EDUCATION CORNER

From the Vascular and Endovascular Surgery Society

Kinematics effectively delineate accomplished users of endovascular robotics with a physical training model

Cassidy Duran, MD,[a] Sean Estrada, PhD,[b] Marcia O'Malley, PhD,[b] Alan B. Lumsden, MD,[a] and **Jean Bismuth, MD,[a]** *Houston, Tex*

Objective: **Endovascular robotics systems, now approved for clinical use in the United States and Europe, are seeing rapid growth in interest. Determining who has sufficient expertise for safe and effective clinical use remains elusive. Our aim was to analyze performance on a robotic platform to determine what defines an expert user.**

Methods: **During three sessions, 21 subjects with a range of endovascular expertise and endovascular robotic experience (novices <2 hours to moderate-extensive experience with >20 hours) performed four tasks on a training model. All participants completed a 2-hour training session on the robot by a certified instructor. Completion times, global rating scores, and motion metrics were collected to assess performance. Electromagnetic tracking was used to capture and to analyze catheter tip motion. Motion analysis was based on derivations of speed and position including spectral arc length and total number of submovements (inversely proportional to proficiency of motion) and duration of submovements (directly proportional to proficiency).**

Results: **Ninety-eight percent of competent subjects successfully completed the tasks within the given time, whereas 91% of noncompetent subjects were successful. There was no significant difference in completion times between competent and noncompetent users except for the posterior branch (151 s:105 s; $P = .01$). The competent users had more efficient motion as evidenced by statistically significant differences in the metrics of motion analysis. Users with >20 hours of experience performed significantly better than those newer to the system, independent of prior endovascular experience.**

Conclusions: **This study demonstrates that motion-based metrics can differentiate novice from trained users of flexible robotics systems for basic endovascular tasks. Efficiency of catheter movement, consistency of performance, and learning curves may help identify users who are sufficiently trained for safe clinical use of the system. This work will help identify the learning curve and specific movements that translate to expert robotic navigation. (J Vasc Surg 2015;61:535-41.)**

In 2007, the Food and Drug Administration approved a flexible robotic catheter designed for use in cardiac mapping and ablation procedures. Soon thereafter, interventionalists began exploring the system for its potential use in the peripheral vasculature, demonstrating promising applications for flexible robotics. In the past 2 years, Hansen Medical (Mountain View, Calif), a leading developer of flexible robotic systems, gained CE Mark and Food and Drug Administration approval for the Magellan robotic system, designed specifically for peripheral vascular interventions. Interest is rapidly growing as an expanding group of users have begun to use the robot to perform increasingly complex and challenging endovascular interventions.

Lessons learned from the early adopters of the electrophysiology system indicated that a longer than anticipated learning curve might impede utilization of the system because of concerns about complications related to lack of user experience.[1] However, effective and safe training and certification processes have not yet been established. As is the case with traditional manual endovascular training, objective performance metrics for skills assessment do not exist. There are, however, several examples of research in other surgical subspecialties in which measurement of expert performance has been assessed by kinematic data derived from motion tracking to quantify smoothness and efficiency (widely accepted surrogates for expertise).

Researchers investigating performance of open, laparoscopic, and even robotic surgery have explored the potential to evaluate surgical tool motions as a means to assess skill level. Results from previous studies have successfully

From the Department of Cardiovascular Surgery, Methodist DeBakey Heart & Vascular Center, Houston Methodist Hospital[a]; and the Mechatronics and Haptics Interfaces Laboratory, Rice University.[b]

Funding: This study was funded in part by an education grant from Hansen Medical.

Author conflict of interest: J.B. and A.B.L. have been paid a consulting fee by Hansen Medical in the past.

Presented at the Annual Meeting of the Vascular and Endovascular Surgery Society, Boston, Mass, June 4-7, 2014.

Reprint requests: Cassidy Duran, MD, Department of Cardiovascular Surgery, 6550 Fannin St, Ste 1401, Houston, TX 77030 (e-mail: caduran@houstonmethodist.org).

The editors and reviewers of this article have no relevant financial relationships to disclose per the JVS policy that requires reviewers to decline review of any manuscript for which they may have a conflict of interest.

0741-5214

http://dx.doi.org/10.1016/j.jvs.2014.10.104

demonstrated an ability to assess the skill level of surgeons with use of quantitative measures derived from motion analysis of surgical tools.[2-4]

Motion-based metrics include those that directly characterize instrument kinematics (eg, path length, acceleration, or input frequency) as well as those inspired from principles of human motor control, such as smoothness of movement and movement efficiency. It is hypothesized that metrics of smoothness and efficiency, which are derived from the kinematic data of tool tip motion, will give insight into the quality of movement.[5] Movement smoothness is widely regarded as a hallmark of skilled, coordinated movement[6,7] and has been used as a measure of motor performance in basic motor control tasks[8] and rehabilitation applications.[9,10] However, it has yet to be demonstrated if such metrics are also relevant to endovascular applications.

This study explores the applicability of motion-based measures of performance, such as those previously demonstrated for laparoscopic procedures, to performance of endovascular tasks on a flexible robotic platform. The lack of an effective training paradigm to identify proficient users underlines the need for the current study, particularly as navigation using flexible robotics is fundamentally different from standard endovascular techniques.

METHODS

Subjects. Twenty-one subjects (19 men, two women) were enrolled in the study, including seven vascular surgery or cardiology residents, six vascular fellows, six faculty vascular surgeons or interventional cardiologists, and two control users of the robotic system (engineers for the system with more than 400 hours of experience driving the robot). The subjects' endovascular experience ranged from novice with fewer than 20 endovascular cases having been performed to vascular surgeons with more than 20 years of experience in endovascular surgery. Institutional Review Board approval was obtained, and all subjects consented to participation voluntarily.

Subjects were classified as either competent or noncompetent with respect to the robot on the basis of previous experience using the system in a training or clinical setting. Five subjects were categorized as competent as they had spent a minimum of 20 hours training on the system and, in the case of two subjects, had experience performing clinical cases using the robotic platform. The remaining 16 subjects were considered noncompetent, although all participants completed the Food and Drug Administration-mandated certification offered by a certified trainer from Hansen Medical. Previous endovascular experience with traditional manual catheter interventions was also examined, with those having experience in >250 cases falling into the competent group.

Procedure. Each participant completed each of four endovascular tasks on a silicon model designed to test fundamental skills of endovascular surgical procedures. The order of tasks was randomly assigned for each session and for each subject to restrict potential learning or recall based solely on order. The four endovascular tasks involved catheterization into an anterior branch, maneuvering "up and over" a bifurcation, cannulating a posterior third-order branch, and cannulating a first-order branch with 90-degree takeoff from the main trunk under fluoroscopic guidance from a Zeego (Siemens, Malvern, Pa) flat panel imaging system. The up and over task as well as the right-angle branch cannulations were performed with the C-arm in the straight anterior-posterior position. The anterior branch was cannulated at 75 degrees left anterior oblique, and the posterior branch required a mid-task reposition (starting in anterior-posterior and rotating after going up and over to left anterior oblique). Success was defined as reaching the target in the branch of interest with the catheter tip within the 5-minute time limit.

Performance measures. Multiple outcome-based performance measures were assessed, including success or failure to achieve target in allotted time, global rating of performance, procedure time, and motion metric analysis. The Global RAting Assessment Device for Endovascular Skill (GRADES) is a validated (submitted for publication) global assessment tool for endovascular performance that is scored on a 5-point Likert scale (Table I). The pertinent GRADES domains included efficiency, ability to manipulate the surgical tools (catheter and guidewire), and use of the device. Data from the GRADES were used to augment the kinematic data, and correlation coefficients between the GRADES scores and motion metrics were obtained.

Motion capture and analysis. An electromagnetic tracking device (Aurora Window Field Generator; National Digital Incorporated, Waterloo, Ontario, Canada) was used to track the position and orientation of the catheter tip (according to previously validated techniques),[11] and kinematic movement of the catheter tip was recorded. Motion tip data were then scored by applying motion metric analysis according to well-validated techniques described in Table II.

Quantitative data postprocessing. Postprocessing steps were conducted on data obtained from the electromagnetic sensors, and Savitzky-Golay filtering techniques[12] were used to remove noise.

Statistics. Statistical analysis was performed with SPSS software, version 22 (SPSS Inc, Chicago, Ill). Each performance measure computed from the motion data was further analyzed by multiple analyses of variance to highlight significant effects of the between-subject factor of group (competent/noncompetent) and of the within-subject factors of session and task.

To determine which metrics demonstrated an ability to discern skill level among the subjects performing endovascular tasks, correlation coefficients between the combined global rating score and metric score were computed. All ability group differences were reported to demonstrate the metric's utility at differentiating skill level, and all relevant main effects and interactions were examined.

RESULTS

Ninety-eight percent of competent subjects successfully completed the tasks within the given time, whereas

Table I. Global RAting Device for Endovascular Surgery (GRADES)

Efficiency	Constantly changing focus of operation or persisting at a task without progress	Slow but planned and reasonably organized	Confidently conducts operation, maintaining focus on component of the procedure until better done by another approach
Wire and catheter manipulation	Often unaware of the wire position; frequent loss of wire without losing position	Maintains awareness of wire position with occasional loss of wire access; can exchange a catheter over wire but slowly and with hesitation; occasional back-and-forth motion of wire	Always aware of wire position; no loss of wire access; efficient exchange of catheters over wire without hesitation
Use of the device	Inappropriate position, pressure, and deployment	With effort can position the device; seems to understand appropriate pressures and deployment procedures but is hesitant	Effortlessly positions the device in the appropriate position and accurately uses the correct pressure and deployment strategies
Image quality	Unable to clearly capture relevant anatomy and does not understand which views are necessary for the case	Clearly captures relevant anatomy after several attempts; uses different views to do so; does not capture all required views for the procedure	Clearly captures relevant anatomy within the first few attempts; understands and uses all required views for optimal imaging
Image safety (fluoroscopy, contrast material use)	Uses much more fluoroscopy or contrast material than is required to capture good-quality images; seems unaware of the fluoroscopy or contrast material use	Makes an effort to minimize fluoroscopy and contrast material use but uses more than is absolutely necessary to capture good-quality images	Clearly understands the importance of minimizing radiation exposure and contrast material use and does so while simultaneously capturing high-quality images
Autonomy	Unable to complete the entire procedure, even with extensive verbal guidance	Able to complete procedure with moderate verbal prompting	Able to complete procedure independently without verbal prompting

Domains of efficiency, wire and catheter manipulation, and use of the device were included for analysis of robotic task performance.

Table II. The fundamental tasks list, as developed and refined by consensus of members of the Education Committee of the Association of Program Directors in Vascular Surgery

Metric	*Definition*
Nondimensional jerk	Jerk, the third derivative of time, is defined by change in acceleration. Nondimensional jerk counts the number of acceleration changes in a given time or task. Expert motion minimizes the number of changes in acceleration.
Submovement number/duration	All motion is composed of smaller submovements. Experts complete movements with a smaller number of total movements that have a longer duration, resulting in a smoother motion curve.
Spectral arc length	Metric assessed on the frequency domain, whereby a count of the frequency of changes in acceleration during a given time/task indicates level of expertise for the given task.

91% of noncompetent subjects were successful. There was no significant difference in completion times between competent and noncompetent users except for the posterior branch, which was the most complex task (Table III). Table IV displays the correlation coefficients for each of the motion metrics and GRADES scores. The values in the table were obtained by averaging the data for each metric across all tasks and all sessions. Metric scoring clearly differentiated the performance levels between the two user groups for each type of motion analysis for the tasks overall (Fig 1) as well as on a per task basis (Fig 2).

Table III. Completion times (seconds) for competent and noncompetent subjects on the fundamentals of endovascular surgery model

Task	*Competent*	*Noncompetent*	P *value*
Anterior	82.1	88.7[a]	.66
Up and over	105.3[a]	106.7[a]	.95
Third-order/posterior	151	196.3[a]	.01
Right angle	86.4	91.3[a]	.73

Times are based on averages for the group and for failures; the 300-second cutoff value was used for the purposes of analysis.
[a]Indicates that there were failures to complete the task by one or more users, falsely lowering the group average.

Table IV. Correlation coefficients and *P* values comparing motion metrics and global rating scores for manual catheterization of physical model

Metric	R *(correlation)*	P *value*
Non-Dimensional Jerk Metric	.52	.016
Spectral arc length metric	.692	<.001
Number of submovements	.688	<.001
Average submovement duration	.628	.0023

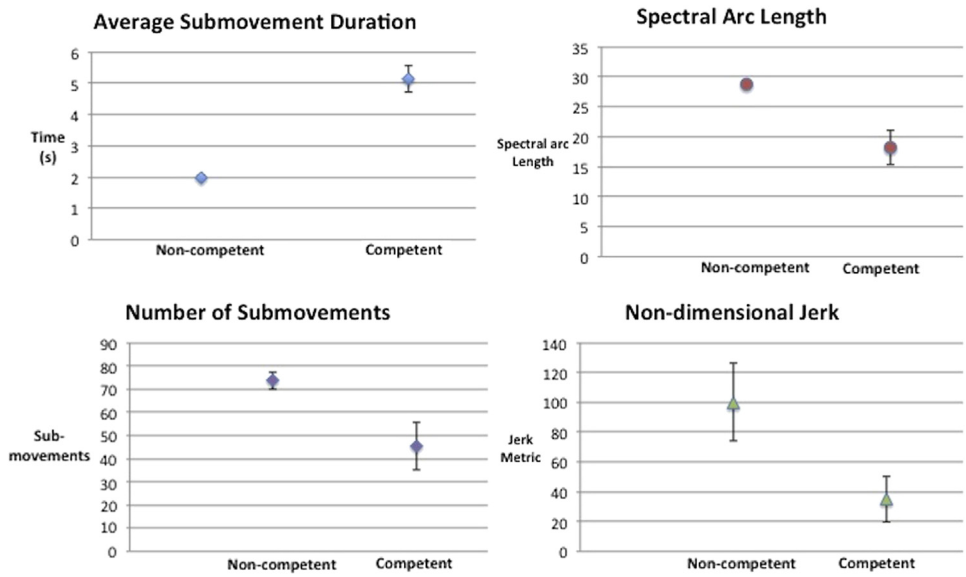

Fig 1. Mean metric score for noncompetent vs competent subjects after performing four endovascular tasks using robotic catheterization on the physical model. The *error bars* represent standard error of the mean.

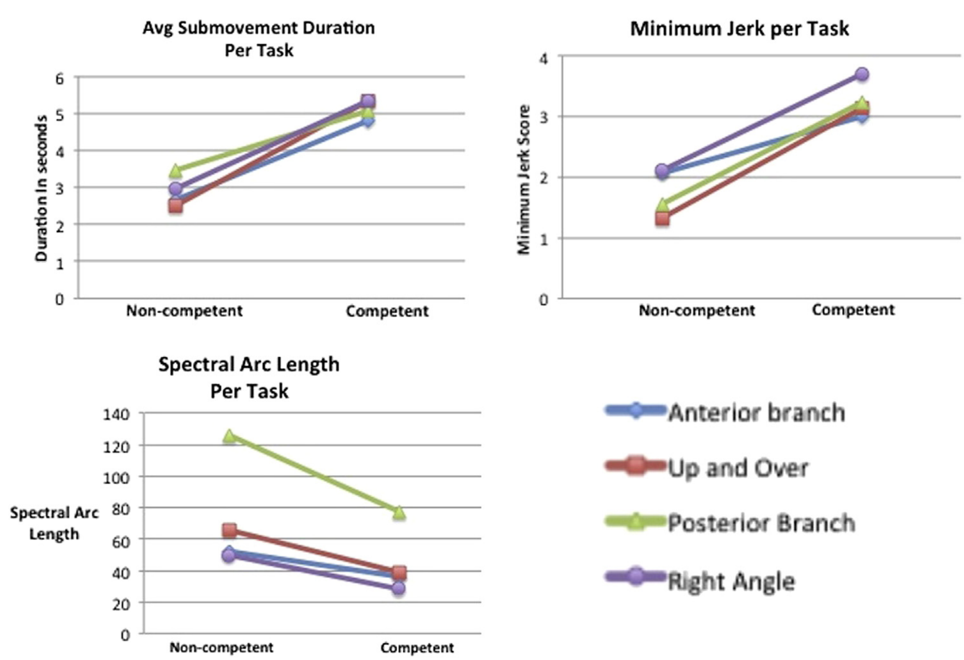

Fig 2. Mean metric scores per task analysis for average submovement duration, minimum jerk, and spectral arc length tasks.

In examining performance by session, a linear trend suggests that subjects exhibit smoother movements on session 3 compared with session 1 (Fig 3). Examined more closely, Fig 4 shows plots of the two reliable session/ability group interactions for scores from the average submovement metrics, which indicate that in fact only the noncompetent groups showed improvement in performance metrics, whereas the competent group performed consistently across all three sessions. The noncompetent subjects showed a reliable effect for the sessions factor ($P < .001$) and a reliable linear contrast for this effect ($P < .001$).

DISCUSSION

Flexible robotics has the potential to become an important tool for performing increasingly complex endovascular procedures. As a growing number of users begin to adopt

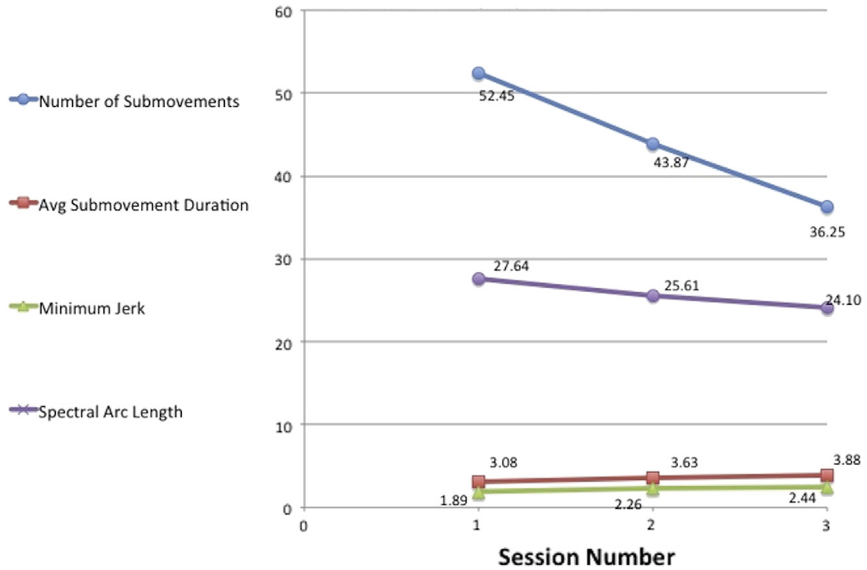

Fig 3. Learning effects: metric score means on per session analysis.

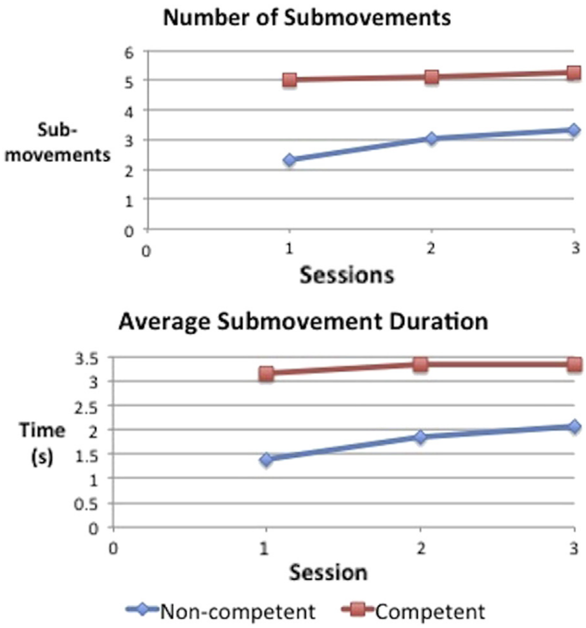

Fig 4. Plots of the two session/ability group interactions for scores from the average submovement duration and submovement number metrics.

this technology into their practice, having the ability to identify those who have gained sufficient mastery of the system for clinical use has the potential to maximize benefit and to minimize complications for patients. Inefficient users are likely to become frustrated and to undergo user fatigue, potentially abandoning the technology. This study presents a mechanism for assessing objective motion-based metrics as they apply to performance of basic endovascular tasks on a robotic platform, which promises to be able to identify user proficiency, thereby promoting effective use of the technology.

Kinematic data give insight into the quality of movement, such as smoothness of movement and efficiency, which is widely regarded as a hallmark of skilled, coordinated movement. Smooth, well-coordinated movements are also a key feature of healthy, well-developed and trained motor behavior, and measurements of smoothness have been used to assess motor performance of healthy persons and in the setting of stroke to quantify improvements in motor function with rehabilitation.[8-11] In this study, motion analysis was used to identify quantitative metrics that differentiate the skill level of subjects with a range of previous related endovascular experience while they perform a set of fundamental endovascular surgical tasks on a robotic platform. Whereas it has been shown that objective metrics of performance can be derived from motion data for simple motor control tasks and rehabilitation applications, this study demonstrates that such metrics are also relevant to more complex tasks, such as those required in surgical applications.

Functionally, the robotic catheter system has a sheath and catheter that telescope within one another, each with six degrees of freedom. Identifying the most cohesive interaction of the sheath and catheter should provide the most effective trajectory, which is ultimately the goal. These interactions between catheter and sheath challenge current endovascular techniques as noted in this study, where endovascular experience does not necessarily lead to effective robotic use. Understanding of these interactions will not only allow more goal-oriented training of novice users but also provide the user with a constructive approach toward endovascular navigation by correlating motion metrics with user inputs into the system.

The metrics in this study are well-validated tools for quantifying smoothness on the basis of motion data.[12-15] The nondimensional jerk metric likely reflects that unfamiliarity with the robot leads users to try different strategies and to make more erratic movements when moving the catheter in multiple directions to attempt to cannulate the target of interest. Spectral arch length examines the frequency spectrum as opposed to the time domain. Because performance was not correlated to time, assessment on the frequency domain offered an alternative approach for quantifying the complexity of the speed trajectory and therefore to demonstrate yet another valuable means for objective measurement of performance. The submovement extraction algorithms are designed to identify the number of discrete units of movements and key characteristics of those movements for motion data. They showed multiple strong correlations with the experimental data because they are sensitive to alterations in motor behavior, robust to measurement noise, and nondimensional and quantify smoothness in a consistent manner.[6] Competent subjects showed lower smoothness scores, and the competent subjects' scores had the smallest variance. The metric scores delineate a pathway for assessing performance of endovascular robotic skills in a reliable, reproducible, and objective fashion.

One weakness of the study is that most metrics did not show as strong a correlation as we have seen in corresponding work analyzing motion for manual techniques. The GRADES tool was not established to evaluate robotic performance; rather, it is a tool for assessment of traditional manual endovascular techniques. As such, although we believe there is value in using it as an additional method for assessment, it probably lacks sensitivity for capturing specifics of robotic performance.

The results highlighted some additional important trends. Perhaps the most striking result was the finding that previous endovascular experience does not affect technical skill on the robotic platform. The implications for credentialing and training may be crucial to the safe and successful implementation of robotic systems into clinical practice. Prior work has shown that novices have steeper learning curves for robotic interventions than experienced interventionalists do,[16] and the learning curves shown here corroborate that. Whereas we cannot extrapolate that the results indicating a strong learning effect also imply that clinically significant skill was obtained, as judgment in the operating room is dependent on far more than technical skill, it has important implications that merit further examination.

The learning effects for the noncompetent subjects, whose smoothness curves improved from session 1 to session 3, whereas the competent subjects' smoothness scores remained consistent, represent an area where the learning curve itself could be an indication of clinical preparedness. Furthermore, there seems to be a threshold of performance that could be indicative of user readiness for clinical cases. Although all subjects had completed the mandatory training by a certified instructor from Hansen, most of the subjects in the noncompetent group had no additional experience using the robotic platform in practice sessions, and none had performed any clinical interventions. The number of previous hours of robotic experience of the competent subjects markedly affected performance as assessed by kinematic data. Experience with traditional endovascular techniques, on the other hand, had no impact on robotic performance. Given the relative ease of capturing this information, we may be able to easily identify an objective goal based on kinematic data that indicates user competence with the system. Pending further studies in clinical settings, this remains an open research question.

CONCLUSIONS

The results of this study confirm that motion metrics reliably differentiate users on the basis of robotic experience. In addition, they highlight an important finding that experience with traditional manual catheter-based interventions does not necessarily transfer to the robotic platform and finally that learning curves may be a surrogate that enables us to identify competent users. These results may serve as a solid basis for future research that could result in meaningful improvements in the way we train surgeons to use flexible robotics. As technology continues to expand our operative horizons, we must begin to use technological advances to bring our approach to surgical training out of the 20th century, and objective assessments through kinematics may represent a meaningful path to do just that.

AUTHOR CONTRIBUTIONS

Conception and design: JB, CD, MO, AL
Analysis and interpretation: CD, SE
Data collection: SE
Writing the article: CD, SE
Critical revision of the article: JB, MO, AL
Final approval of the article: JB, MO, CD, SE, AL
Statistical analysis: SE
Obtained funding: JB, CD
Overall responsibility: CD

REFERENCES

1. Bai R, Biase L, Valderrabano M, Lorgat F, Micohova H, Meverfeldt U, et al. Worldwide experience with the robotic navigation system in catheter ablation of atrial fibrillation: methodology, efficacy and safety. J Cardiovasc Electrophysiol 2012;23:820-6.
2. Rosen J, Brown D, Barreca M, Chang L, Hannaford B, Sinana M. The blue dragon—a system for monitoring the kinematics and the dynamics of endoscopic tools in minimally invasive surgery for objective laparoscopic skill assessment. In: Westwood JD, Westwood SW, Fellander-Tsai L, Haluck RS, Robb RA, Senger Set al., editors. Medicine Meets Virtual Reality 02/10. Studies in Health Technology and Informatics. Washington, DC: IOS Press; 2002. p. 412-8.
3. Hofstad EF, Vapenstad C, Chmarra MK, Lang T, Kuhry E, Marvikl R. A study of psychomotor skills in minimally invasive surgery: what differentiates expert and nonexpert performance. Surg Endosc 2014;27: 854-63.
4. Hernandez JD, Bann SD, Munz Y, Moorthy K, Datta V, Martin S, et al. Qualitative and quantitative analysis of the learning curve of a

simulated surgical task on the Da Vinci System. Surg Endosc 2004;18: 372-8.

5. Balasubramanian S, Melendez-Calderon A, Burdet E. A robust and sensitive metric for quantifying movement smoothness. IEEE Trans Biomed Eng 2012;59:2126-36.
6. Flash T, Hogan N. The coordination of arm movements: an experimentally confirmed mathematical model. J Neurosci 1985;5:1688-703.
7. Huang FC, Gillespie RB, Kuo KD. Visual and haptic feedback contribute to tuning and online control during object manipulation. J Mot Behav 2007;39:179-93.
8. Huegel JC, Celik O, Israr A, O'Malley MK. Expertise-based performance measures in a virtual training environment. Presence: Teleoperators and Virtual Environments 2009;18:449-67.
9. Rohrer B. Evolution of movement smoothness and submovement patterns in persons with stroke [PhD dissertation]. Massachusetts Institute of Technology; 2002.
10. Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, et al. Movement smoothness changes during stroke recovery. J Neurosci 2002;22:8297-304.
11. Wood BJ, Zhang H, Durrani A, Glossop N, Ranjan S, Lindisch D, et al. Navigation with electromagnetic tracking for interventional radiology procedures: a feasibility study. J Vasc Interv Radiol 2005;16:493-505.
12. Savitzky A, Golay MGE. Smoothing and differentiation of data by simplified least squares procedures. Anal Chem 1964;36:1627-39.
13. Nagasaki H. Asymmetric velocity and acceleration profiles of human arm movements. Exp Brain Res 1989;74:319-26.
14. Hogan N, Sternad D. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. J Mot Behav 2009;41:529-34.
15. Takada K, Yashiro K, Takagi M. Reliability and sensitivity of jerk-cost measurement for evaluating irregularity of chewing jaw movements. Physiol Meas 2006;27:609-22.
16. Riga CV, Bicknell CD, Hamady MS, Cheshire NJ. Evaluation of robotic endovascular catheters for arch vessel cannulation. J Vasc Surg 2011;54:799-809.

Submitted Aug 10, 2014; accepted Oct 30, 2014.