The Use of Navigation Forces for Assessment of Wrist Arthroscopy Skills Level

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Abstract

Purpose To provide an efficient learning process, feedback on performance is crucial. In skills laboratories, it is possible to measure the skills and progression of skills of the trainees objectively. This requires metrics that represent the learning curve of the trainee, which were investigated for wrist arthroscopy. The research questions were:

- What are the forces used by novices during wrist arthroscopy?
- What aspects of these navigation forces are discriminative for the wrist arthroscopy skills level?

Methods A cadaver wrist was mounted in a custom-made distraction device mounted in front of a force platform (ForceTrap). Eleven novices were invited to perform two tasks on the wrist:

- Insertion of the scope through the 3–4 portal and the hook through the 6R portal, and visualization of the hook in the center of the image
- Navigation through the wrist from radial to ulnar with probing and visualization of five predefined landmarks

The second task was repeated 10 times. The absolute force (F_{abs}) and the direction of force were measured. The angle α is defined in the vertical plane, and the angle β in the horizontal plane.

Results The median F_{abs} used by novices remained below the force threshold as defined from the expert data (7.3 N). However, the direction of the applied forces by novices in both planes was not consistent with expert data and showed a wider range. Also, there was no improvement after more trials.

Conclusion Our study suggests by the absence of a learning curve for the novices and a significant difference between novices and experts that novices can benefit from feedback on the magnitude and direction of forces to improve their performance.

Keywords

- arthroscopy wrist
- education
- forces
- learning
- navigation

To provide an efficient learning process, feedback on performance is crucial. In the clinical setting, tools such as the Objective Structured Assessment of Technical Skills (OSATS) are used for assessment of skills.¹⁻³ This type of assessment, by its nature, is subjective and time-consuming.⁴ Moreover, they do not assess important elements that are related to safe tissue manipulation, which is mandatory in the beginning of a training process.⁴ In skills laboratories objective measurement of various aspects of surgical and endoscopic skills is possible, as well as monitoring trainees' progress.² A precondition is the identification of metrics that represent the learning curve of the trainees. The literature presents quite a variety of metrics, of which time to task completion has been shown to be a strong predictor of task efficiency.³ Tracking of motion has also been investigated.⁵ Cutoff values for the scores of motion analysis devices have yet to be defined, making them suitable only for formative assessment.² Oropesa et al concluded that most training systems for laparoscopy assess performance using task time and motion-derived parameters such as path length, speed, economy of movements, and motion smoothness.³ These efficiency parameters are objective and reproducible and related to measurable physical metrics.

However, an effective or efficient performance of the task does not necessarily mean a safely performed task. A prerequisite for a safe wrist arthroscopy is the gentle introduction of the scope and secondary instruments, as well as a smooth and adequate manipulation of the instruments during the arthroscopic sweep through the wrist. Cartilage especially needs to be respected during arthroscopy, as it is a tissue with poor healing potential. Thus, force-related parameters could be valuable to assess the technical skills of trainees in wrist arthroscopy.

The literature presents a few studies on measurements of forces during arthroscopy. Tashiro et al measured both motion and force data.⁶ The forces and torques were measured using a six-degrees-of-freedom sensor attached to a dummy knee. The authors conclude that motion and force data were equally able to distinguish between levels of experience in a joint inspection and probing task. In a more complicated task (meniscectomy), all force parameters were similar for each group, suggesting that beginners take care to execute safe tissue manipulation. Chami et al measured forces and torques

during knee arthroscopies in the operating room by fitting a six-degrees-of-freedom force torque sensor to the arthroscopic hook.^{4,7} Their results on "efficiency of movement" and "consistency of performance" indicate that it is possible to assess experience objectively using force measurements.⁴

Our purpose was to investigate further the usefulness of force parameters in monitoring safe tissue manipulation. To this end, we previously studied the forces used by experts during wrist arthroscopy in a cadaver with a custom-made force platform. (►Table 1, ►Fig. 1). (Obdeijn MC, Horeman T, de Boer LL, van Baalen SJ, Liverneaux P, Tuijthof GJM. Navigation forces during wrist arthroscopy: Assessment of expert levels. Submitted Aug 2013 KSSTA.) These data were used as reference for safe manipulation for this study, where we investigated the following questions:

- What are the forces used by novices during a wrist arthroscopy?
- What aspects of these navigation forces (e.g., in terms of magnitude or direction) are significantly different between novices and experts in wrist arthroscopy?
- What aspects of these navigation forces (e.g., in terms of magnitude or direction) show a distinct learning curve?

Methods

Experimental Setup

Three left-handed cadavers were used in this experiment. In a session of measurements one left-handed cadaver wrist was mounted in a custom-made distraction device (►Fig. 1) that loaded the wrist via a set of "traction fingers" and a spring to 5 kg. The cadaver wrist with the distraction device was mounted in front of a special force platform (ForceTRAP) (►Fig. 1). A vertically oriented base platform was used to affix both the force platform and the mounted cadaver wrist in a vertical position to mimic the clinical setting closely. The ForceTRAP was developed to measure forces during surgical actions in training settings.^{8,9} The ForceTRAP contains three parallelogram mechanisms, each built from two stiff elements and two spring blades that decouple the applied forces from the moments.⁸ This allows measurement solely of the applied forces, without measuring the moments. The ForceTRAP measures forces from 0 to 20 N in three dimensions,

Table 1 Demographic data of the experts

Experts	Age (years)	Training	Expert hand surgery (Years)	Expert WA (years)	Nr WA per month	Nr KA/SA per month
1	43	Ortho	14	8	5-10	5-10
2	47	Ortho	15	13	5-10	None
3	47	Ortho	20	15	5-10	None
4	55	Ortho	27	26	>10	None
5	47	Plastic	15	15	5-10	None
6	43	Ortho	13	12	5-10	>10

Abbreviations: Expert WA, years of experience in wrist arthroscopy; KA, knee arthroscopy; Ortho, orthopedic surgery; Plast, plastic Surgery; SA, shoulder arthroscopy; WA, wrist arthroscopy.

Fig. 1 Experimental setup. A, cadaver wrist; B, camera; C, tripod; D, vertical traction device; E, force platform; F, force platform holder; G, laptop registering the data input from the three cameras and the scopic image.

with an accuracy of 0.1 N and a sample frequency of 100 Hz. This setup records the combined forces exerted on the cadaver wrist by the arthroscope and the hook. Thus the forces are a summation of direct (e.g., probing) and indirect (e.g., force on the portal) tissue manipulation.

In addition to the recording of the forces, two CCD cameras (Bullet CCD Camera model DV-2301CW360, Shenzhen D-Vitec Industrial Co. Ltd., Shenzhen Guangdong, China) and one digital video camera (GRD77, JVC, Kanawaga-ku Yokohama, Japan) were used to record the arthroscopic tasks from both sides and above the hand (►Fig. 1). The images from the three cameras and the arthroscopic view were recorded simultaneously and represented in a split-screen image using a color quad processor (QC-904R, Przedsiębiorstwo Wielobranzowe, Poznań, Poland) and an analog-to-digital converter (Canopus/Grass Valley ADVC 110, Thomson, San José, USA; ►Fig. 1).

To perform the arthroscopic tasks, an instrument set and a 30° angled, 2.4-mm diameter arthroscope from Karl Storz (Germany) were used. Before the start of the experiment the senior author (MO) established the 3–4 portal and the 6R portal in each of the cadaver wrists.

Participants

Eleven participants were recruited (►Table 2). The participants were residents in training for plastic surgery or orthopedic surgery. None of the participants had any experience in performing wrist arthroscopy. The residents in training for orthopedic surgery had some experience in assisting during knee arthroscopies, but they had experience of less than 5 procedures in which they performed the procedure by them-

selves. We considered this experience negligible, as independent performance of 50 knee arthroscopies is considered needed to become competent.¹⁰

Study Design

Two tasks were defined that reflect important steps in learning wrist arthroscopy and require safe tissue manipulation. First, the creation of portals is an important step during arthroscopy. As we used cadavers, only one set of portals could be created per cadaver, which would not reveal sufficient data to draw any conclusions. Therefore, we focused on insertion of the arthroscope and hook, which could be repeated multiple times. Similar to portal localization, the insertion of the arthroscope is also primarily guided by haptic feedback. Second, safe navigation and orientation in the wrist are difficult because of the confined complex shapes in the wrist and the 30°-oriented arthroscope. To be able to compare all data, the tasks were more specifically defined as follows:

Task 1: Insertion

This task consisted of two separate steps. The participants were required to insert the arthroscope through the 3–4 portal and visualize the central part of the radiocarpal joint. Subsequently, they were required to insert the arthroscopic hook through the 6R portal and visualize the tip of the hook in the center of the arthroscopic image (►Fig. 2).

Task 2: Navigation and Probe

This task consisted of five separate steps. With the instruments in the afore-mentioned portals, navigation had to be

Table 2 Demographic data of the novices

Novices	Age (Years)	Training	Hand surgery experience (y)	Nr WA	Nr KA/ SA (total)
1	31	Plastic	3	None	None
2	29	Ortho	1	None	<5
3	28	Ortho	1	None	< 5
4	27	Plast	0	None	None
5	27	Ortho	1	None	< 5
6	37	Plastic	3	None	None
7	33	Plastic	1	None	None
8	33	Plastic	2	None	None
9	33	Plastic	1	None	None
10	32	Surgery	0	None	None
11	31	Plastic	2	None	None

Abbreviations: KA, knee arthroscopy; Ortho, orthopedic surgery; Plast, plastic surgery; SA, shoulder arthroscopy; WA, wrist arthroscopy.

performed through the wrist from the radial to the ulnar side while probing five predefined anatomic landmarks consecutively: radial styloid process (RSP), scaphoid (SC), scapholunate ligament (SL), lunate (LU), and triquetrum (TR).¹¹ Each structure had to be touched by the hook and visualized in the center of the arthroscopic image (► **Fig. 3**). For this purpose, a circle with a diameter of 18 cm was glued to the screen.

Each participant performed the insertion task. The time needed to insert the arthroscope and the time needed to visualize the hook in the center of the arthroscopic image were documented separately. Subsequently, each participant performed the navigation task. The first author stood next to the participants, verifying visually whether each of the structures had been visualized according to the protocol. Once the structure had been visualized correctly, the participant was allowed to proceed to the next anatomic landmark. There was no urging to perform the tasks as fast as possible. The participants were asked to perform the tasks as if they

would be operating on a real patient. The total task time was defined as the summation of all time periods to identify and probe each of the five landmarks of Task 2. Both tasks were repeated 10 times. The participants were randomly allocated to the different wrists, so as to use each wrist a maximum of 4 times. Only the forces that were exerted within the indicated timeframes were used for further analysis.

Data Processing and Statistical Analysis

The data were processed using Matlab (version R2011b, The Mathworks Inc., Natick, MA, USA) and IBM SPSS Statistics (version 19, SPSS Inc., Chicago, IL, USA). The task times for all seven steps were determined and used to select the force trajectories for further processing. Using the force signals in the x -, y -, and z -directions, the absolute force (F_{abs}) per sample was calculated from the square root of F_x , F_y , and F_z force components. The angle α is defined in the vertical plane, which is aligned with the cadaver wrist mounted in the setup (► **Fig. 1**). A positive angle implies upward (distal) rotation, and a negative angle implies downward (proximal) rotation. The angle β is defined in the horizontal plane, where a positive angle implies rotation to the ulnar side and a negative angle implies rotation to the radial side. The experts performed the same two tasks on a different specimen and their data were processed identically as described for the novices.

The presence of normal distributions for the parameters F_{abs} , α , and β was assessed with the Kolmogorov–Smirnov test for the seven individual landmarks and both tasks combined. As the data were not normally distributed, they were expressed as medians. Normally, the median is complemented with the minimum and maximum values, but as we processed the raw data without filtering, we propose to use the 10th and 90th percentiles of the datasets for visualization. The raw datasets of the novices for F_{abs} , α , and β were compared with those of the experts as previously measured using a Mann–Whitney U test ($p < 0.05$) to highlight any significant differences. For illustration purposes, the descriptive values of F_{abs} ,

Fig. 2 Scopic image of the hook centrally in the circle that is glued to the screen.

Fig. 3 Scopic images with the hook on the five predetermined anatomical landmarks. L, lunate; PSR, styloid process of the radius; S, scaphoid; SL, scapholunate ligament; T, triquetrum.

α , and β of both tasks combined, as executed by the novices, are graphically presented per trial, together with the proposed safe threshold values for F_{abs} , α , and β that were previously determined from expert data. These thresholds are proposed to consist of the 10th and 90th percentiles, as indicated in ►Table 3. As these experts all had more than 8 years of experience in wrist arthroscopy (►Table 1), we assumed that they are at the end of the learning curve for wrist arthroscopy. Therefore, we considered the forces they use to be safe for wrist arthroscopy. Inherent to the navigation task, angle β shifts from radial (negative) to ulnar (positive) when navigating through the wrist. Therefore, angle β is presented per landmark for all novices. The presence of a learning curve for the median of F_{abs} , the minimum of F_{abs} , the maximum of F_{abs} , and the medians of α and β were determined per landmark and total task using a Friedman test. The Friedman test, like the parametric repeated-measures analysis of variance (ANOVA), is used to detect differences in treatments across multiple test attempts. Only the results of the first, fifth, and 10th trial were used; therefore, the significance level was set at 0.05.

Results

The overall force magnitude and directions (F_{abs} , α , and β) for both tasks are summarized in ►Table 3. Noticeable are the substantial larger ranges of the 10th and 90th percentiles of the novices compared with the experts. All three parameters (F_{abs} , α , and β) show significant differences between novices and experts, with the force magnitude applied by novices being lower, the angle in the vertical plane being lower, and the angle in the horizontal plane being shifted to the radial

side (►Table 3). The lower angle α indicates that the novices keep their scope in a more horizontal plane, failing to follow the natural inclination of the radius.

►Fig. 4 shows the graphical presentation of the magnitude of forces per trial as applied by the novices. More specifically, the median values (bars) and the 10th and 90th percentiles (error bars) of F_{abs} for all novices and landmarks together are plotted per trial. The horizontal lines indicate the 10th and 90th percentile of F_{abs} of the experts (►Table 3). The median F_{abs} of the novices remains the same and is located at the 10th percentile threshold of the experts. The range of F_{abs} formed by the 10th and 90th percentiles remains similar by repeated trials executed by the novices. ►Fig. 5 has an identical structure but shows the results for angle α , the direction of the force in the vertical plane as defined in ►Fig. 1. The range of angle α as indicated by the error bars is consequently larger than the threshold lines. ►Fig. 6 shows angle β per landmark per trial for all novices. The direction of force in the horizontal plane is quite similar to those of the experts for probing the processus styloideus radii. Also, the shift from radial to ulnar can be identified from the radial styloid toward the lunate when viewing the median values. Again a noticeable difference is shown between the ranges of angle β and the threshold ranges as measured with the experts. The experts also use quite a large range of force direction in the horizontal plane to insert the scope.

As already suggested by ►Figs. 4–6, but confirmed by the Friedman tests, no significant differences were found between the first, fifth, and 10th trials of the novices for all parameters (median, minimum, and maximum of F_{abs} and medians of α and β). Consequently, no learning curve was assessed for any of the tested parameters.

Table 3 Median values of absolute force F_{abs} with 10th and 90th percentiles for all repetitions of the novices versus the experts

	Novices ($n = 11$)	Experts ($n = 6$)	Mann–Whitney U
	Median [10th,–90th perc]	Median [10th, –90th perc]	
F_{abs} [N]	2.1 [0.7, 6]	3.8 [1.8, 7.3]	$p < 0.05$
α [deg]	18 [–22, +139]	26 [0, +72]	$p < 0.05$
β [deg]	–1 [–171, +53]	4 [–54, +44]	$p < 0.05$

Similar values are given for the angles α and β , which indicate the direction of F_{abs} in the vertical and horizontal planes, respectively. The 10th percentile for α is defined as rotation to the dorsal side, and the 90th percentile is defined as rotation to the volar for a left wrist. The 10th percentile for β is defined as rotation to the radial side for a left wrist, and the 90th percentile is defined as rotation to the ulnar side for a left wrist. All three parameters are significantly different between novices and experts.

Fig. 4 The median values of F_{abs} of all novices for both Tasks 1 and 2 per trial. The error bars indicate the 10th and 90th percentiles of F_{abs} . The two horizontal dotted lines indicate the 10th and the 90th percentile of F_{abs} of the experts.

Fig. 5 The median values of angle α of all novices for both Tasks 1 and 2 per trial. The error bars indicate the 10th and 90th percentiles of α . The two horizontal dotted lines indicate the 10th and the 90th percentile of α of the experts.

Fig. 6 The median values of angle β of all novices for 6 landmarks per trial. The error bars indicate the 10th and 90th percentiles of β . The two horizontal dotted lines indicate the 10th and the 90th percentile of β of the experts.

Discussion

Objective, reliable, and reproducible evaluation of skills is important in training of arthroscopic procedures, not only to monitor skills progression but also to ensure safe tissue handling.^{12–14} The findings of this study indicate that force information during training in wrist arthroscopy can be recorded and that there is a significant difference between novices and experts.

Furthermore, the ranges of the force directions in both planes remain consistently large compared with the smaller ranges of the experts. A smaller range of force directions indicates a smoother movement.

Since the forces exerted on the wrist cannot be seen or felt by the supervisor, it is difficult to give adequate directions. As we demonstrated in accordance with other studies that objective force measurement is possible in a skills training setting, the next step can be taken to provide and implement proper feedback as determined from the measurements. For example, Horeman et al studied force feedback by providing a colored arrow visualized in the arthroscopic view with augmented reality. The color of the arrow indicates proper (green) or improper (red) tissue contact, and the direction of the arrow indicates the direction of the force.¹⁵ Other cues are also feasible, such as audible signals.

This study has limitations. All of the testing was done on cadaver specimens, which may not approximate the clinical situation. Furthermore, the establishment of the portals was not assessed, which is a major difficulty for most novice arthroscopists. The numbers were too small to perform a statistical analysis to determine whether the force parameter and angle α and β differences between the novices and the experts were statistically significant. Measurements were performed on only three cadaver wrists and 11 participants. After repetitions, the portals will widen and tissue inside the wrist can deteriorate. We took measures to minimize this by using several wrists and creation of the portals by ourselves to make sure they were at the proper locations. This was a trade-off, since using more than one cadaver introduces a bias in terms of complexity. Different wrists could have been more tight or present scar tissue. To minimize the differences, one of us (MO) performed the navigation task after the creation of the portals and removed fibrous tissue to allow normal navigation. Another limitation is the number of participants.

As Howells et al eloquently described, arthroscopy has some notable differences in techniques compared with other operative procedures. One hand is often used for camera manipulation, the instruments are shorter, the operating field is a more confined space, and there is greater degree of tactile feedback from the cartilaginous surfaces.¹³ Our results indicate that learning to navigate through a wrist and to use the tactile feedback for safe tissue manipulation could benefit from monitoring the force and the amount of manipulation of the scope and instruments exerted during training. Although the experts used more force to navigate through the wrist, this allowed an economy of motion, and they avoided cartilage injury by more precise instrument manipulation. The magnitude of the force does not seem to be as important,

since the articular injury does not occur by “pushing” the cartilage with the probe but rather by improper positioning of the instruments.

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Conflict of Interest

None

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