Kinematic Analysis of Surgical Dexterity in Intraocular Surgery

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Objective: To evaluate the potential of motion analysis as a discriminator of surgical skill during intraocular surgery.

Methods: Twenty-four subjects were divided into 3 groups (n=8 each) based on the number of completed phacoemulsification procedures: novice (n<10), intermediate (n=10-150), and expert (n>150). The Qualisys motion-capture system obtained data from the surgeons performing (1) corneal wound construction (incision), (2) continuous curvilinear capsulorrhexis (CCC), and (3) phacoemulsification lens extraction on artificial eyes. The main outcome measures were time, overall path length, and total number of movements. Statistical significance was set at P<.05.

Results: For the incision task, significant differences between the levels of experience were found for time (P=.001), number of movements (P=.001), and path length (P=.05). For the CCC task, significant differences were found between groups for time (P=.03) and number of movements (P=.03), but not for path length (P=.08). For the phacoemulsification task, significant differences were found between the 3 groups for time (P=.04), path length (P=.02), and number of movements (P=.04).

Conclusions: Motion analysis differentiated between surgeons with varying levels of experience performing phacoemulsification tasks, thus demonstrating construct validity. This technique may be useful in the subjective quantitative measurement of microsurgical skill with potential applications for training and research.


Surgical training and assessment is undergoing change, with a shift away from the apprenticeship model to include more emphasis on competency and outcome-based models. This has been driven, in part, by increasing evidence that high subjectivity, poor reproducibility, and large interobserver variation exist with traditional methods. The Accreditation Council for Graduate Medical Education in the United States and the Postgraduate Medical Education and Training Board in England have begun to address these issues by defining core competencies for residents to attain. Within ophthalmology, the assessment of surgical competence and technical skill has emerged as a core constituent of training.

Several useful surgical skill assessment tools have recently been described. These tools, however, retain a degree of subjectivity. Another development in the assessment of surgical skill is motion analysis, developed by Darzi. This technique involves the evaluation of the movements the surgeon’s hand makes, using various parameters leading to purely objective and quantitative numerical outcomes. This method has been shown to be a valid measure of dexterity in laparoscopic, open, and other surgical simulations. Saleh and Darzi recently validated this technique for corneal suturing using an electromagnetic tracker. Phacoemulsification is one of the core surgical skills in ophthalmic training and the most frequently performed procedure in ophthalmology. To date, kinematic analysis has not been adapted to intraocular surgery. In this study we apply a highly sensitive optoelectronic motion capture system to certain steps of the phacoemulsification procedure and evaluate its capability and usefulness as a discriminator of surgical dexterity.

METHODS

Participants

Twenty-four subjects were recruited from ophthalmic training hospitals in the greater London area. The level of prior ophthalmic training varied from first-year ophthalmology
trainees to ophthalmic surgeons with 30 years’ experience in intraocular surgery. Participants were divided into 3 groups (n=8 each) based on their total number of previously completed phacoemulsification procedures; novice was defined as less than 10 independently completed cases; intermediate, 10 to 150 procedures, and expert, more than 150 procedures. The stratification into subgroups was used for consistency with previous studies evaluating motion analysis in surgical training.1,2,14 The cutoff values for experience were determined prior to commencing the study and were selected based on previous experience with motion analysis,1,2,14 which helped define the lower cutoff, along with data from both human reliability analysis in cataract surgery10 and objective structured assessment in cataract surgery,5 which helped define the upper limit.

SIMULATED SURGICAL TASKS

Subjects performed 3 separate simulated surgical tasks that are components of phacoemulsification cataract extraction. All subjects were given standardized instructions prior to the task. All tasks were performed on artificial eyes (Royal College of Ophthalmologists, London, England) (Figure 1).

- Task 1: Construction of a standard 2-step incision (incision) using a 3.2-mm keratome blade (Rhein Medical Inc, Tampa, Florida).
- Task 2: Anterior chamber re-formation of the artificial eye with viscoelastic (Healon; Advanced Medical Optics [now Abbott Medical Optics], Abbott Park, Illinois) through the previously formed incision and constructing a continuous curvilinear capsulorrhexis (CCC) using a preformed Cystotome (BD Visitech, Franklin Lakes, New Jersey) and Utrata capsulorrhexis forceps (Rhein Medical Inc).
- Task 3: Complete removal of lens nucleus using the “divide and conquer” technique with the Storz Millennium phacoemulsification machine (Bausch & Lomb, Rochester, New York).

The simulated surgical tasks were designed to emulate stepwise modular training of phacoemulsification cataract surgery and be representative of core phacoemulsification skills. All subjects undertook each of the tasks in a standardized laboratory environment with the same prepositioned instruments and artificial eyes (Figure 1). An independent expert observer was present for all cases; their role was to ensure that each task was completed correctly.

MOTION ANALYSIS TECHNIQUE

The marker locations were selected to track both finger and hand segment motion in 3 dimensions and, at the same time, minimize encumbrance to the subject. Four markers were attached per hand as follows: the second metacarpal head (MCP2), fifth metacarpal head (MCP5), the midpoint between the base of the second and third metacarpal base (hand), and dorsally on the midpoint of the middle phalanx of the second phalange (index) (Figure 1). Size and placement of markers were determined following extensive pilot laboratory work calibrating the instrument for ophthalmic use.13 This distribution of markers allows for maximal sensitivity and accuracy for motion detection of the microsurgical hand movements seen during phacoemulsification cataract surgery.

DATA PROCESSING AND ANALYSIS

Detailed 3-dimensional coordinates for individual markers were captured at a sufficiently high sampling rate of 100 Hz.13,14 The data are then combined to compute the 3-dimensional position of individual small (10-mm-diameter) and lightweight markers. The marker locations were selected to track both finger and hand segment motion in 3 dimensions and, at the same time, minimize occlusion due to body parts, tools, and instruments present in the environment.

To accurately measure the fine hand movements seen during intraocular surgery, a previously validated tracking system was used.13 The 6-camera Qualisys ProReflex system (Qualisys Medical AB, Gothenburg, Sweden) was set up with motion capture units carefully positioned to cover the measurement volume and minimize occlusion due to body parts, tools, and instruments present in the environment.

Each motion capture unit (Figure 1) comprises a low-noise high-speed sensor, built-in microprocessor, and 250 infrared light-emitting diodes around a lens; this produces a strong and short strobe light. Using double-sided adhesive tape, retroreflective markers (Figure 1) are attached to the body segment for which motion is to be tracked. Reflected infrared light is then used to track the motion of the marker, with each motion capture unit providing a 2-dimensional view of the volume. A dynamic wand calibration of the system is performed with the aid of Qualisys Track Manager (Qualisys Medical AB) software; 2-dimensional data from multiple motion capture units are then combined to compute the 3-dimensional position of individual small (10-mm-diameter) and lightweight markers. The marker locations were selected to track both finger and hand segment motion in 3 dimensions and, at the same time, minimize occlusion due to body parts, tools, and instruments present in the environment.
The data were then exported and filtered using a 0-lag second-order digital Butterworth filter with a cutoff frequency of 10 Hz to reduce high-frequency noise. Simultaneous video recordings were carried out using a digital camcorder, allowing motion tracking data to be simultaneously synchronized and processed with the video recording.

Three parameters were analyzed to evaluate surgical dexterity: the time taken, the total path length covered, and the total number of movements to complete the surgical task. These indices were selected because they have been previously validated for use in ophthalmic surgery.12,13

A Kruskal-Wallis test was used to evaluate the statistical significance of the differences seen between the 3 groups (implemented in SPSS version 14; SPSS Inc, Chicago, Illinois).

### RESULTS

The novice group’s experience consisted of 0 to 3 prior procedures; intermediate, 22 to 71 procedures; and expert, 380 to more than 10 000 procedures.

The Table summarizes the results for time, number of movements, and total path length for the incision, CCC, and phacoemulsification tasks, respectively. The results demonstrate significant differences in path length, number of movements, and time taken, with the more experienced surgeons demonstrating greater efficiency in completing the given tasks.

A graphical representation of the results for the 3 tasks is given in Figures 2, 3, and 4. Evaluation of the incision task showed that significant differences were found between the 3 levels of experience for time ($P = .001$), number of movements ($P = .001$), and path length ($P = .05$). For the CCC task, significant differences were found for time ($P = .03$) and number of movements ($P = .03$), but not path length ($P = .08$). For the phacoemulsification task, significant differences were found between the groups for experience for time ($P = .04$), path length ($P = .02$), and number of movements ($P = .04$).

The data showed that time, path length, and number of movements were inversely associated with skill level, with higher skill level producing a lower numerical result. These figures showed that the variability within each group was also inversely related to the skill level.

### COMMENT

In this study we adapt kinematic and motion analysis technology, a purely objective tool, for both the acquisition and analysis of data to ophthalmic microsurgical tasks. This technique, though previously validated in ophthalmic surgery12 and other surgical specialties,5,14-16 was found to be difficult to adapt to phacoemulsification surgery. This was primarily owing to the fact that the system was not able to discriminate the very fine movements made in intraocular surgery. Technological advances now facilitate this discrimination with increased spatial resolution and sampling rate.

Our results show that motion analysis using the Qualisys system is not only capable of detecting the small move-

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**Table. Surgical Task Performance per Group**

<table>
<thead>
<tr>
<th>Parameter by Stage and Skill Level</th>
<th>Time Taken, min</th>
<th>Path Length, m</th>
<th>Subjects, No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Median (Range)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td><strong>Incision</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expert</td>
<td>1.05 (0.50)</td>
<td>0.95 (1.53)</td>
<td>3.83 (1.41)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1.57 (0.34)</td>
<td>1.60 (1.12)</td>
<td>4.47 (1.12)</td>
</tr>
<tr>
<td>Novice</td>
<td>3.15 (1.68)</td>
<td>2.89 (5.45)</td>
<td>7.60 (5.22)</td>
</tr>
<tr>
<td><strong>Continuous curvilinear capsulorrhexis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expert</td>
<td>1.85 (0.96)</td>
<td>2.02 (2.88)</td>
<td>3.11 (0.96)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>2.53 (1.14)</td>
<td>2.15 (3.41)</td>
<td>4.15 (2.43)</td>
</tr>
<tr>
<td>Novice</td>
<td>3.69 (1.43)</td>
<td>3.91 (3.64)</td>
<td>5.28 (2.49)</td>
</tr>
<tr>
<td><strong>Phacoemulsification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expert</td>
<td>3.51 (1.01)</td>
<td>3.42 (3.04)</td>
<td>1.66 (0.40)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>4.10 (0.82)</td>
<td>4.11 (2.53)</td>
<td>2.61 (2.57)</td>
</tr>
<tr>
<td>Novice</td>
<td>5.63 (1.72)</td>
<td>5.78 (4.77)</td>
<td>5.48 (3.47)</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td>.001</td>
<td>.05</td>
<td>.001</td>
</tr>
</tbody>
</table>

**Figure 2.** Box plot showing the overall number of movements used by each of the 3 groups to complete the 3 tasks.
ments of ophthalmic microsurgery, it can use this data to objectively discriminate between surgeons of differing levels of experience. The data showed that as surgeons’ experience increased, less surgical time, shorter path lengths, and fewer hand movements were required to complete the given tasks. This suggests an increasing efficiency in task execution with greater surgical experience.

The data from this study show that the motion analysis of phacoemulsification tasks with Qualisys has construct and concurrent validity, the ability to differentiate between different levels of skill when applied to the 3 tasks from phacoemulsification cataract surgery. Furthermore, as experience increased there was a reduction in the variability between the individuals within the cohort, perhaps suggesting that surgical skill may converge to a narrower spread of efficiency that all trainees should be aspiring toward. Additional information, including patient outcomes (such as visual acuity data) and surgeon complications (such as vitrectomy rates), was not collected as part of the study because a key aspect of motion analysis in surgical training is that it is to be used as an adjunct to existing tools (including logbook and audit). It adds further information to that currently recorded and, although future study will likely analyze the correlation between these parameters and motion analysis data, we felt that this analysis would comprise a substantial additional analysis and would be better formed as the basis of further study.

There are certain inherent limitations to our findings. First, the study was conducted in a wet laboratory environment on artificial eyes. Conducting the study under the conditions of live surgery would provide more accurate reflection of the surgeons’ performance. Second, the surgical tasks selected did not assess the entire surgical procedure; they only evaluated specific components of technical competence. However, these tasks were selected from modular steps used in the early training of phacoemulsification surgeons and represent core microsurgical skills that residents should be familiar with. The small sample size of this study incurs statistical limitations, and unequivocal proof that experience correlates with increased surgical skill has not, to the best of our knowledge, been demonstrated in any surgical discipline. However, previous studies have shown that this system is useful, with significant differences in skill between different experience levels having been demonstrated using a variety of evaluation methods, and was therefore used in this study. The effectiveness with which the surgical experience was stratified is encouraging and will hopefully spur further investigation into quantifying other variables and more clearly defining their relationship to surgical proficiency.

The findings presented here offer encouragement for the use of motion tracking as a potential additional objective method of assessment for microsurgical skill. It may therefore be of use as an adjunct in current training systems. By providing an objective and numerical rating, trainees could benchmark and aim to improve their score through enhancement of surgical skill. Furthermore, breakdown of the operation into individual parts with normative pools of motion data for surgeons of varying experience could prove helpful to the feedback of junior surgeons. A trainee experiencing difficulty with a certain portion of a procedure could then compare their motion data and get objective data regarding efficiency of task completion to help improve their skill. We are also currently investigating parameters in addition to efficiency that may help describe the movement quality, variability, and other biomechanically relevant variables.

In conclusion, motion analysis can be used to stratify surgical proficiency according to levels of surgical experience in phacoemulsification cataract surgery. Further research on the practical implementation of this method is required, including its potential to evaluate live surgery. Different forms of motion analysis have been successfully adapted to areas such as corneal suturing under the microscope and oculoplastic surgery. Our results offer encouragement that as further research takes place in this field, motion analysis will prove to be a useful modality in accomplishing the current goal of more objective surgical evaluation.
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REFERENCES


Archives Web Quiz Winner

Congratulations to the winner of our January quiz, Matthew T. Feng, MD, Research Fellow, Department of Ophthalmology and Vision Science, University of Arizona, Tucson. The correct answer to our January challenge was orbital ganglioneuroma. For a complete discussion of this case, see the Letters: Research Letters section in the February Archives (Choi HY, Lee JH, Park JM, Shin MK. Orbital ganglioneuroma in a young healthy person. Arch Ophthalmol. 2009;127[2]:223-225).

Be sure to visit the Archives of Ophthalmology Web site (http://www.archophthalmol.com) and try your hand at our Clinical Challenge Interactive Quiz. We invite visitors to make a diagnosis based on selected information from a case report or other feature scheduled to be published in the following month’s print edition of the Archives. The first visitor to e-mail our Web editors with the correct answer will be recognized in the print journal and on our Web site and will also be able to choose one of the following books published by AMA Press: Clinical Eye Atlas, Clinical Retina, or Users’ Guides to the Medical Literature.