time at which their neck was broken. Action sequences based on this point were compared among participants. Specifically, the above-mentioned customization involved vertically binding the top of the ampoule head to a stick measuring approximately 6 cm in length, as depicted in Fig. 4. Rapid movement of the stick signaled the precise moment at which the ampoule neck was broken by a participant.

The AO operation was recorded using a motion-capture system and five video cameras; the overall setup is depicted in Fig. 5. The motion-capture system comprised 12 infrared cameras mounted at different locations on a square ceiling, and positions of reflective markers attached to each participant were determined at 200 fps. The said positions of reflective markers were represented by dots depicted in Fig. 3. Video cameras were placed in front, to the left and right of, as well as on the ceiling facing the participants to facilitate continuous capturing of AO operation. Under these conditions, each participant performed five consecutive AO actions, each of which was performed in the standing position under the assumption of that being the usual practice.

Table 1  Body parameters of all participants and ampoule-holding types

| Participant ID | Sex | Height (cm) | Weight (kg) | Ampoule holding types |
|----------------|-----|-------------|-------------|----------------------|
| 1              | M   | 176         | 58          | a                    |
| 2              | M   | 170         | 56          | a                    |
| 3              | M   | 177         | 65          | a                    |
| 4              | M   | 170         | 70          | b                    |
| 5              | M   | 185         | 84          | c                    |
| 6              | F   | 163         | 53          | a                    |
| 7              | F   | 157         | 54          | a                    |
| 8              | F   | 162         | 51          | b                    |
| 9              | F   | 163         | 53          | a                    |
| 10             | F   | 145         | 40          | a                    |

Fig. 4  Customized ampoule with 5-mL capacity.
3.2. Data extraction and processing

AO operations performed by the ten participants were analyzed. Fifty such operations were analyzed because each participant performed AO five times. Data captured by video cameras and motion-capture system were analyzed for determining motions of the dominant and nondominant upper limbs.

Video data were observed in slow-motion replay, and the time instant immediately preceding AO performed by each participant was defined as 0.0 s. As regard motion-capture data, the time instant immediately preceding rapid acceleration over the distance between the dominant and nondominant thumbs was defined as 0.0 s. Angular displacements at each time instant were calculated; furthermore, the angular displacement of the joint angle at 0.0 s was also calculated and set as the reference value (i.e., 0°). The two datasets were displayed graphically and analyzed through visual observation.

During analysis, we first compared common movements as well as differences between motions performed by each participant, and a similar comparison was subsequently performed between different participants. In the analysis of motion-capture data of different participants, the average coordinates of five trials performed by each participant were used as representative data centered around a time of 0.0 s.

4. Results

4.1. Video data

Video data recorded in this study revealed a series of AO actions, as depicted in Fig. 6. All participants initially held the ampoule body in the nondominant hand to ensure that the dot (point mark) on the ampoule head remained in front. Subsequently, the participants held the ampoule head in the dominant hand, to ensure that the thumb covered part or all of the point mark. They then opened the ampoule by applying pressure at the ampoule neck. Approximately 0.2 s after ampoule breaking, the participants moved the dominant hand—holding the broken ampoule head—a safe distance away from the cutting plane of the broken ampoule body. Soon thereafter, the above-described dominant-hand motion was slowed down. Within approximately 0.3 s of performing this action, the participants, once again, moved their dominant hand toward the midline of their body to perform the action of discarding the broken ampoule. Based on these observations, the analysis time of the video and motion-capture data was set between -0.2 s and 0.2 s by setting the time instant immediately preceding ampoule breaking as 0.0 s.

Further, by observing the AO action in detail, common movements and differences among participants were identified. For the first observation, the participants held the ampoule head in the dominant hand in three different ways (a, b, and c), as presented in Table 1 and Fig. 7. Seven participants held the ampoule head as per type a (Fig. 7(a)), i.e., with the ampoule head sandwiched between the thumb and the index finger, while the index, second, ring, and little fingers were bent. Two participants held the ampoule head as per type b (Fig. 7(b)), i.e., with the ampoule head between the thumb and
the index and middle fingers with the backside of the ampoule head sandwiched between the index and second fingers. Finally, one participant held the ampoule head as per type c (Fig. 7(c)), i.e., with the ampoule head sandwiched between the thumb and the index finger with the index, second, ring, and little fingers extended.

As regards the dominant hand, two motions were observed to be common in all trials performed by each participant. These include breaking of the ampoule neck and moving the dominant hand away from the cutting plane of the broken neck. On the other hand, the direction in which participants moved their dominant hand away from the cutting plane of the broken ampoule body and distance between the dominant and nondominant hands 0.2 s after ampoule breaking were observed to be different among participants.

Last, with respect to the nondominant hand, all participants, except ID2, held the ampoule body in their hands such that it barely demonstrated any movement between the time instant immediately preceding ampoule breaking and 0.2 s. In contrast, only participant ID2 moved his nondominant hand away from the broken ampoule head whilst still holding it in the dominant hand.

| Type a | Type b | Type c |
|--------|--------|--------|

Fig. 7 Ampoule-holding types.

4.2. Motion-capture data

In terms of motion-capture data, participant movements demonstrated a similar tendency during all trials. Figure 8 depicts trends in variation of $\theta_{D,Elb1}$ (elbow joint; supination/pronation) of the dominant hands of participants ID1 and ID2, the corresponding trajectory during each of the five trials, and the five-trial average. Trajectories of each participant exhibited a similar shape during all trials. Although trends concerning variation in only $\theta_{D,Elb1}$ (i.e., one of seven movements) are presented here, all dominant- and nondominant-hand movements demonstrated identical results. This was observed to be common for all participants.

Upon comparing the seven upper-limb-joint movements among participants, the following commonalities and differences were observed.

First, the only movement common to all participants was that of $\theta_{D,Elb1}$ of the dominant hand. Figure 9 depicts seven movements of the dominant hand for each participant. Further, Fig. 10 depicts movements of the nondominant hand. Each
movement corresponded to a displacement of the joint angle, which at the time instant immediately preceding ampoule breaking was set equal to the reference value (i.e., $0^\circ$). As regards $\theta_{D,Eb1}$ of the dominant hand, all participants exhibited a sudden supination of approximately $2^\circ$–$25^\circ$ on the dominant hand immediately following ampoule-neck breaking.

Second, with respect to the dominant hand, $\theta_{D,Eb2}$ (elbow joint; flexion/extension) and $\theta_{D,Sh3}$ (shoulder joint; external/internal rotation) of participants demonstrated two movement types. Figure 11 depicts these two movements with an altered scale along the y axis. The upper row of the figure denotes the H group, which demonstrates observed trends for five participants exhibiting either an exaggerated extension movement of $\theta_{D,Eb2}$ or external rotation of $\theta_{D,Sh3}$ after ampoule breaking. Likewise, the lower row of this figure denotes the L group, which demonstrates observed trends for five participants exhibiting rather small extension and external rotation. As regards $\theta_{D,Eb2}$, two participants (ID6, ID8) in the H group demonstrated extensions exceeding $4^\circ$ in conjunction with the supination observed after breaking of the ampoule neck. In contrast, all participants in group L demonstrated extensions measuring less than $4^\circ$.

Third, as regards the nondominant hand, the largest movement observed corresponded to that of $\theta_{D,Eb1}$ (elbow joint; supination/pronation) after breaking of the ampoule neck, and the same comprised two movement types (Fig. 10). All participants, except ID2, demonstrated either a small pronation or displacement of $\theta_{D,Eb1}$ measuring less than $1^\circ$. In contrast, only ID2 demonstrated supination.

Fourth, for all participants, excluding ID2, the total distance covered by the dominant hand between 0.0 s and 0.2 s approximately equaled that between the dominant and nondominant hands 0.2 s after ampoule breaking. In Fig. 12, the x-axis represents distance covered by the dominant hand while the y-axis represents the change in distance between the dominant and nondominant finger thumbs. The observed values of these variables varied in the range of 21.5–207.8 mm and 17.4–205.5 mm for each participant, respectively. The absolute errors in the determination of these variables equaled 25.1 mm for ID2 and 1.8–9.1 mm for the remaining nine participants.

Finally, participants in groups H and L exhibited the greatest and smallest distances, respectively, traversed by the dominant hand between 0.0 s to 0.2 s. Figure 12 depicts the distinction between groups H and L. Table 2 lists the presence or absence of supination, extension, and external rotation along with distance traversed by the dominant hand, which exceeded 50 mm in group H and measured less than 50 mm in group L.
### Fig. 9 Seven dominant-hand movements of each participant.

| Seven movement of the dominant hand | + displacement | - displacement |
|-----------------------------------|---------------|---------------|
| $\theta_{p,MA}$                   | extension and adduction | flexion and abduction |
| $\theta_{p,NA}$                   | horizontal flexion | horizontal extension |
| $\theta_{p,EA}$                   | external rotation | internal rotation |
| $\theta_{p,EA}$                   | Pronation | Supination |
| $\theta_{p,EA}$                   | extension | flexion |
| $\theta_{p,EA}$                   | palmar flexion | dorsiflexion |
| $\theta_{p,MA}$                   | radial deviation | ulnar deviation |

Time [s] (Point 0 corresponds to time instant immediately preceding ampoule breaking)

### Fig. 10 Seven nondominant-hand movements of each participant.

| Seven movement of the nondominant hand | + displacement | - displacement |
|---------------------------------------|---------------|---------------|
| $\theta_{n,NA}$                      | extension and adduction | flexion and abduction |
| $\theta_{n,NA}$                      | horizontal flexion | horizontal extension |
| $\theta_{n,EA}$                      | external rotation | internal rotation |
| $\theta_{n,EA}$                      | Pronation | Supination |
| $\theta_{n,EA}$                      | extension | flexion |
| $\theta_{n,EA}$                      | palmar flexion | dorsiflexion |
| $\theta_{n,NA}$                      | radial deviation | ulnar deviation |

Time [s] (Point 0 corresponds to time instant immediately preceding ampoule breaking)
Fig. 11  Trends concerning $\theta_{D,Elb}$ and $\theta_{D,Sh}$ of dominant elbow and shoulder joints, respectively; results depicted correspond to average of five trials performed by each participant (ID1, 2, ..., 10).

Fig. 12  Distance traversed by dominant hand and change in distance between dominant and nondominant thumbs. Numbers in figure indicate participant IDs; participants in groups H and L are marked in red and black, respectively.

Table 2  Presence or absence of pronation, extension, and external rotation, and distance traversed by the dominant hand.

| Participant (ID) | Group (H/L) | Supination (exceeding 2°) | Extension (exceeding 4°) | External rotation (exceeding 4°) | Distance traversed (mm) |
|-----------------|-------------|--------------------------|--------------------------|---------------------------------|------------------------|
| 1               | H           | o                        | x                        | x                               | 57.1                   |
| 2               | L           | o                        | x                        | x                               | 43.4                   |
| 3               | L           | o                        | x                        | x                               | 26.5                   |
| 4               | L           | o                        | x                        | x                               | 28.2                   |
| 5               | L           | o                        | x                        | x                               | 21.5                   |
| 6               | H           | o                        | o                        | o                               | 207.8                  |
| 7               | H           | o                        | x                        | o                               | 122.3                  |
| 8               | H           | o                        | o                        | o                               | 50.1                   |
| 9               | H           | o                        | x                        | o                               | 84.1                   |
| 10              | L           | o                        | x                        | x                               | 26.7                   |
5. Discussion

5.1. Mechanism of AO operations revealed by analysis of commonalities among participants

The commonalities observed among participants clearly revealed that AO operation comprises two functions—the motion of ampoule neck breaking and the motion of the dominant hand away from the cutting plane of the broken ampoule. After ampoule breaking, participants were observed to move the dominant hand away by 17.4–207.8 mm away from the cutting plane of the broken-ampoule body over a 0.2-s period whilst still holding the broken head; thereafter, the said motion was gradually slowed down. Within approximately 0.3 s of completing this action, participants, once again, moved the dominant hand toward the midline of their bodies to discard the broken ampoule. This indicates that experienced participants completed AO operation rather quickly (within 0.2 s). In this study, use the motion-capture system to measure agile movements must therefore be considered significant.

Supination movement of the dominant hand to break the ampoule neck was determined to be an essential joint movement during AO operation. In fact, the value of $\theta_{D,Elb1}$ (elbow joint; supination/pronation) of all participants exhibited a sudden supination (2–25°) of the dominant hand immediately following ampoule-neck breaking. Ampoule-neck breaking requires participants to push their thumb downward on the ampoule head and rotate the elbow (forearm) along the distal direction away from the body. This is possible only via supination of the upper limb. In addition, it was inferred that rapid supination occurred because the greatest force was exerted on the elbow joint when the ampoule neck was broken. This rapid angular displacement immediately following ampoule breakage was only due to the supination movement. It can be, therefore, concluded that supination of the dominant elbow joint forms an essential aspect of the AO operation. The above results allow the movements of “Open so as to draw an arc from the front to the back” and “Apply force and bend backward quickly” described in some textbooks to be interpreted as the movement for breaking the ampoule neck, that is, as elbow joint supination.

All participants were verified to be skilled in AO because joint movements of all participants demonstrated similar trajectories during all trials.

5.2. Mechanism of AO operations revealed by analysis of differences among experienced participants

The differences observed among participants revealed that the multiple joint movements correspond to one of the two functions constituting AO operation.

It was verified that the contribution of extensions and external-rotation movements is considerably large when the dominant hand moves away from the cutting plane of the broken ampoule body. Assuming that a participant moves his/her hand over a large distance, elbow extension allows him/her to first move the hand away from a certain position. Further, it is generally known that the elbow allows for performing adjustments in limb height and length, thereby allowing one to correctly position the hand (Kapandji, 2007; Magree, 2007). Further, if a participant turns the upper arm toward the distal side of the body (i.e., external rotation) without any extension of the elbow, it is possible to move the hands through a large distance. In this study, participants were divided into two groups depending on the changes in $\theta_{D,Elb2}$ (elbow joint; flexion/extension) and $\theta_{D,Sha3}$ (shoulder joint; external rotation/internal rotation). These divisions include group H (comprising five participants, who exhibited a large value of either $\theta_{D,Elb2}$ or $\theta_{D,Sha3}$ exceeding 4°) and group L (comprising five participants, who exhibited corresponding angle values measuring less than 4°). Two participants from group H demonstrated extension values synchronized with supination during the period after ampoule breaking. In this regard, it was considered that participants broke the ampoule neck through supination whilst simultaneously moving their dominant hand away via extension. Subsequently, the five participants in group H exhibited external rotation that was synchronized with supination after the ampoule was broken. In this regard, it was considered that participants broke the ampoule neck via supination and simultaneously moved their dominant hand away through external rotation. In contrast, values of extension and external rotation for all the participants in group L were observed to be rather small. This led to the inference that participants moved their dominant hand away through a small distance via supination (i.e., via elbow rotation). Here, the distance moved by the dominant hand of participants in group H was observed to exceed that of participants in group L. It can, therefore, be concluded that movements responsible for motion of the dominant hand away from the cutting plane of the ampoule include extension, external rotation, and supination, and that the contribution of extension and external rotation increases as the dominant hand is moved further away. Additionally, it was observed that even if the extension and external rotation movements are small, AO can only be performed via supination.

It is believed that $\theta_{D,Sha1}$ (extension and adduction/flexion and abduction) and $\theta_{D,Sha2}$ (horizontal flexion/horizontal extension) of the shoulder joint probably decide the direction along which participants move their dominant hand away.
from the cutting plane of the broken ampoule body. This is because the shoulder joint, in general, demonstrates three degrees of freedom, thereby permitting movement of the upper limb with respect to a three-dimensional reference frame in space (Kapandji, 2007). Considering different movements with regard to $\theta_{D, Elb}$ and $\theta_{D, Sn2}$ among participants, however, there probably exist no important rules concerning the said directional choice as long as the hand moves from the anterior towards the lateral side of the body.

It was verified that $\theta_{N, Elb1}$ (elbow joint; supination/pronation) of the nondominant hand performs either of the following two roles—holding the ampoule body, so that it hardly moves or move the nondominant hand away from the dominant hand whilst holding the broken ampoule head. In fact, all the participants except ID2 demonstrated the former movement, and $\theta_{N, Elb1}$ either demonstrated pronation or an angular displacement measuring less than $1^\circ$. In contrast, participant ID2 exhibited the latter movement, wherein $\theta_{N, Elb1}$ corresponded to supination. Here, absolute values of the error between the distance moved by the dominant hand between the time instant immediately preceding ampoule breaking and 0.2 s and the change in distance between the dominant and nondominant hands at 0.2 s were evaluated. This was done to verify whether the two variables match. The absolute errors of the determination of these variables equaled 25.1 mm for ID2 and 1.8-9.1 mm for the remaining nine participants. It can be inferred that for nine participants, the values of the said two variables demonstrated a good match, whereas the difference between the same variables for participant ID2 was rather large. In this regard, it was observed that all participants, except ID2, moved only their dominant hand away after ampoule breaking, whereas participant ID2 moved both his hands away from each other. It was, therefore, concluded that pronation of $\theta_{N, Elb1}$ corresponds to holding the ampoule body with one’s nondominant hand to ensure it does not move while supination of $\theta_{N, Elb1}$ corresponds to moving the nondominant hand away from the dominant hand.

Last, it was confirmed that there exist three ways in which the ampoule head can be held in the dominant hand. In turn, this probably affects the movement of and force exerted by the upper limbs. To facilitate easy supination for AO, holding types a and b, in which cases pressure can be exerted by the entire upper limb as well as by the fingertips, are preferred over type c (Fig. 7). However, when the ampoule is held with the first and second joints of fingers stretched out, the associated risk of suffering an injury increases, because fingertips in this case are positioned closer to the cutting plane of the ampoule. Type a, therefore, seems to be the safest way of handling an ampoule.

5.3. Guidance points for ensuring safe AO performance

Three guidelines aiming to ensure safety during AO operation were deduced based on the mechanism of AO operations revealed by analysis of commonalities and differences among participants.

First, to perform the AO operation, the ampoule neck must be broken through supination of the dominant elbow joint. This is equally applicable to all experienced participants, and the ampoule neck cannot be broken with any other movement. That is, elbow-joint supination of the dominant hand is indispensable and forms the most important movement in AO.

Here, we would like to stress that one of the two functions comprising AO operation, namely the motion to break the ampoule neck and the joint movement corresponding to its function (supination of the dominant elbow joint) were clarified, as there is currently no textbook that says “Break the neck of the ampoule through supination of the dominant elbow joint”. Regarding the motion for breaking the ampoule neck, described as “Open so as to draw an arc from the front to the back” and “Apply force and bend backward quickly” in some textbooks, it has not been described that these motions can be performed by supination of the elbow joint. This knowledge is one of the guidance points which everyone who wants to open the ampoule must know, and can be immediately incorporated into conventional education programs.

Second, performers of AO must move their dominant hand away from the cutting plane of ampoule just after ampoule breaking to avoid unnecessary finger contact with the cutting plane. This is equally applicable to all experienced participants, although the distance of dominant hand movement was different for each participant. The greater the distance moved by the dominant hand, the farther is the distance between the dominant and nondominant hands. Consequently, the possibility of the dominant and nondominant hands touching the cutting plane of the broken ampoule substantially reduces. Further, although there exists a way of moving the nondominant hand away from the dominant hand just after ampoule breaking, it must be noted that the said movement may cause inconvenience from the drug administration viewpoint. When moving the nondominant hand, it is possible for the liquid medicine contained within the ampoule to come in contact with the cutting plane of the ampoule or get spilled. If the chemical comes in contact with the cutting plane of the ampoule, glass microparticles may get mixed with the chemical liquid. Further, spilling of chemical solutions, such as anticancer agents, can be harmful to a human body from the viewpoint of diffusion of harmful substances in the surround-
ing environment. Above all, beginners unaccustomed to AO may find it difficult to perform cooperative operation of both hands owing to the necessity to controlling the movement with seven degrees of freedom of the nondominant upper limb. Based on the above discussion, it is recommended that only the dominant hand is moved away from the cutting plane of the ampoule without movement of the nondominant hand.

What is particularly significant in above argument is that the other function comprising AO operation, namely the motion to move the dominant hand away from the ampoule cutting plane, was clarified. There has never been a textbook that says “Move the dominant hand away from the cutting plane of the broken ampoule body.” Moreover, photographs taken before and after breaking the ampoule while holding the ampoule head in the dominant hand can be found in numerous textbooks, however, photographs taken after opening the ampoule show the close distance between the dominant and nondominant hands (Kaharu and Saitou, 2018; Shijiki et al., 2014; Smith et al., 2002). Therefore, few people can recognize that the dominant hand must be moved away for a safe distance. To date, only one element, i.e., ampoule neck breakage, had been scrutinized by many educators and researchers, while the other element of moving the dominant hand away is presented herein for the first time.

Third, to move the dominant hand away from the cutting plane of the ampoule, AO operators must perform extension of the elbow joint and synchronize the same with supination in one of the following three ways— (i) supination of elbow joint exclusively; (ii) extension of elbow joint synchronized with supination; and (iii) external rotation of shoulder joint synchronized with supination. Actions (ii) and (iii) above are considered safer compared to (i), because they tend to move the dominant hand farther away. Additionally, action (ii) is simpler compared to (iii). This is because it is anatomically easier to control the movement of the elbow joint with only one degree of freedom compared to that of the shoulder joint with three degrees of freedom. Consequently, action (ii) can be considered as the safest and simplest.

Here, one should note that based on the findings of this study and anatomical information, the motion to move the dominant hand away from the cutting plane of the ampoule is best performed by extension of the elbow joint in synchronization with supination. The instruction “Move the dominant hand away from the cutting plane of the broken ampoule” alone is insufficiently explanatory, entrusts instinctive behavior to beginners, and is not rational. As there are many movements for moving the dominant hand away, instructions should be carried out in such a way as to well clarify how the upper-limb-joint movements are to be used. This knowledge is also one of the guidance points which everyone who wants to open ampoules must know and can be incorporated into conventional education programs immediately.

Finally, as movement differences between ampoule-holding types have not been examined in detail, the corresponding information is not reflected in the guidance points.

6. Conclusion

The proposed study clarifies the following guidance points concerning motion of the upper limb for safe and efficient AO operation.

(1) Supination of the elbow joint as the necessary motion for breaking the ampoule neck.
(2) Movement of the dominant hand away from the ampoule cutting plane immediately following ampoule breaking without moving the nondominant hand to avoid unnecessary touching of a finger with the cutting plane.
(3) Performing extension of the elbow joint and synchronizing it with supination to move the dominant hand away immediately following ampoule breaking.

The main merit of this study is the clarification of the AO operation mechanism, namely insights into the two functions comprising AO operation and the joint movements corresponding to its function, as well as the establishment of guidance points regarding the best combination of joint movements for ensuring safe AO performance. These guidance points can be immediately incorporated into conventional education programs. Further, the mechanism of AO operations indicated the points to focus on and analyze in more detail. That is, the elucidated mechanism should allow one to precisely evaluate not only the joint movement, but also the entire motion based on various data such as those on force, center of gravity, and characteristics of hand size and arm length.

In future endeavors, the authors intend to compare motions of experienced and beginner participants to identify the motion factor responsible for injury and microparticle dispersal. Further, we believe that the manner in which pressure is applied affects body motion in AO; therefore, it is important to clarify the effect of applying dynamic loads to upper limbs. Additionally, because the manner in which an ampoule is held significantly influences the magnitude of the required elbow-joint supination and extension, which are important movements in AO, as well as the presence or absence of an
injury, it is necessary to clarify the relationship between these factors.

In the nursing field, an optical three-dimensional system has so far been used to analyze large movements, e.g., those required for moving a patient or for providing transportation assistance to a wheelchair patient. In this study, however, it was proven that the quick and fine movements of the upper limb can also be captured. Therefore, it should be possible to expand the scope of analyzable target motions to injection, blood collection, etc. Inevitably, this approach not only ensures safe AO but also helps in learning other skills related to technical nursing education.

7. Appendix

This section briefly describes the methods for calculating the seven joint-angle types of the right hand with marked positions described in Fig. 3. The same treatment applies equally to the left hand as well.

7.1. Shoulder joints

$\theta_{Sh1}$ and $\theta_{Sh2}$ are two declination types representing the position of $D^R$ in the spherical coordinate system centered at $A^R$, $\vec{e}_u$, $\vec{e}_v$, and $\vec{e}_w$ can be as three orthogonal vectors as under.

$$\vec{e}_u = \frac{A^R A^E - (A^R A^E \cdot \vec{e}_z) \cdot \vec{e}_z}{|A^R A^E - (A^R A^E \cdot \vec{e}_z) \cdot \vec{e}_z|}, \quad \vec{e}_v = \vec{e}_w \times \vec{e}_u, \quad \vec{e}_w = \vec{e}_z$$

(1)

where $\vec{e}_z$ denotes a unit vector directed vertically upwards while $\vec{e}_u$ and $\vec{e}_v$ denote the projection of a unit vector directed from the left to the right shoulders onto the horizontal plane and a unit vector directed from the back of the body to the front, respectively. Using these unit vectors, $A^R D^R$ can be represented as follows.

$$A^R D^R = u \cdot \vec{e}_u + v \cdot \vec{e}_v + w \cdot \vec{e}_w$$

(2)

where

$$u = A^R D^R \cdot \vec{e}_u, \quad v = A^R D^R \cdot \vec{e}_v, \quad w = A^R D^R \cdot \vec{e}_w$$

(3)

$\theta_{Sh1}$ and $\theta_{Sh2}$ are then given as follows:

$$\theta_{Sh1} = \arccos \left( \frac{w}{A^R D^R} \right), \quad \theta_{Sh2} = \arctan \left( \frac{v}{u} \right)$$

(4)

$\theta_{Sh3}$ is given in terms of the inner product of $D^R E^R$ and $B^R C^R$:

$$\theta_{Sh3} = \arccos \left( \frac{D^R E^R \cdot B^R C^R}{|D^R E^R| \cdot |B^R C^R|} \right)$$

(5)

7.2. Elbow joints

$\theta_{Elb1}$ is given in terms of the inner product of $H^R F^R$ and $D^R E^R$:

$$\theta_{Elb1} = \arccos \left( \frac{H^R F^R \cdot D^R E^R}{|H^R F^R| \cdot |D^R E^R|} \right)$$

(6)
Similarly, $\theta_{EB2}$ is given in terms of the inner product of $\overrightarrow{D^A_E}H^2$ and $\overrightarrow{D^A_E}H^2$:

$$\theta_{EB2} = \arccos \left( \frac{\overrightarrow{D^A_E}H^2 \cdot \overrightarrow{D^A_E}H^2}{||\overrightarrow{D^A_E}H^2|| \cdot ||\overrightarrow{D^A_E}H^2||} \right) \quad (7)$$

7.3. Wrist joints

$\varepsilon^R$ can be defined as the midpoint of $F^R$ and $G^R$, and $\omega^R$ can be defined as a point on the line connecting $H^R$ and $I^R$ with its position determined such that $\overrightarrow{e^R_\varepsilon}H^R$ and $\overrightarrow{H^R}I^R$ are perpendicular to each other. From the preceding definition,

$$\overrightarrow{e^R_\varepsilon} \omega^R = \sigma \cdot \overrightarrow{e^R_\varepsilon}H^R + (1 - \sigma)\overrightarrow{e^R_\varepsilon}I^R \quad (8)$$

Equation (8) is true when

$$\sigma = \frac{\overrightarrow{e^R_\varepsilon}I^R}{||I^R||} \quad (9)$$

$\overrightarrow{e_p^R}, \overrightarrow{e_q^R}$ and $\overrightarrow{e_s^R}$ could be defined as three orthogonal vectors:

$$\overrightarrow{e_p^R} = \frac{\overrightarrow{H^R}I^R}{||H^R I^R||}, \quad \overrightarrow{e_q^R} = \frac{\overrightarrow{e^R_\varepsilon}H^R}{||\overrightarrow{e^R_\varepsilon}H^R||}, \quad \overrightarrow{e_s^R} = \overrightarrow{e_p^R} \times \overrightarrow{e_q^R} \quad (10)$$

Using these unit vectors, $\overrightarrow{\omega^R}K^R$ can be represented as follows.

$$\overrightarrow{\omega^R}K^R = p \cdot \overrightarrow{e_p^R} + q \cdot \overrightarrow{e_q^R} + s \cdot \overrightarrow{e_s^R} \quad (11)$$

where

$$p = \overrightarrow{\omega^R}K^R \cdot \overrightarrow{e_p^R}, \quad q = \overrightarrow{\omega^R}K^R \cdot \overrightarrow{e_q^R}, \quad s = \overrightarrow{\omega^R}K^R \cdot \overrightarrow{e_s^R} \quad (12)$$

$\theta_{WR1}$ and $\theta_{WR2}$ can then be expressed as

$$\theta_{WR1} = \arccos \left( \frac{s}{||\overrightarrow{\omega^R}K^R||} \right), \quad \theta_{WR2} = \arctan \left( \frac{q}{p} \right) \quad (13)$$

Conflicts of Interest

The authors declare no conflicts of interest.

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