Motion-based Technical Skills Assessment in Transoesophageal Echocardiography

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Abstract. This paper presents a novel approach for evaluating technical skills in Transoesophageal Echocardiography (TEE). Our core assumption is that operational competency can be objectively expressed by specific motion-based measures. TEE experiments were carried out with an augmented reality simulation platform involving both novice trainees and expert radiologists. Probe motion data were collected and used to formulate various kinematic parameters. Subsequent analysis showed that statistically significant differences exist among the two groups for the majority of the metrics investigated. Experts exhibited lower completion times and higher average velocity and acceleration, attributed to their refined ability for efficient and economical probe manipulation. In addition, their navigation pattern is characterised by increased smoothness and fluidity, evaluated through the measures of dimensionless jerk and spectral arc length. Utilised as inputs to well-known clustering algorithms, the derived metrics are capable of discriminating experience levels with high accuracy (>84%).

Keywords: Skill Assessment, Motion Analysis, Transoesophageal Echocardiography

1 Introduction

Transoesophageal echocardiography (TEE) is carried out by imaging the heart with an ultrasound (US) transducer, attached to the tip of a flexible endoscope (probe), navigated through the oesophagus proximally to the heart. TEE provides clear and detailed imaging of the four chambers and the valves, enabling accurate cardiovascular diagnosis and monitoring. As a minimally-invasive (MI), image-guided procedure, TEE requires complex psychomotor skills and a high level of coordination. Professional accreditation organisations routinely publish guidelines and recommendations on training practices and the cognitive and technical skills required for performing TEE [3,9]. In summary, TEE practitioners must demonstrate proficiency in: (a) navigating the US probe safely through the oesophagus; (b) adjusting the scanning plane so as to obtain the necessary imaging views; (c) accurately evaluating the heart's functionality and recognising abnormal conditions. Essentially, (a) and (b) pertain to technical manipulation skills while (c) to medical knowledge and understanding of pathologies.

In order for new interventionalists to develop the necessary technical skills, specific and constructive assessment/feedback is necessary. However, the current gold standard of surgical evaluation through expert supervision and manual assessment is inefficient, laborious and with limited standardisation. As a result, alternative directions for training and assessment ought to be explored. Breakthroughs in computing enabled the development of virtual reality (VR) systems that simulate the operational environment with high fidelity. They provide a platform for trainees to hone primarily their dexterous skills in an environment that poses no patient risk, without the need for direct supervision. To fully compliment surgical training, VR simulators must incorporate detailed performance feedback that will assist users to refine their skills. So far these systems are restricted in providing generic metrics without benchmarking, that are generally considered as surrogate markers of surgical competency [6, 8].

Motion analysis as a tool to evaluate competency is currently unexplored in the field of TEE. Motivated by studies in MI procedures (e.g. laparoscopic, endovascular) that have reported a strong correlation between tool kinematics and surgical ability [5,7,10], we hypothesised that by analysing the motion pattern of the tip of the TEE probe (that carries the US transducer) and deriving representative metrics, surgical skills can be objectively evaluated. Thus far, basic probe kinematics have only been used to measure the improvement of trainees during training/teaching with simulators, but not for TEE skills assessment [4,11]. This work differs from such studies, which chiefly employ qualitative manual evaluation [2,11]. Intuitively, differences are expected between experts and novices, but the features to best represent these are not established. Our main objective is to identify the motion metrics that can effectively characterise and assess TEE surgical experience. This is crucial towards automated assessment and has not been reported for TEE.

We employed a high-fidelity TEE simulator, equipped with a probe with the same manoeuvrability as standard probes, in experiments with both expert and novice practitioners. The motion of the probe was captured with the simulator's software. A set of kinematic features was derived , introducing previously unexplored smoothness measures as we expect this feature to be indicative of the skill level. We then investigated their correlation with experience and found that the majority of the formulated metrics show statistical significance. Ultimately, the derived features were used as inputs to clustering algorithms yielding high accuracy ($> 84\%$) in classifying the participants according to their experience group.

(a) (b) (c)

Fig. 1: (a) A volunteer operating the HeartWorks simulator ; (b) 3D Rendering of the heart model, the probe and US scanning field; (c) The simulated US image

2 Methods

2.1 HeartWorks VR simulator

The HeartWorks TEE simulator (Inventive Medical, Ltd, London, U.K.) was used as the experimentation platform. This system, illustrated in Fig. 1a involves an upper-torso mannequin with a mouth opening to emulate probe insertion. The HeartWorks probe has similar shape, dimensions and articulation capabilities (flexion, rotation, angulation), as standard TEE probes. Dedicated VR software generates a high-fidelity 3D rendering (Fig. 1b) of a beating human heart simulating cardiovascular activity (normal and abnormal). An ultrasound detector in the mannequin detects the position and orientation of the US plane which is then used to generate the 2D US image (Fig. 1c) from the heart model. Both the 2D US image and the 3D animation of the heart with the inserted probe are illustrated in the simulator's monitor. This allows the user to associate the obtained US image with the anatomical position of the probe. By visualising only the US screen the overall experience of the HeartWorks simulator is similar to an actual TEE system in the operating theatre, as it was the case in our experimentation.

Similar to standard multi-plane TEE probes the HeartWorks probe is capable of five movements, visualised in Fig. 2. Firstly, moving the probe up and down (advancement/ withdrawal) in the oesophagus. The probe can be also twisted to the right (clockwise from the operators prospective at the head) or left (counterclockwise) at the full range of $\pm 180°$. Control knobs enable anteflexion (flex anteriorly) and retroflexion (flex posteriorly) as well as lateral flexion (flex left and right) at the range of ±90°. Finally the US transducer on the tip can be rotated within the range of 0°(horizontal plane) to 180°, using buttons on the probe's handle.

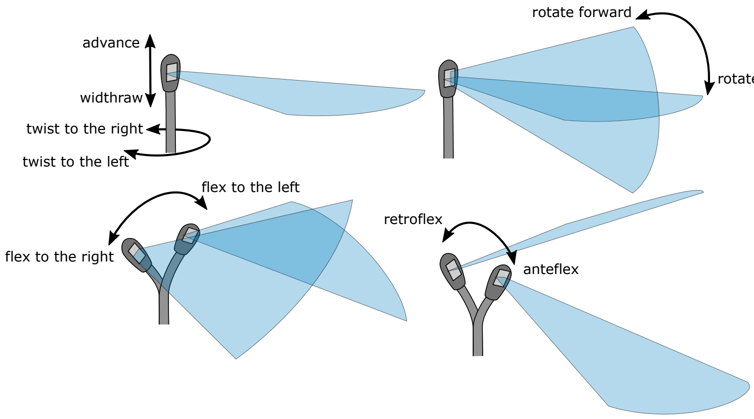


Fig. 2: The HeartWorks TEE probe movements: (upper-left) advancement/withdrawal and twist, (lower-left) flexion, (upper-right) US transducer rotation, (lower-right) anteflecion/retroflexion

2.2 Designed Study

For our assessment study, an experiment was designed where the participant was asked to obtain 10 image planes in a specific sequence with the simulator. These 10 cross-sectional views, listed in Table 1, are a subset of the 20 suggested views, designated by various organisations, as essential for a comprehensive cardiovascular evaluation during a TEE exam [3]. In the experiments, the participant operated the US probe while a supervisor (expert anaesthetist) provided support by guiding the participant through the views sequence and operating the HeartWorks software.

A total of 19 participants volunteered for this study and were divided into two experience groups. The experts group (n=7) comprised exclusively of accredited anaesthetists with more than 500 performed TEE exams while the novices group (n=12) consisted of trainees (cardiac and thoracic) during their residency program. No individual from the novice group had performed more than 10 TEE exams. Novice participants were recruited during a one-day simulation introduction course which included lectures on the basic diagnostic aspects of TEE intervention and two practice sessions, with the HeartWorks system. Experiments were performed at the end of the course, when volunteers had acquired familiarity with the simulator. Experts were also given time at the beginning of the experiments to familiarise themselves with the setup and the simulator.

Table 1: Sequence of the 10 US image planes used in the study

Sequence	US image view
1	Mid-Esophageal 4-Chamber (centered at tricuspid valve) - ME4C (TV)
2	Mid-Esophageal 2-Chamber - ME2C
3	Mid-Esophageal Aortic Valve Short-Axis - ME AV SAX
4	Transgastric Mid-Short-Axis - TG mid SAX
5	Mid-Esophageal Right Ventricle inflow-outflow - ME RV inflow-outflow
6	Mid-Esophageal Aortic Valve Long-Axis - ME AV LAX
7	Transgastric 2-Chamber - TG2C
8	Mid-Esophageal 4-Chamber (centered at left ventricle) ME4C (LV)
9	Deep Transgastric Long-Axis - dTG LAX
10	Mid-Esophageal Mitral Commissural - ME MV commissural

3 Data Analysis

Data are logged in a timestamped datafile with the values of the probe articulation parameters (depth of insertion, ante/retro flexion, lateral flexion, twist and transducer angulation). These are controlled directly by the operator. The software-generated 6DoF (3D position and orientation) of the probe's tip, used for positioning the probe in the 3D scene based on the user's handling, are also included. Fig. 3 illustrates representative examples of the depth and resulting probe trajectory, obtained from an expert and a novice volunteer. The differences are obvious with the expert demonstrating superior dexterity skills, resulting in smoother and fluid probe manipulation. Moreover the novice's erratic movement is dangerous for causing oesophageal perforation or trauma. The total procedure time (T_t) was extracted from the timestamp values. From the depth ($d(t)$) which is the main translation parameter we calculated the total path length (pl) travelled by the tip, the average velocity (v_d) and acceleration (a_d) as well as two measures of smoothness. The dimensionless jerk (j_d), a jerk metric independent of duration and amplitude and the spectral arc length (η_{sal}) a recently proposed, also dimensionless metric, found to be consistent and robust in measuring movement smoothness [1]. Considering the 1D parameter of depth, the two smoothness metrics are defined as:

$$j_d = \left(0.5 \int_{t_i}^{t_e} \dddot{d}(t)^2 dt\right) \cdot \frac{T_t^5}{p^2} \qquad \eta_{sal} = -\int_0^{\omega_c} \sqrt{\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{\|dV_d(\omega)\|}{d\omega}\right)^2} d\omega$$

where $\|V_d(\omega)\|$ is the amplitude normalised Fourier magnitude spectrum of the speed and ω_c is the upper frequency limit of the movement spectrum. This was set to $\omega_c = 40\pi$ rad/s or 20 Hz considering the spectrum of human hand movement. From the rotational parameters of the probe, the average values of twist (tw) and flexion (fl), were calculated and included in our analysis.

The obtained data were compared with the nonparametric Mann-Whitney U test with the difference considered significant for p-value < 0.05. The median and p-values for each parameters are listed in Table 2. We observe that experts complete the test faster (226.2s vs 439.9s, p=0.0007) and demonstrate

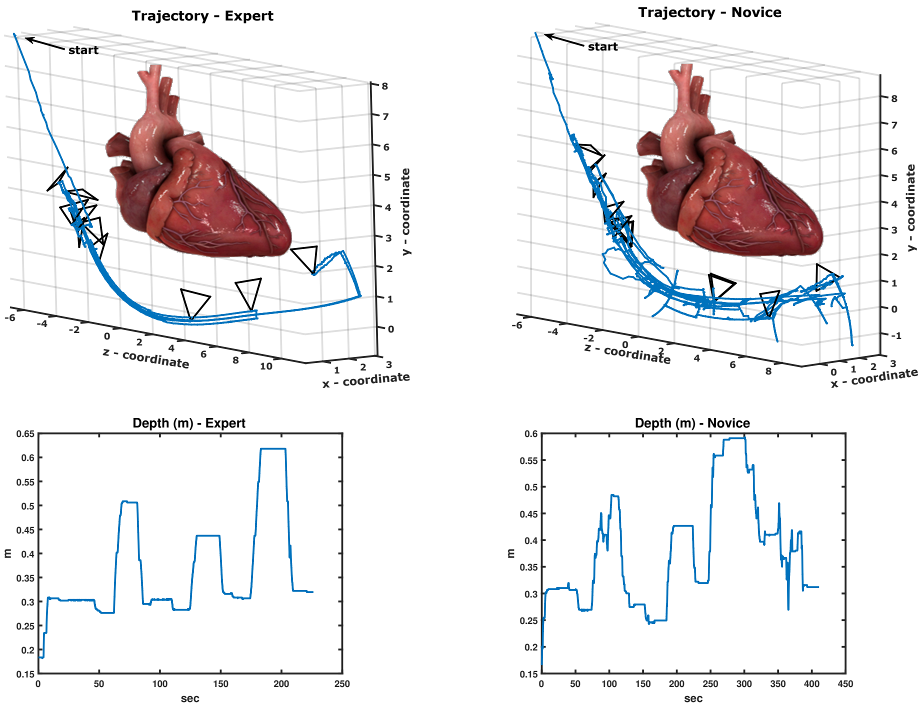
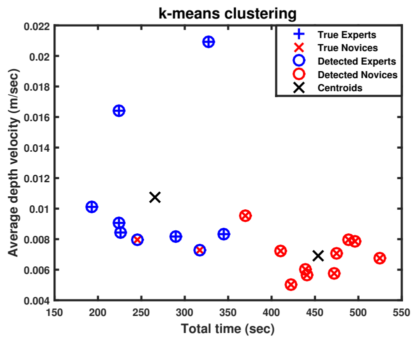


Fig. 3: Probe tip trajectories (top), coordinates are in 3D scene units (i.e. scaled meters), with position and orientation of US scanning fields (black triangles) in the 10 captured views; and depth (bottom) for an expert (left) and a novice (right). The smoothness and fluidity of the expert operator is evident compared to the novice.

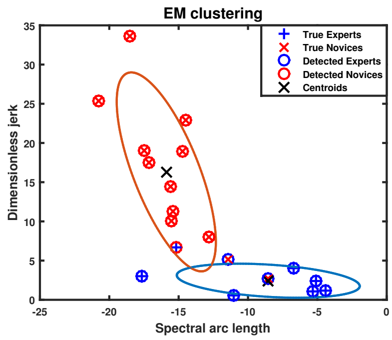
Table 2: Median Values and p-values of the calculated features

Parameter	**Novices**	**Experts**	**p-value (MW)**
T_t - Total time (sec)	439.9	226.2	0.0007
pl - Depth path length (m)	2.838	2.509	0.482
v_d - Average depth velocity (m/s)	0.007	0.009	0.0004
a_d - Average depth acceleration (m/s^2)	0.240	0.304	0.009
j_d - Depth dimensionless jerk	15.938	2.353	0.0004
η_{sal} - Depth Spectral arc length	-15.478	-6.684	0.028
tw - Average twist (deg)	18.832	11.906	0.0004
fl - Average flexion (deg)	6.748	5.619	1

higher velocity (0.009m/s vs 0.007m/s, p=0.0004) and acceleration (0.304m/s vs 0.240m/s, p=0.0009) with the differences being statistically significant. This is attributed to the experts superior handling ability that allows them to reach the



(a)



(b)

Fig. 4: Clustering results; (a) K-means with T_t and v_d (89.47%); (b) Expectation-maximisation with j_d and η_{sal} (84.21%)

target images in a more efficient, economical way. The smoothness parameters of the experts exhibit a lower median value for dimensionless jerk (2.353 vs 15.938, p=0.0004) and higher for spectral arc length (-6.684 vs -15.478, p=0.028) with significant differences. Both observations (lower j_d and higher η_{sal}) suggest that the experts handling of the probe is smoother and more fluent. Finally, significant difference was found for the average twist exercised on the probe by the two groups. The rest of the rotation parameters (flexion, lateral flexion and scanning field rotation) did not show statistical significance. This is because these are used to adjust the US scanning field at a specific orientation once the tip has reached the desired position, but users do not alter them during probe navigation (advance/withdrawal and twist) resulting in them having a static pattern. Also their nominal value in the 10 views, is roughly known from practice, thus the lack of variation across users.

To further evaluate the ability of the derived kinematic parameters to discriminate the level of experience, we conducted experiments with established unsupervised learning methods. Fig. 4 illustrates two clustering examples; (a) k-means clustering using the total time and average depth velocity resulting in 89.47% (17/19) classification accuracy; and (b) expectation - maximisation (EM) with the two smoothness features which yields a 84.21% (16/19) accuracy.

4 Conclusions

This paper presented an investigation on the applicability of motion-based metrics for TEE skill evaluation. A cohort of 19 participants, comprising of novice and expert practitioners performed experiments, acquiring 10 standard TEE views, on the HeartWorks VR simulator. Statistical analysis revealed significant differences ($p<0.05$) in motion-based metrics that represent economy and efficiency (procedure time, average speed, average acceleration) as well as motion smoothness and fluidity (dimensionless jerk, spectral arc length). We run clustering experiments with the derived feature set and participants were classified to their respective group with high accuracy ($> 84\%$). We thus conclude that the kinematic analysis of the TEE probe presents high potential for the development of objective skill assessment methods in TEE. Future work will focus on integrating information about tool-tissue interaction (force exercised by probe's tip) and from the image analysis of the acquired TEE views. Ultimately, we aim to develop an automated performance score that correlates well with manual assessment. Such a system, can be integrated into the HeartWorks software providing detailed self-assessment and further facilitating the development of dexterous skills with VR simulation training.

References

1. Balasubramanian, S., Melendez-Calderon, A., Burdet, E.: A robust and sensitive metric for quantifying movement smoothness. IEEE Trans. Biomed. Eng. 59(8), 2126–2136 (2012)
2. Charron, C., Prat, G., Caille, V., et al.: Validation of a skills assessment scoring system for transesophageal echocardiographic monitoring of hemodynamics. Intensive Care Med 33(10), 1712–1718 (2007)
3. Hahn, R.T., Abraham, T., Adams, M.S., et al.: Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. J Am Soc Echocardiogr 26(9), 921–964 (2013)
4. Matyal, R., Montealegre-Gallegos, M., Mitchell, J.D., et al.: Manual Skill Acquisition During Transesophageal Echocardiography Simulator Training of Cardiology Fellows: A Kinematic Assessment. J. Cardiothorac. Vasc. Anesth. 29(6), 1504–1510 (2015)
5. Mazomenos, E.B., Chang, P.L., Rippel, R.A., et al.: Catheter manipulation analysis for objective performance and technical skills assessment in transcatheter aortic valve implantation. Int. J. Comput. Assist. Radiol. Surg. 11(6), 1121–1131 (2016)
6. Mitchell, E.L., Arora, S., Moneta, G.L., et al.: A systematic review of assessment of skill acquisition and operative competency in vascular surgical training. J. Vasc. Surg. 59(5), 1440–1455 (May 2014)
7. Moorthy, K., Munz, Y., Sarker, S.K., Darzi, A.: Objective assessment of technical skills in surgery. Brit. Med. J. 327(7422), 1032–1037 (Nov 2003)
8. Neequaye, S.K., Aggarwal, R., Van Herzeele, I., et al.: Endovascular skills training and assessment. J. Vasc. Surg. 46(5), 1055–1064 (Nov 2007)
9. Quinones, M.A., Douglas, P.S., Foster, E., et al.: ACC/AHA clinical competence statement on echocardiography: a report of the American College of Cardiology/American Heart Association/American College of Physicians-American Society of Internal Medicine Task Force on Clinical Competence. J. Am. Coll. Cardiol. 41(4), 687–708 (2003)
10. Rolls, A.E., Riga, C.V., Bicknell, C.D., et al.: A pilot study of video-motion analysis in endovascular surgery: Development of real-time discriminatory skill metrics. Eur. J. Vasc. Endovasc. Surg. 45(5), 509–515 (2013)
11. Sohmer, B., Hudson, C., Hudson, J., et al.: Transesophageal echocardiography simulation is an effective tool in teaching psychomotor skills to novice echocardiographers. Can J Anaesth 61(3), 235–241 (2014)