




Effective Catheter Manoeuvre for the Removal of Phlegm by Suctioning: A Biomechanical Analysis of Experts and Novices

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Abstract

Purpose The aim of this study was to determine the effective biomechanical technique for suctioning phlegm.

Methods A novel tracheal suctioning simulator combined with a motion capture system was used to calculate the amount of simulated phlegm suctioned and the biomechanical parameters of the associated suctioning manoeuvre. A laboratory study, including 12 nurses with > 3 years of suctioning experience and 12 nursing students without any clinical suctioning experience, was conducted. The amount of phlegm suctioned, the maximum length of catheter insertion, and the biomechanical parameters of hand movement were calculated.

Results The mean amount of phlegm suctioned per second was significantly larger in the experienced group than in the non-experienced group. The amount of phlegm suctioned correlated positively with the length of the vertical path of motion of the wrist and forearm, and with the angular velocity of thumb rotation in both the groups.

Conclusion Greater vertical motion of the wrist and thumb rotation improved the effectiveness of phlegm suctioning and prevented the need for deep suctioning, which is unsafe.

Keywords Catheter manoeuvre · Tracheal suctioning · Motion capture system · Nurse · Simulator

1 Introduction

The main purpose of tracheal suctioning is to remove secretions from patients' airways to maintain breathing [1]. The most recent guidelines of the American Association

of Respiratory Care (AARC 2010) recommend the use of shallow, rather than deep, suctioning, with a duration of suction of < 15 s, based on evidences from infant and paediatric studies [2]. However, optimal manoeuvring of the suctioning catheter for effective shallow suctioning is unclear, with

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Schults et al. (2018) insisting that high-quality, powered clinical trials are needed to determine the safety and efficacy of airway management [3].

The safety and efficacy of tracheal suctioning have been addressed in various studies. Within the context of intensive care settings, research has focused on the association between suctioning and the prevention of adverse events, such as ventilator-associated pneumonia [4–7]. Day et al. (2002) conducted a literature review and identified three phases of suctioning [8]. The first, pre-suctioning, phase, includes patient assessment, preparation, pre-oxygenation, and infection control, with a focus on evaluating the potential for adverse events. During the second, suctioning, phase, catheter selection, catheter insertion depth, negative pressure, suction duration, and number of suctioning passes are important assessment points considered. In the third, post-suctioning, phase, reconnection to oxygen therapy, patient assessment, reduction of patient stress and anxiety, appropriate titration of oxygen, and again, infection control, are related to the quality of care. The quality of suctioning skills is an important factor to consider, having been associated to complications, including respiratory infection, atelectasis, hypoxemia, and cardiovascular instability [9, 10]. However, to our knowledge, the association between the biomechanics of the suctioning manoeuvre and the amount of secretions suctioned has not been specifically evaluated.

Motion capture has been used to compare upper body and hand movements between expert and novice surgeons with the aim of improving surgical technique [11–13]. In these studies, highly stable head position, a short performance time, and fast finger movements differentiated expert from novice surgeons. Lin et al. (2018) used motion capture to quantify transfer skills among nurses, with differences in key biomechanical parameters of the trunk and lower extremities during the different phases of the transfer motion having been identified between experts and novices [14].

As the biomechanical features of effective tracheal suctioning are not yet defined, the aim of our study was to determine the effective biomechanical technique of tracheal suctioning for phlegm removal. Specifically, we compared the biomechanics of dominant arm movements during tracheal suctioning between expert and novice nurses.

2 Methods

2.1 Participants

Twelve expert nurses and 12 novice students, with no history of neurological and/or motor disorders, were recruited into this study. Expert nurses had > 3 years of experience with tracheal suctioning in clinical settings (Ns group). The novice group included nursing students who had no prior

experience with suctioning of patients in a clinical setting (St group). Participants' age, sex, dominant arm, and clinical experience were recorded (Table 1).

The study protocol was approved by our institutional ethics committee (Reference Number, 17-81-1), and written informed consent was obtained from all the participants, according to the Declaration of Helsinki.

2.2 Equipment

For this study, a new tracheal suctioning simulator was specifically developed. The simulator consists of a mannequin with a styrofoam head and neck, with metal braces used to form the thorax (Fig. 1a). A cuff-less tracheotomy cannula (inner diameter: 8 mm, Koken Co., Japan) was inserted at the approximate level of the second to fourth tracheal cartilages of the neck. In addition, an acrylic pipe (14 cm in length and 2 cm in diameter) was used to imitate the trachea and the main bronchus of an adult patient [15]. A gravimetric digital scale was located at the tip of the cannula to quantify the amount of phlegm suctioned. The scale was placed under the acrylic pipe and attached to it using a custom three-dimensional printer fixture (Fig. 1b). The angle between the pharyngeal axis and the laryngeal axis in the sagittal plane was set to approximately 7°, which is the normal angle for an adult patient in the supine position, with the tracheal bifurcation inclined to lie below the pharyngeal axis, as per a previous report [16]. The inner surface of the acrylic pipe was coated with a soft urethane gel that closely mimicked the real trachea. The distance between the tip of the tracheal tube and the acrylic pipe was adjusted to pass the catheter into the pipe. The outside diameter of the suctioning catheter was set to 4 mm (12F, Nipro Co., Japan), which was approximately half of the insider diameter of the tracheal tube (#3276, Koken Co.). The viscosity of the simulated phlegm was realistic at 21.64 mPa·s (11229-070, Kyoto Kagaku Co., Japan). The temperature and humidity of the room were maintained at 24 °C and 35%–45% to maintain the appropriate viscosity of the simulated phlegm within the simulated endotracheal tube. Prior to the experiment, 10 g of simulated phlegm were placed into the pipe and evenly distributed within the pipe before suctioning. The thorax

Table 1 Characteristics of the nurse and student groups

	Nurse (n = 12)	Student (n = 12)
Age (years)	35.2 ± 9.5	21.3 ± 0.4
Sex	10 females, 2 males	12 females
Dominant arm	12 right hands	12 right hands
Clinical experience (years)	14.0 ± 8.8	0

Mean ± SD

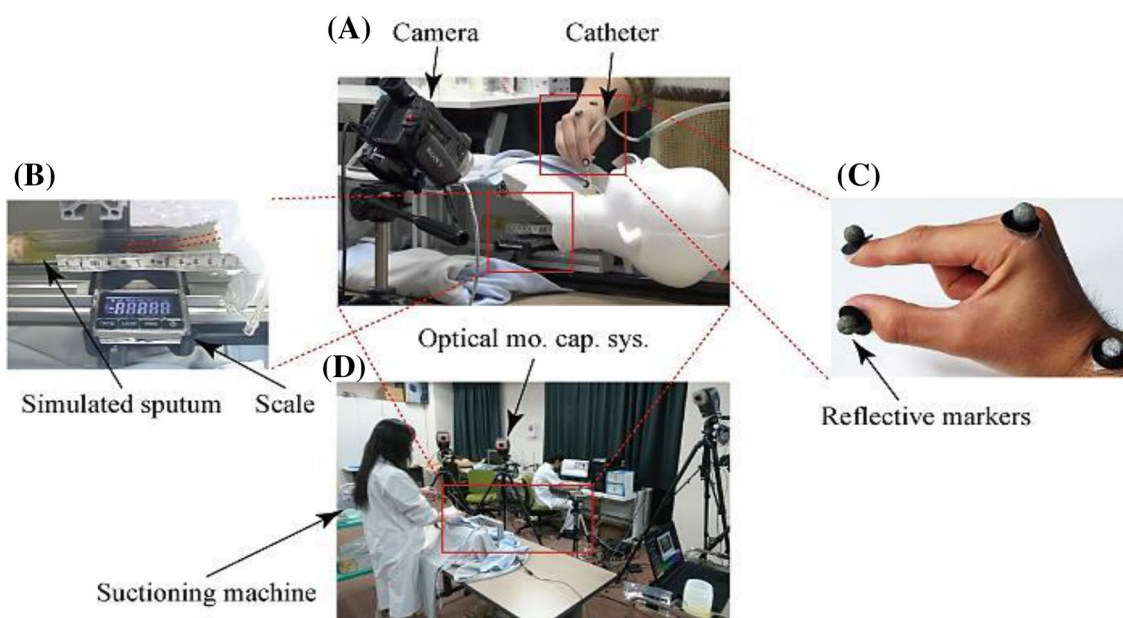


Fig. 1 Experimental set-up. **a** Locations of the simulator and video camera. The latter used to monitor the location of the tip of the catheter within the acrylic pipe, which simulating the trachea. **b** The simulated airway, including the acrylic pipe, imitating the main bronchus. The gravimetric digital scale was used to quantify the amount

of phlegm suctioned. The red dotted lines represent the motion of the catheter. **c** The location of reflective markers, for motion capture, placed on the tip of the thumb, tip of the index finger, head of the second metacarpal, and radial styloid process of the dominant hand. **d** The entire experimental set-up

of the simulator was covered with a cloth so that it was not visible to the participants.

The motion of the hand, wrist, and forearm was measured using a three-dimensional motion capture system (Cortex system, Motion analysis, USA), with a 7-camera set-up. Motion was tracked at 200 Hz. Six reflective markers (6.4 mm in diameter) were placed on the following reference points: landmarks of the dominant hand (tip of the thumb, tip of the index finger, head of the second metacarpal, and radial styloid process); tip of the non-dominant thumb; and opening of the tracheal tube (Fig. 1c). The location of the catheter tip within the tracheal tube was recorded using a video camera, which was time synchronised to the motion capture system. A sample of the view obtained through the camera is provided in Fig. 1b.

2.3 Procedures

Participants stood facing the simulator, aligning their body centre with the tracheal tube in the frontal plane. Participants were instructed to place the tip of the suctioning catheter just above the tracheal tube and to maintain this position with both hands. Upon a verbal signal by the experimenter, participants inserted the catheter into the tracheal tube and proceeded with a 10-s (time controlled) period of suctioning, being asked to suction *as much simulated phlegm as possible within the 10 s*. No instructions were provided regarding the

suctioning manoeuvre to be used. A few practice trials were performed to allow participants to practice completing the suctioning within the required 10 s. For analysis, 2 trials were completed by each participant, with the trial in which the greater amount of phlegm was suctioned being used for the biomechanical analysis.

2.4 Data Processing and Statistical Analysis

All signals were processed offline using MATLAB R2015a (MathWorks, USA) and Cortex (Motion analysis, USA). The motion capture data were filtered using a 4th-order low-pass (10 Hz), zero-lag, Butterworth filter. The maximum length of the catheter inserted (L_{max}) and suctioning time (within the 10-s period) were measured from the video data time synchronised to motion capture. For analysis, suctioning was sub-divided into two phases, namely, the insertion phase (T_0 – T_1) and the withdrawal phase (T_1 – T_2). The start of the insertion phase (T_0) was defined as the time point when the catheter tip reached the opening of tracheal tube, and the end of the insertion phase (T_1) as the time point when the tip of the catheter reached L_{max} . The end of the withdrawal phase (T_2) was defined as the time point when the tip of the catheter reached the opening of the tracheal tube. The amount of phlegm suctioned was calculated as the change in weight, using the digital scale placed inside the tube. For analysis, the amount of phlegm was normalised by the suctioning time

(g/s). The biomechanics of the suctioning manoeuvre were defined using the total vertical length of the path of motion of the marker placed on the head of the second metacarpal of the dominant hand relative to the radial styloid process, which defined the path of wrist motion. The vertical motion of the forearm was calculated from the total vertical length of the path of motion of the marker placed on the radial styloid process of the dominant hand. These path lengths were normalised using the suctioning time to yield the total vertical path length per 10 s. The mean angular velocity of the tip of the thumb of the dominant hand was also calculated in the horizontal plane during the suctioning manoeuvre.

The statistical analysis was processed using SPSS Statistics version 22.0 (IBM, Armonk, NY, USA). Shapiro–Wilk test was used to verify the normality of distribution of each parameter. For data with a normal distribution, an unpaired *t* test was used to evaluate differences between the expert and novice groups. Pearson's correlation coefficient was calculated to evaluate the association between the amount of phlegm suctioned and L_{\max} and measured biomechanical parameters. Statistical significance was set at $p < 0.05$.

3 Results

The time series profile of the vertical displacement of the radial styloid process (mm; upper line) and of the angular velocity of the tip of thumb (rad/s; lower line) are shown in Fig. 2 for two different trials with a different amount of phlegm suctioned (Fig. 2a: 0.636 g/s; Fig. 2b: 0.301 g/s). Note the rapid small vertical movements of the radial styloid process and higher angular rotation of the thumb in trial Fig. 2a compared to Fig. 2b.

The duration of suctioning was 8.27 ± 1.52 s for the Ns group and 7.65 ± 1.02 s for the St group (Fig. 3a; $p > 0.05$). The mean amount of phlegm suctioned per second was significantly larger for the Ns group than for the St group ($p = 0.039$, Fig. 3b). In addition, the mean L_{\max} and the mean total length of vertical wrist motion were significantly longer in the Ns group than in the St group ($p = 0.017$ and $p = 0.022$; Fig. 3c and d, respectively). The mean total length of the vertical path of motion of the forearm and the mean angular velocity of the thumb were not different between the two groups ($p > 0.05$).

The amount of phlegm suctioned was positively correlated to L_{\max} ($r = 0.45$, $p = 0.026$). However, the tip of the catheter reached the edge of tracheal tube ($L_{\max} = 14$ cm) for nine of the 24 participants. Insertion of the tip of the catheter to the edge of the tracheal tube would increase the risk of membrane damage around the tracheal bifurcation. When these

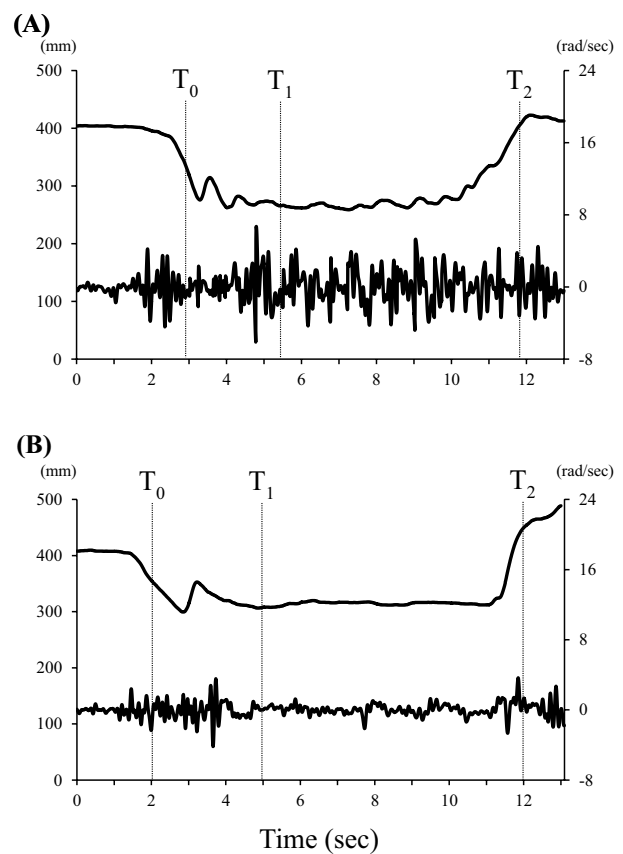


Fig. 2 The time series profiles of the vertical displacements of the radial styloid process and angular velocity of the tip of thumb rotation. The horizontal axis represents time, with the left and right vertical axes representing the vertical displacements of the radial styloid process and angular velocity of the thumb rotation. The three vertical lines represent each time event: T0, time at which the catheter tip reached the opening of the tracheal tube; T1, time at which the catheter tip reached the maximum length of catheter insertion; and T2, time at which the catheter tip reached the opening of tracheal tube during pull out

nine participants were excluded, no correlation was identified between L_{\max} and the amount of phlegm suctioned ($r = 0.31$, $p = 0.248$; Fig. 4a). The amount of phlegm suctioned, however, did correlate positively with the length of the vertical path of motion of the wrist ($r = 0.62$, $p = 0.001$), the length of the vertical path of motion of the forearm ($r = 0.47$, $p = 0.021$; Fig. 4c), and the angular velocity of the thumb ($r = 0.44$, $p = 0.036$; Fig. 4d). These correlations were significant for all participants. The significant positive correlation between the vertical wrist motion and the amount of phlegm suctioned was retained, even after the extreme value of 90.0 cm for one participant was excluded from the analysis ($r = 0.54$, $p = 0.008$; Fig. 4b).

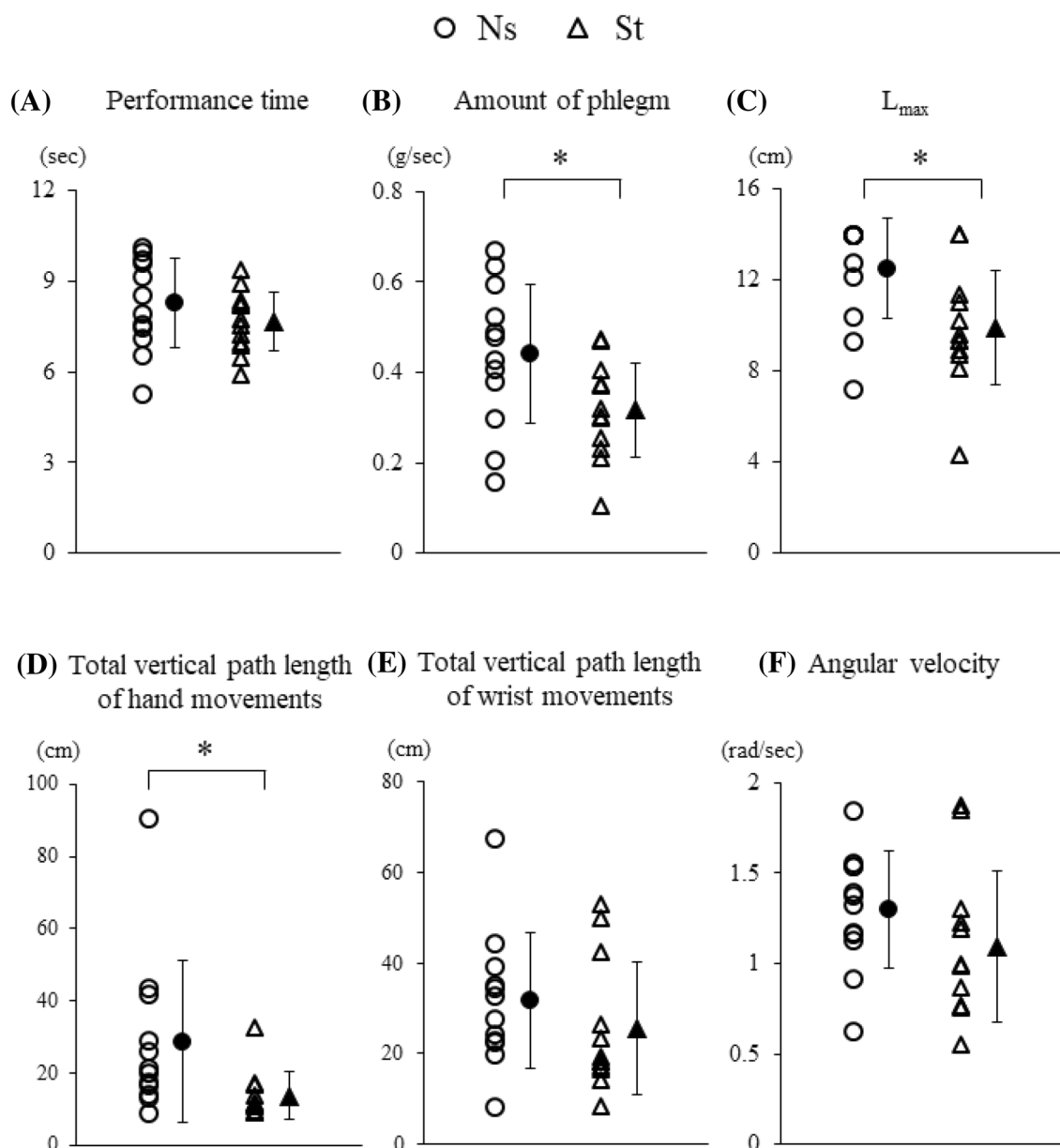


Fig. 3 Results of all parameters for the expert and novice groups. Panels from top to bottom show **a** the suctioning time, **b** the amount of phlegm suctioned per second, **c** the maximum length of catheter insertion, **d** the total length of the vertical path of wrist motion per 10 s, **e** the total length of the vertical path of forearm motion per 10 s,

and **f** the mean angular velocity of the thumb. Data for the Ns group are shown by circles, and those for the St group are shown by triangles. Filled markers represent mean values (\pm SD) for each group. * $p < 0.05$

4 Discussion

Our study provides evidence that the biomechanics of the suctioning manoeuvre contribute to the effectiveness of tracheal suctioning. Specifically, faster vertical wrist and forearm motions, combined with higher angular velocities of thumb motion, may improve the effectiveness of the suctioning manoeuvre. Although we did observe a greater depth of insertion of the catheter by expert nurses compared to novice

students, considering the comparable volumes of phlegm suctioned by the two groups, deeper suctioning may not be necessary and may in fact be unsafe in practice.

4.1 Comparison Between the Expert and Novice Groups

As expected, the mean amount of phlegm suctioned per second and the length of catheter insertion were significantly

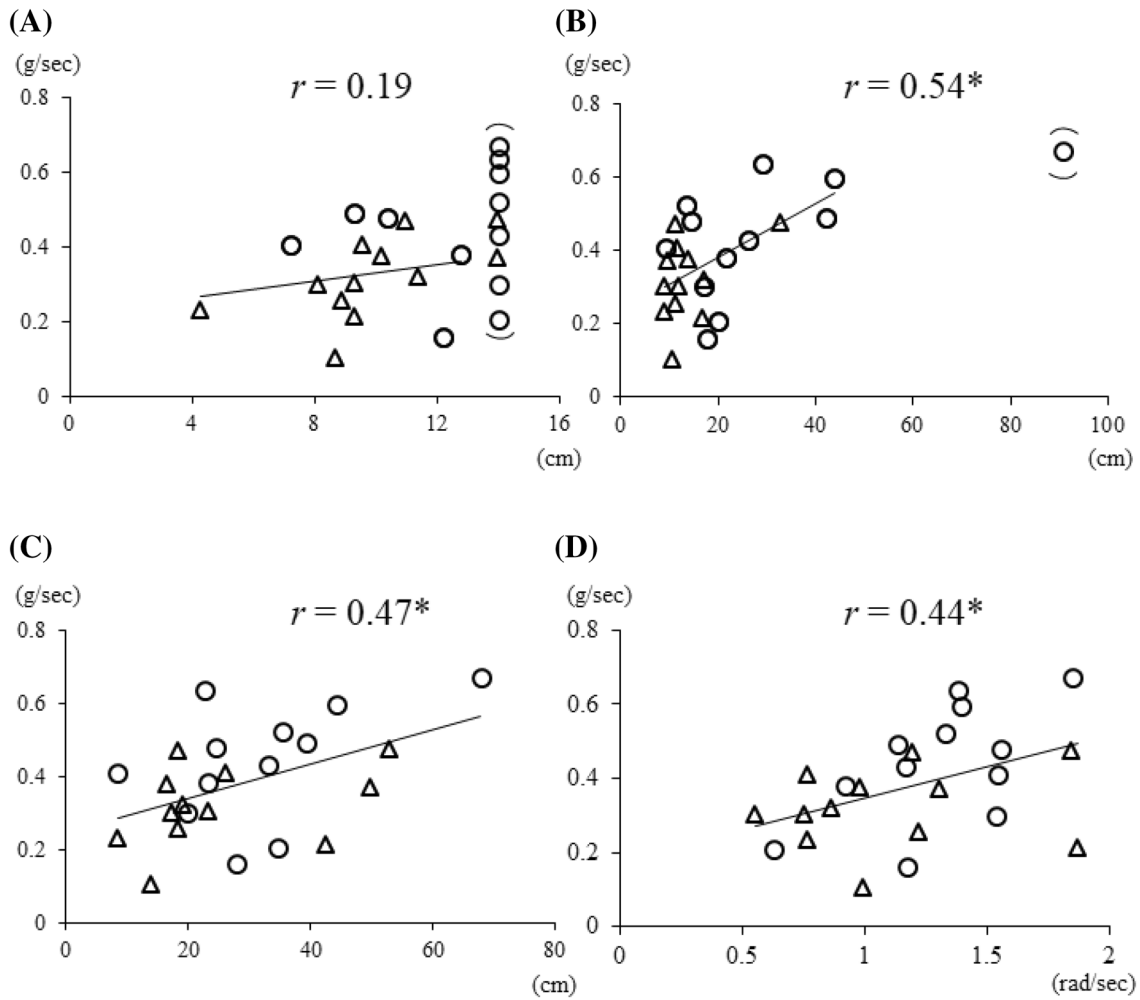


Fig. 4 Correlation between the amount of phlegm and **a** the maximum length of catheter insertion (L_{max}), **b** the total length of the vertical motion of the wrist, **c** the total length of the path of forearm motion, and **d** the mean angular velocity of the motion of the thumb.

Data for the Ns group are shown by circles, and those for the St group are shown by triangles. The correlation coefficients were calculated by excluding the data in brackets. * $p < 0.05$

greater for the Ns than St group. In fact, 10 of the 12 nurses in the Ns group inserted the catheter to a length > 10 cm, which was achieved by only four of the 12 students in the St group (Fig. 3c). This difference might reflect the knowledge of expert nurses regarding pooling of phlegm around the tracheal bifurcation, due to its lower inclination relative to the pharyngeal axis, as well as their skill to insert the catheter to a greater depth in the trachea without stimulating the coughing reflex.

Regarding the biomechanics of the manoeuvre, we noted a longer vertical motion of the wrist in the Ns than St group, but with no difference in forearm motion between the two groups. The greater distal movement (of the hand and wrist) by experts could enhance control and, thus, performance skill of the suctioning manoeuvre. However, the absence of a difference in the angular motion of

the thumb between the two groups likely reflects the condition of our simulated suctioning task, with the position of the phlegm being similar in each trial and, therefore, not requiring instantaneous changes in movement to adapt to unexpected conditions. The quasi-invariant condition of our task might explain differences between the biomechanical characteristics of expert and novice performance observed in the present study and those described in previous studies. Takayasu et al. (2019) reported differences in the motion of the proximal joints of the arm (the shoulder and elbow) and not the distal joints (wrist and fingers) between experts and novices during laparoscopic suturing manoeuvres [12], while Uemura et al. (2014) and Sun et al. (2017) reported greater flexibility and instantaneous changes in movement by experts than by novices while performing repetitive and complicated tasks [11, 13].

4.2 Association Between the Catheter Manoeuvre and the Amount of Phlegm Suctioned

The amount of phlegm suctioned was positively correlated to the maximum length of catheter insertion (L_{\max}). However, we do note that the tip of the catheter reached the edge of the tracheal tube in nine of the 24 participants, which would cause the tip of the catheter to brush up along the contours of the edge, increasing the risk of damaging the membrane around the tracheal bifurcation. When the data from these nine participants were excluded, the significance of the correlation between L_{\max} and the amount of phlegm suctioned was not retained (Fig. 4a). Moreover, the amount of phlegm suctioned by these nine participants varied widely, between 0.21 and 0.70 g/s. This finding supports the caution issued in the AARC [2] guidelines that deep suctioning may not have a superior benefit over shallow suctioning, while increasing the risk for adverse events.

The amount of phlegm suctioned did correlate positively with the length of the vertical path of wrist and forearm motion, and the mean angular velocity of the thumb (Fig. 4b–d), indicating that faster linear and angular motion of the catheter improved the effectiveness of suctioning. Tracheal catheters have three holes, one located at the tip and two located on either side of the catheter, the first located at 7–11 mm from the tip of the catheter and the second at 16–20 mm from the tip, each hole having a length of 4 mm and a width of 1 mm. These two holes on either side of the catheter prevent excessive negative pressure, and contribute to the suction of secretions [17]. Therefore, the combination of linear and rotational movement of the catheter reduces the risk of suction-induced bleeding, and increases the likelihood of contact with phlegm located on the wall of the trachea.

4.3 Limitations

The limitations of our study need to be acknowledged in the interpretation of results. Foremost is the small sample size, which may have limited the identification of between-group differences. Second, the viscosity of the simulated phlegm may have required greater negative pressure for suction than that generally required in real situations. Third, the motion of the catheter was not directly measured, and the effectiveness of the side holes in increasing the amount of phlegm suctioned in the relatively short duration of our experimental set-up (10 s) could not be assessed. Therefore, further studies should be performed by considering the effects of phlegm viscosity, level of negative pressure, and the role of the side holes to further determine effective manoeuvres for safe tracheal suctioning. With regards to the simulator, including the sounds associated with phlegm suctioning, which provides important feedback, should be considered

to more appropriately approximate the suctioning of patients in clinical settings.

5 Conclusion

In this study, we investigated the biomechanical features of effective catheter manoeuvre during tracheal suctioning by using a novel simulator. We found that a faster vertical wrist and forearm motion, combined with a greater angular motion of the thumb, improved the effectiveness of the suctioning. Although expert nurses did insert the catheter deeper in the trachea more often than the novice students, deep suctioning did not increase the amount of phlegm suctioned and, therefore, may not provide a distinct benefit over shallow suctioning. Our biomechanical analysis of the suctioning manoeuvre could facilitate the development of a standard with regard to catheter manipulation, which could be important for the teaching and the assessment of tracheal suctioning techniques, as suggested by Mietto [18].

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Code Availability All signals were processed offline using MATLAB R2015a (MathWorks, USA) with custom codes and Cortex (Motion analysis, USA). The statistical analysis was processed using SPSS Statistics version 22.0 (IBM, Armonk, NY, USA).

Author Contributions N.C., H.M., S.N., S.K. E.M. and T.A. conceived and planned the experiments. N.C., H.M., S.N., H.O., K.T. and Y.S. carried out the experiments. N.C., H.M., and T.A. contributed to the interpretation of the results, and wrote the manuscript. All authors discussed the results and contributed to the final manuscript.

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Data Availability Our manuscript has associated data in a data repository.

Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest.

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