Blink-based estimation of suturing task workload and expertise in microsurgery

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Abstract—**Eye-hand coordination is a central skill in microsurgery. To develop efficacious microsurgical training environments to support development of eye-hand coordination, it is important to understand the workload associated with visuomotor tasks in microsurgery. We embedded an eye-tracker to a surgical microscope and collected eye-blink data of 10 participants during a microsuture training task. Blink-rate was shown to drop to low levels compared to a resting-state rate and be sensitive to the phases of microsurgical suture. We discuss these findings in the light of operator training in microsurgical environments.**

Index Terms—**Eye tracking, stress management, microsurgery**

I. INTRODUCTION

Potentials of workload assessment during microsurgical tasks are many. In in-vivo applications in OR, intelligent systems can track workload of operators in real-time. In general, workload estimation and in particular workload management, as tasks of human factors engineering, can help to decrease mental workload that in turn can contribute to error avoidance and better operator performance [1]. For example, such functionalities can be used for improving team-collaboration and for increasing safety [2].

Workload and stress are one of the often cited sources of medical error [1]. Highly difficult tasks are associated with high mental workload which in turn creates situations opportune for errors [3] and poorer performance [4]. At the same time, mental workload is a finite resource, it is therefore important to understand the sources of workload and to be able to monitor them during clinical procedures. One of the measures of workload is eye-blink activity [5], [6]. However, there are other features like blink rate, duration, amplitude, tear film integrity, and eyebrow frowning are known to be highly correlated with variation in concentration, fatigue, and cognitive effort [7], [8].

Understanding of endogenous eye-blink activity has been a subject of interest for many years [9], although spontaneous blink behaviors are together with pupil-based measurements two of the lesser utilized indicators of cognitive activity based on eye-tracking [10]. Eye-tracking, indeed, suits particularly well in understanding of cognitive processes, for example during reading [11].

While blinking serves to maintain good vision and to create a tear film on the eye surface [12], blinking rate is modulated by dopamine levels in central nervous system and has been linked to learning and goal-directed behavior [10]. During a blink, vision is interrupted, both optically and neurally [13].

Blinking has been previously used a marker of internal processing such as learning [14]. Here, in more applied settings, we investigate whether blink-rate is linked to expertise differences and could be employed as the indicator of suturing task complexity in microsurgery.

Although numerous tools to estimate workload during surgical procedures exist and could be applied, ranging from questionnaire based through performance to physiological ways, eye-based techniques provide both an instantaneous, second-to-second and non-invasive way to collect the data.

A. Workload estimation using eye-blink monitoring

It has been previously reported that the normal rate of blinking in resting state is 17 blinks per minute [15], but other sources report various rates from 12 [16], through 17 [6], up to 22 blinks per minute [17], with a great individual variability [18].

When the task difficulty increases, blink rate decreases [6]. Stress and blink rate are related too, as summarized in the recent review of 21 studies [18]. Optometrists however warn that blink rates depend on experimental conditions [9].

In medical contexts, blink-based workload estimation has been recently investigated in laparoscopic environments [19]. Zheng et al. found that blink frequency (rate) declined with the increasing levels of mental workload reported by surgeons through the use of NASA-TLX measure.

In this work we estimate blink-rate from a video-camera based eye-tracker embedded onto an ocular of a surgical microscope. Subjects of two expertise levels performed a session of microsuture training.

We aim to answer the following questions: 1) Is microsurgeon's expertise and task workload reflected in blink-rate? 2) Could blink-rate be employed as an indicator of suturing task complexity?

II. METHODS

We conducted a study focused on microsurgical suture training performed on a designed task board (illustrated in
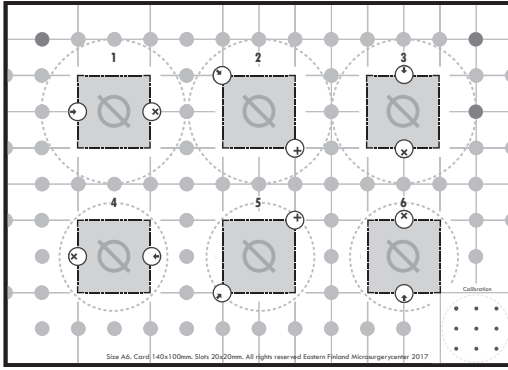
Fig. 1. Suturing task board. The first row of tasks was performed under magnification 2X, the second row of tasks was performed under magnification 4X.

Figure 1). To investigate blink-rate as a indicator of task difficulty and workload, we analyzed the workload with respect to suture phases (segment) as described below.[1]

A. Experimental design

A team of experienced microsurgeons collaborated in the design of the task board. The design of the training board aimed to promote the practice of microsurgical fundamental tasks, requiring bimanual dexterity, surgical suture handling, eye-hand coordination, precision, and speed. The task board consists of two rows with three blocks, each lined with a latex material, simulating fine brain tissues.

In this study, each box had a pre-cut incision in the latex skin. In each block, participants were required to perform two sutures, each containing three knots. Each suture constitutes a trial.

The task of the participants was to complete altogether 12 sutures in the simulation board under required magnification and in desired suture orientation. As this was an exploratory

[1]This section may share similarities with authors' current other work, as the same setup created large datasets that are reported in distinct publications.

TABLE I

SUTURE PHASES WITH EXPLANATIONS

Suture phase	Description
needle pick	a needle is picked up with a needle holder or a loaded needle holder is brought to the field of view
touch edge	an instruments or the needle touches the edge of the target surface
pierce	a needle tip pierces the first surface wall
needle push & pull	a needle tip penetrates the second surface wall
extraction	a needle holder grabs the needle on the edge of the needle
thread handling	a base of the needle penetrates the second wall
knot 1-3	a non-dominant instrument grabs thread for suturing (this hand can pull thread also after this time point)
cutting	both suture threads are cut

TABLE II

OVERVIEW OF THE TWO GROUPS FORMED. SURGICAL AND MICROSURGICAL SKILLS ARE REPORTED IN NUMBER OF MONTHS, AVERAGED OVER THE PARTICIPANTS. ONE NOVICE HAD HIGH SURGICAL EXPERTISE, RESULTING IN HIGH SD OF THE NOVICE GROUP. STANDARD DEVIATIONS ARE GIVEN IN PARENTHESIS.

Group	Novice	Experts
Gender	2 females, 4 males	5 males
Avg. Age [year]	30.50 (8.26)	31.40 (1.36)
Surgical practice [month]	60.00 (91.65)	61.20 (19.03)
Microsurgical practice [month]	0.00 (0.00)	31.20 (24.71)

study, participants used the task board as would be required in training: they performed first the upper row in one magnification and they performed the lower row in another magnification. Participants were equipped with a delicate 9/0 suture needle with a thread, micro forceps, a needle-holder, and micro-scissors.

Before the task, each participants was greeted and seated in a quiet evenly lit laboratory. After the introduction to the experiment and the recording apparatus, he or she signed a consent form, answered a demographic questionnaire, and set up the microscope ergonomics.

Prior to recordings, the eye-tracker was calibrated with a 9-point routine. The participants were asked to look and hold gaze at consecutive nine points according to experimenter's guidance. After the calibration routine, a validation was performed by repeating the 9-point steps again.

After the calibration, the participant was allowed to proceed to the first suture. After completion of twelve sutures, a participant evaluated the quality of their sutures using UWOMSA [20] and overall task demands using SURG-TLX [21], a surgical version of the NASA TLX instrument.

B. Participants

11 participants (2 females, 9 males, mean age = 30.91 years, SD=6.19) with normal or corrected-to-normal vision participated in the experiment. Data from one participant had to be discarded due to technical problems.

Details on the background of participants are summarized in Table II. Two of the novice participants reported high surgical expertise from other field (120 and 240 months), skewing the average and standard deviation of the novice group closer to the expert group. The novice group, however, had no prior microsurgical skills (0 months) which was used as the primary criteria.

C. Apparatus

We used a SeeTrue [2] embedded eye-tracker, a model designed as an adapted version of an ocular-mounter eye-tracker previously introduced by Eivazi et al. [22] and employed e.g. in [23]. The system was attached to the last piece of a microscope ocular, and using a video camera collected the images of the right users' eye. The camera used fixed zooming lens and sampling rate of the camera

[2]SeeTrue eye-tracking `http:\\seetrue.fi`

was 30Hz. The overall emitted radiation power fulfilled the safety standards of International Commission on Non-Ionizing Radiation Protection 2013.

The scene under the microscope was recorded using an Intensity BlackMagic framegrabber [3]. The synchronization of the eye-tracker and scene recording was implemented in custom C++ scripts. Eye-images were stored at a local computer for later analysis.

The study was conducted using a Zeiss OPMI Vario S88 surgical microscope [4]. The scene illumination was the same for each participant and unchanged during recordings.

D. Microsuture segmentation

We devised a detailed segmentation of the suturing task. Microsuture had previously been divided into three major phases: penetration, needle handling and knotting [24], [25]. However, this segmentation omits the initial needle pick-up and the final cutting of the needle; both of which can be of considerable duration and difficulty - especially for novices. In this study, we developed a more detailed segmentation scheme of microsuture and divided each to acts delineated by the following way-points: *needle pick*, *edge touch*, *pierce*, *needle push*, *extraction*, *thread handling*, *throws/knots 1, 2, 3*, and *cutting* to better include all of the suturing action and even distribution of the duration the phases. The sequence is in detail described in Table I, and illustrative examples of waypoints are shown in Figure 2.

E. Data analysis

The eye-tracker camera captured the right eye of the participants (Fig. 3 (a) – (h)). Due to untypical setup of used eye tracker when compare to conventional head-mounted and screen-based eye tracking systems, traditional automatic blink detection approaches would not deliver expected results. Three annotators were trained to annotate frames corresponding to the eye closure. Each of them observed assigned videos frame-by-frame and detected eye blinks based on occurrence criteria.

Blink occurrence is recognized when the upper eyelid covers completely the pupil (see Fig.3(c)). In case of partially closed blinkers, the eyelid has to drop over more than half of the pupil (see Fig.3(e)). After the blink occurrence event was recognized the start and end criteria were applied. Usually, the eyelid falls quickly what results in blurry image of the upper part and hardly distinguishable eyelashes (see Fig.3(b)). The blink start event was then associated with the frame presented just before the distorted upper eyelid. The same blink start frame was further used as a reference in the end blink criteria detection. The last frame assigned to the complete blinking event had to be comparable with the one classified to the start blink, thus sharp upper eyelid that covers similar part of the pupil (see Fig.3(h)). The procedure

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[3] Intensity Black Magic: https://www.blackmagicdesign.com/fi/products/intensity
[4] Zeiss OPMI: https://www.zeiss.com/meditec/int/products/spine-surgery/surgical-microscopes/opmi-vario-s88.html

including such criteria could be successfully employed for both completely closed eye blinkers, and partially closed eye blinkers, in which the upper eyelid would cover pupil only in part.

While reviewing the videos, we observed another blink patterns being relatively difficult to classify by both automatic detectors and annotators as well. We also learned that traditional automatic blink detection approaches could not be applied and performed sub-optimally on this dataset, and thus we resorted to manual blink annotation.

Another factor preventing the use of available automatic methods is related to innovative application domain in this paper. It is typical that microscope operator tilts his head from the eyepieces during the task for various reasons related to handling with tools. The blink detection during this event is rather impossible, therefore frames associated with the tilting when the eye was away from the eyepiece were also manually removed and have not been included when calculating blink rates. Figure 3 demonstrates an example eye-image sequence with a blink.

The eye blinks were annotated using the Boris tool [26] and post-processed in Python using Pandas [27]. The time spent on blink annotation was different for each participant and was highly related with the type of blinking pattern and the eye position on the eyepiece. However, our rough estimation is that each annotator has spent six minutes to process each minute of the raw video.

In this work, we report on blink rate, expressed as number of blinks per minute.

III. RESULTS

A. Time to completion

On average, one suture took 114.77 s (SD=68.06). Experts spent 70.60 s (SD=14.86) and novices 168.84 s (SD=68.75). The difference was statistically significant according to a two-tailed t-test, $t(108) = 10.78$, $p < .001$).

A two-way ANOVA showed a significant effect of the segment ($F(9,1070) = 36.600$, $p < .001$, $\eta^2 = .235$). A significant effect of expertise was found ($F(1, 1070) = 152.573$, $p < .001$, $\eta^2 = .125$). The interaction effect was also significant ($F(9, 1070) = 13.439$, $p < .001$, $\eta^2 = .102$).

B. Subjective evaluation of workload

Table III provides the comparison of subjective workload assessment using SURG-TLX. Two-tailed t-test comparisons revealed significant differences between the novice and expert groups in physical demands, situational awareness, and overall.

C. Blink rate

Altogether, we captured 1659 blinks from all participants. Of these, 946 occurred during the sutures. An overall blink-rate was 3.82 blinks per minute. Novices average blink rate was 3.87, and experts' average blink rate was 3.77.

Blink rate was analyzed with respect to the expertise and the segment. Figure 6 illustrates an overall distribution across suture segments in both groups. The blink rates were
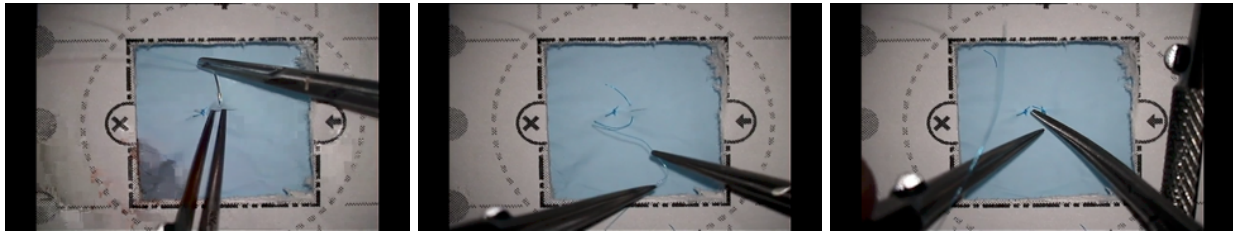
Fig. 2. Snapshots from the microsurgical suture tasks, left-to-right: 1) the surgeon pierces the needle through the latex, 2) the knotting phase starts, 3) the final thread is cut to trim the extensive length.
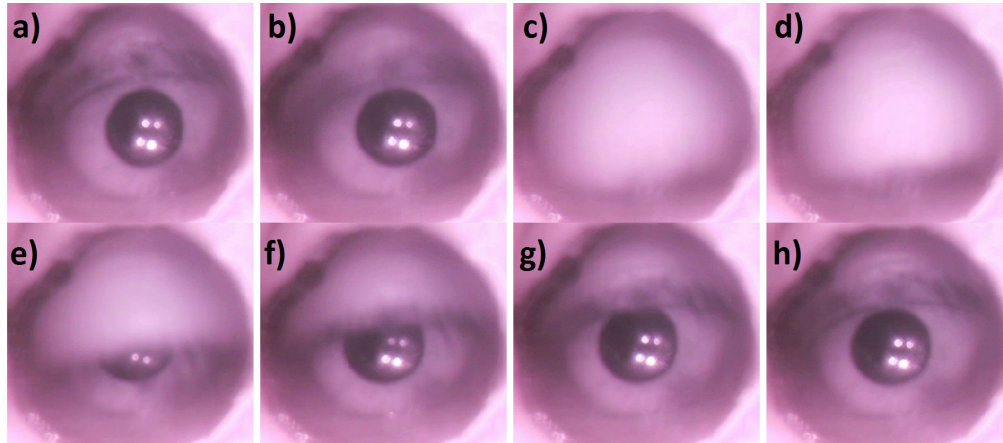

Fig. 3. The eye-lid movement during a blink. In this particular case, the lid completely closed the eye. However, in several cases we observed only a partial blink.
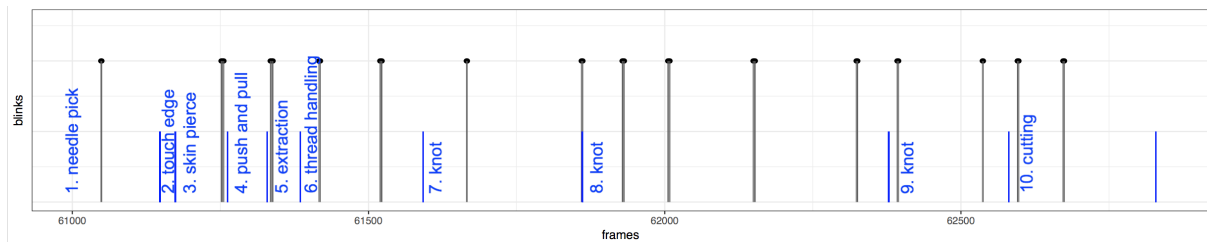

Fig. 4. Timeline of blinks in one suture, performed by a novice participant. Blue and black lines correspond to the occurrence of suture phase and the start of blink, respectively.

	Novices	Experts	P-value
Mental demands	13.06 (2.17)	8.34 (3.91)	0.068
Physical demands	14.88 (2.61)	5.82 (2.51)	**0.001***
Temporal demands	8.70 (4.54)	7.76 (1.55)	0.706
Task complexity	12.50 (6.09)	5.44 (2.28)	0.062
Situational awareness	14.30 (1.03)	8.50 (4.65)	**0.041***
Distractions	2.50 (2.77)	6.14 (3.50)	0.142
SURG TXL Sum	65.94 (10.48)	42.00 (12.32)	**0.018 ***

TABLE III

SURGICAL TLX COMPARISON OF THE TWO GROUPS.

calculated as a number of blinks per a segment. Figure 4 demonstrates a number of blinks in different segments during one suture.

A two-way ANOVA (expertise x segment) revealed a significant effect of the segment $F(9, 1070) = 31.099$, $p < .001$, $\eta^2 = .207$. The effect of expertise was not significant ($F(1,1070) = .049$, $p = .825$). However, the interaction effect was significant $F(9, 1070) = 5.438$, $p < .001$, $\eta^2 = .044$, indicating blink rates strongly depend on the phases of suture and additionally on participant's expertise. At the beginning, both groups blink rate dropped to less than one blink per minute.

The largest deviation in the blink rate between novices and experts occurred in the cutting segment (Fig. 6). When the blink rate in segments before cutting were averaged and compared to the blink rate during cutting (Fig. 7), we can see a significant interaction effect $F(1,1086) = 44.255$, $p < .001$, $\eta^2 = .039$ with a strong significance in the segment, $F(1,1086) = 188.800$, $p < .001$ $\eta^2 = .148$. The effect of expertise was also significant, $F(1,1086) = 26.970$, $p < .001$, $\eta^2 = .024$.

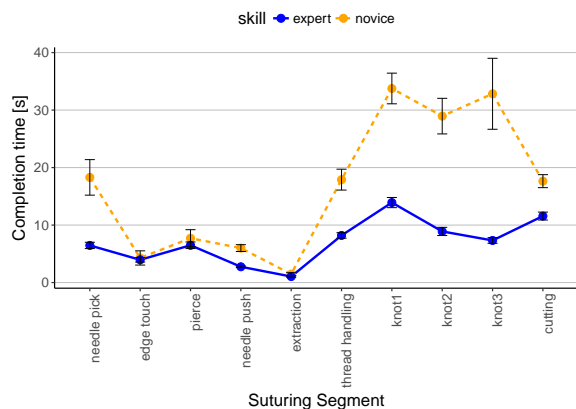To test whether and how knotting phase influenced the

Fig. 5. Time to completion in segments. Both groups, expert (blue) and novices (yellow), required more time in knotting, the difference is even more apparent in the novice group.
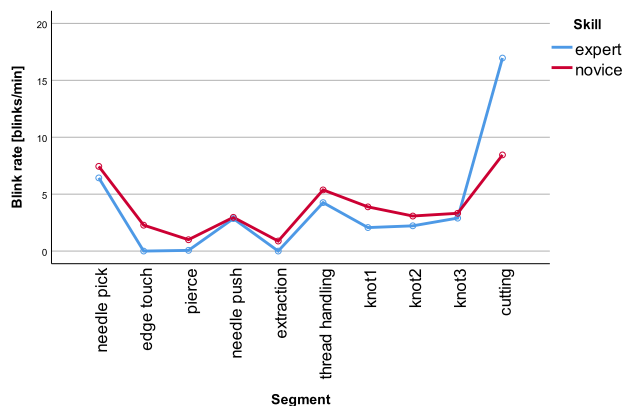

Fig. 6. Average blink rate with respect to the consecutive phases of suture for experts (blue) and novices (red).

blink rate, we aggregated the phases before and during knotting into two groups and compared these. Here expertise alone had no effect, $F(1,1086) = .095$, p=.758, but the effect of segment was significant, $F(1,1086) = 28.497$, p $< .001$, η^2 = .026. The interaction effect was also significant, $F(1,1086)$ = 6.280, p = .012, η^2 = .006.

IV. DISCUSSION AND CONCLUSIONS

The conventional way for assessing surgical skill and performance has been by the supervision and feedback of more experienced surgeons. This method has been found to have several problems, including subjectivity and case-dependence, which are then seen in patient safety issues. For these reasons there have been calls for more objective evaluation techniques. [25], [28] Understanding how expertise and workload is reflected in surgeons' psychomotor behavior would help in development and implementation these methods.

While previous studies in this domain often focused on utilization of eye-tracking to obtain eye-position data and gain insights into cognition and attention, in this work we utilized eye-tracking to collect blink-related signals. This
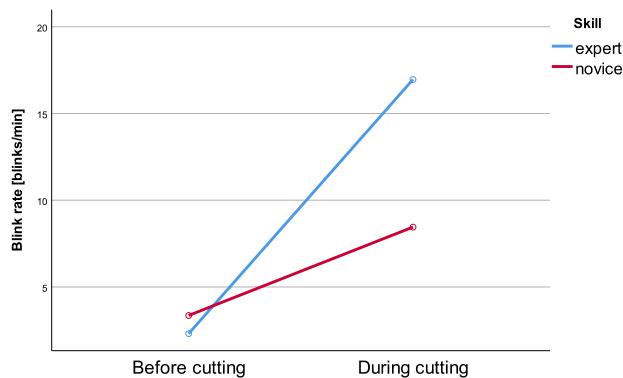

Fig. 7. Average blink rates compared for the aggregated segments before cutting and during the cutting segment.

work is the first one to report on the blink-rates during microsurgical procedures, and complements the reports using pupil monitoring during microsurgical training [23]. Our motivation was to uncover the differences between expert and novice microsurgeons and to relate blink-rates to suturing task workload and complexity.

Our results showed that some of the phases of the microsurgical suture task were accompanied by extremely decreased blinking rate, indicating heightened workload and more difficult sub-task. Overall, blink-rates of 3.82 during microsurgical suture training were far below rates reported in normal resting states. Edge touch, piercing, and extraction were tasks associated with the lowest blink-rates overall.

Despite the differences in subjective workload evaluation as shown in Table III, expertise did not affect blink-rate, both experts' and novices' patterns closely resembled each other. This appears to be somewhat contradictory to earlier results by Zheng et al. [19], who had found the decreased blink rate to be correlated with increased workload. Their study did not take into account the expertise of the participants, and one explanation for our results could be that novice surgeons overestimate the task workload compared to experts. Taken together, however, blink-rate seems to be a valid indicator of sub-task complexity and associated workload in microsurgical training.

These findings further advance our understanding of the workload and task difficulty in microsurgical suturing tasks. Previously, gaze-direction data such as fixation durations and locations were shown to distinguish experts from novices in microsurgical tasks [29], [30]. Here, for the first time, we show how various phases of the suture act produce workloads variations.

Our results show a promise and potentials of employing blink-rate as a proxy to microsurgical task complexity and the related workload. We envision that with real-time monitoring of surgeon's eye area, future systems can actively estimate and manage the workload of the microsurgical team. Training environments can adapt the materials and tasks presented in order to optimize the learning path of the

residents based on the required workload at different suturing phases.

Future work relating spontaneous blinking to surgical tasks should further investigate the effects of expertise and their interaction with the type of the task. Another line of future investigations will focus on team workload [31] and its blink-based monitoring because microsurgical procedures are always conducted by a team of clinicians and nurse-surgeon collaboration is critical for the success and patient safety [32].

ACKNOWLEDGMENT

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