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Development of a Prospective Method for Rating Surgical Task Workloads

Sergey Drobinsky[1], Patrick Korte[1], Rastislav Pjontek[2], Armin Janß[1], Verena Nitsch[3], and Klaus Radermacher[1]

[1]Chair of Medical Engineering, RWTH Aachen, Germany
[2]Department of Neurosurgery, University Hospital RWTH Aachen, Germany
[3]Institute of Industrial Engineering and Ergonomics, RWTH Aachen University, Germany

ABSTRACT

Surgical adverse events can have serious consequences for patients ranging from temporary injuries to death. Thereby, up to 40% of surgical adverse events are preventable and over 60% of causal factors were found to be linked to human factors. To improve surgical performance and safety, computer-assisted surgical (CAS) systems can be used to reduce excessive workloads. This paper presents a method for prospective assessment of surgical task workloads. S-TAWL, developed with the support of a senior neurosurgeon and a usability engineer, consists of three parts: surgical task decomposition, workload rating scale application, and performance shaping factors characterization. For the proposed rating scales, composed of reference operators, relative workloads were determined by 11 neurosurgeons through pairwise comparison. Afterwards, one senior neurosurgeon, not involved in method development, analysed workloads of four common surgical tasks with the proposed method S-TAWL and a reference workload assessment method Surg-TLX. Qualitatively, S-TAWL provides more detailed information about workloads with respect to human resources compared to the reference method. Quantitatively, however, the reliability of the results is still limited, as indicated by high standard deviations. Further research is needed to develop reliable and valid rating scales, compute compound workloads and identify overloads. Incorporating quantitative workload assessment in prospective human performance analysis will provide valuable information for targeted model-based design of assistance systems, supporting safe and successful surgery in the future.

Keywords: Prospective task and workload analysis, Computer-assisted surgery, Human factors

INTRODUCTION

Surgical adverse events can have serious consequences for patients ranging from temporary injuries to death [Schwendimann et al., 2018]. Up to 40% of surgical adverse events are preventable and over 60% of causal factors were found to be linked to human factors [Zegers et al., 2011]. Workloads, i.e., all external influences acting on a human, have an impact on human performance [VDI 4006 Part 1 2015]. Inadequate workloads can lead to human performance deficiencies and therefore must be avoided for safe and successful surgery [Suliburk et al., 2019].

To reduce overloads computer-assisted surgical (CAS) systems, such as cooperative robotic assistants, can be used [Schleer et al., 2021]. However, introducing technical support systems into the operating room can also increase the overall complexity of the socio-technical system, therefore increasing risks of human errors [Liu et al., 2021]. Interaction with complex systems, forces surgeons to allocate more attention on monitoring and controlling the support systems and less on the patient. Out-of-loop unfamiliarity and associated risks, like overreliance, skill deterioration, mode confusion, and reduced situational awareness can cause human errors, limiting the safety and usability of technical support systems [Endsley and Kiris 1995].

Model-based usability and human-centered risk analysis can support evidence-based design and integration of surgical assistance systems [Janß 2015] [Catchpole et al., 2022]. Various methods and models like CPM-GOMS [John and Gray 1995], Multiple Resource Theory [Wickens 2008], and mAIXuse [Janß 2015] have been proposed in literature. In military contexts, prospective workload assessment methods such as LHX or TAWL have been developed to predict task loads [Hamilton and Bierbaum 1990]. These methods involve domain experts assessing the workloads of tasks by assigning reference tasks with known workloads [Mitchell 2009]. This paper presents a method for surgical task and workload assessment (S-TAWL).

MATERIAL AND METHODS

S-TAWL is developed iteratively in accordance with the problem-solving cycle [Haberfellner et al., 2019] supported by a senior neurosurgeon and a senior usability engineer. Therefore, existing process and workload models like GOMS [Card et al., 2008], mAIXuse [Janß 2015], MRT [Wickens 2008], SPM [Neumuth 2015], TAWL [Bierbaum et al., 1989], Imprint [Mitchell 2009], and CTAWC [Knisely et al., 2021] were reviewed, adapted, and extended where necessary. The development and evaluation of S-TAWL were conducted in German and later translated into English for this publication, with the assistance of a native speaker.

S-TAWL consists of three parts: task decomposition, workload assessment using rating scales, and performance shaping factor characterization (see Figure 1). The application scope of the proposed workload assessment method is constrained to neurosurgery. Task interdependencies and resource conflicts of parallel activities are not considered and must be evaluated separately.

In a first step, the surgical process is decomposed into elementary components by a domain expert and a modelling expert. For the proposed task decomposition, terms and concepts are defined in accordance with Lalys and Janin [2014]. A *surgical process* consists of *surgical phases* that consist of a set of *surgical tasks* performed to achieve a surgical objective. A *surgical task* forms the smallest logical unit from a medical domain perspective. From a human factors domain perspective, surgical tasks are further decomposed into *surgical activities* that form a perception-cognition-action cycle [IEC 62366–1 2015]. Surgical action-type activities are also called *surgical gestures* or *surgemes* in the literature [Lin et al., 2006].

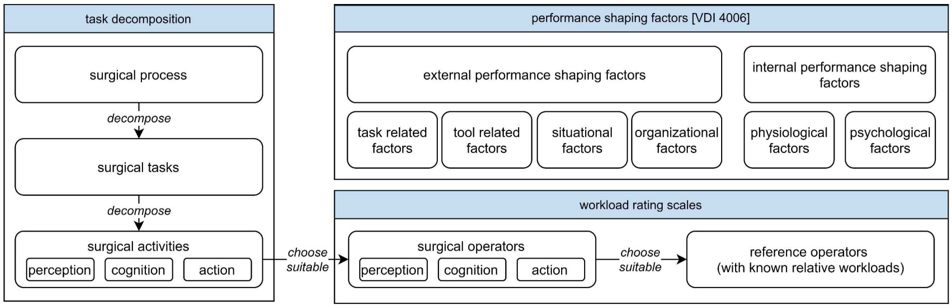


Figure 1: Structure of the proposed prospective workload assessment method S-TAWL.

In a second step, relative workload magnitudes of *surgical activities* are assessed by choosing suitable *operators*, i.e., standardized generic activities [John and Gray 1995]. Then, corresponding rating scales composed of *reference operators* with known relative workloads are applied. Thereby, various sets of operators were proposed for surgical and non-surgical process modelling in the literature [Card et al., 1980; Card 1981; Rasmussen 1983; Hamilton and Bierbaum 1990; John and Gray 1995; Hoc and Lemoine 1998; Troccaz et al., 1998; Anderson et al., 2001; Holleis et al., 2007; Estes 2021]. For the presented study a relevant subset of operators was identified and clinically meaningful reference operators were defined in workshops with clinical experts (Table 1). Further components and sources of workload are analyzed by identifying and characterizing relevant PSFs [VDI 4006 Part 1 2015]. Within the scope of this paper, a formative evaluation of the proposed rating scales is presented.

For perception and action operators, relative workloads on a 7-point scale (1- lowest workload) were determined through pairwise comparison by 11 neurosurgeons from the department of neurosurgery of the university hospital Aachen. For cognition operators, reference operators and relative workload magnitudes were defined based on an adaptation of Bloom's taxonomy [Anderson et al., 2001].

S-TAWL was then evaluated by analyzing the workloads of four common surgical tasks in posterior cervical spine fixation. This surgical procedure is an example of a very complex surgical procedure associated with high risks. The examined tasks were: (1) navigated drill guide alignment, (2) non-navigated drill guide alignment, (3) canulated pedicle screw placement, and (4) non-canulated pedicle screw placement. First, these tasks were decomposed into surgical activities with the support of a senior neurosurgeon. Subsequently, a different senior neurosurgeon from the university hospital Aachen, who had conducted approximately 50 cervical spine fixations, assessed the workloads. For each activity, the surgeon was asked to identify suitable reference operators that they believed to be most similar in terms of workload. The reference operators were presented without numeric workload values and were not ordered on a rating scale. This approach ensured that the surgeon assigned reference operators based solely on relative comparisons, rather than absolute workload assessments. Cognitive activities were not predetermined;

instead, the surgeon was asked to select all cognitive operators they deemed necessary to complete each surgical task under analysis. Following the workload assessment, the surgeon was asked to indicate which surgical activity presented the greatest challenge in assigning a reference operator. Surg-TLX [Wilson et al., 2011], an adaptation of NASA-TLX, was used as a reference method to assess workloads. The participating surgeon was not involved in the development of S-TAWL.

RESULTS

For perception and action operators, the identified mean relative workloads and standard deviations are shown in Table 1. Reference operator workload estimates show that the proposed rating scales are not equidistant. Due to high standard deviations (up to ± 2 points) some rating scales are ambiguous, such as for the operator *primarily coordinative actions*. For the two operators *visual search* and *haptic interpretation*, two reference operators within one rating scale were determined to have the same workload. Furthermore, no rating scale covers the entire 7-point range. The smallest rating scale span is 2.9 points (*visual search*, *primary physical actions*) and largest rating scale span is 4.5 points (*visual identification*).

Workloads assessed with the proposed method S-TAWL and the reference method Surg-TLX are shown in Table 2. For drill guide alignment, reported total workload with Surg-TLX (0-lowest, 100-highest) was similar with (32) and without (33) navigation. Raw ratings were highest for mental demands and task complexity and lowest for physical demands. For pedicle screw placement, total weighted workloads are lower for placing canulated screws (22) than for placing non-canulated screws (35). Raw ratings indicated that for canulated screw placement physical demands were highest, while for non-canulated screw placement mental demands were highest. Weights determined through pairwise comparison show that mental demands ($w = 5$) are more important than any other factor, while physical demands are not relevant at all ($w = 0$). Therefore, despite being rated higher for pedicle screw placement compared to drill guide alignment, physical demands do not contribute at all to the total weighted workload.

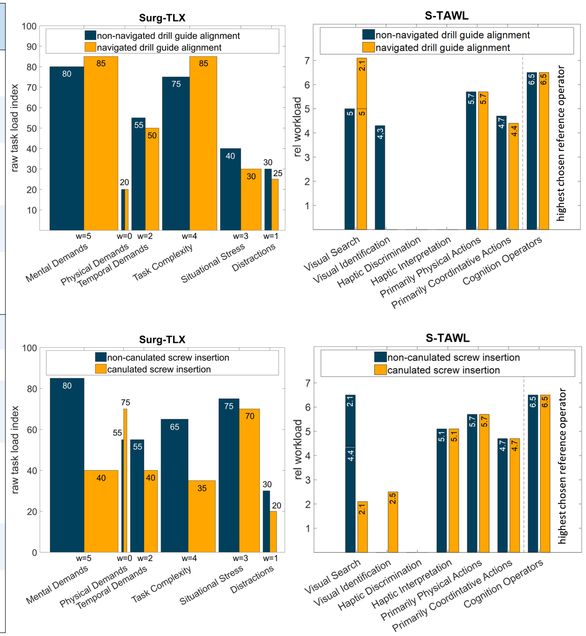
With S-TAWL main differences for assessed workloads were related to perception type activities. S-TAWL task decomposition suggests that drill guide alignment only includes visual perception, while pedicle screw placement includes visual and haptic perception. For navigated and non-navigated drill guide alignment, workloads for monitoring and verifying the alignment using anatomical landmarks were rated highest. Alignment verification in X-ray imaging was rated as a high-workload *visual identification* task, while monitoring alignment on a navigation display was rated as a low-workload *visual search* task. For pedicle screw placement, workloads for visual checks of the screw alignment are rated lower for canulated screws (2.1) than for non-canulated screws (4.4). Visual screw depth monitoring is rated as the lowest *visual search* task (2.1) for non-canulated screws and as the lowest *visual identification* task (2.5) for canulated screws. For haptic alignment control, different reference operators were assigned, however both having the

Table 1. Rating scales and relative workloads for cognition-type surgical operators adapted from [Anderson et al., 2001]. Rating scales for perception- and action-type surgical operators and relative workloads identified in expert workshops and surveys (1-lowest workload, 7-highest workload).

activity type	**Cognition**									
operator	**Remember** retrieve relevant knowledge from long-term memory	rel. workload	**Understand** construct meaning	rel. workload	**Analyse** break material into its constituent parts and determine interrelations	rel. workload	**Evaluate** make judgements based on criteria and standards	rel. workload	**Create** put elements together to form a coherent or functional whole	rel. workload
reference operators	**recognising** locating knowledge in long-term memory that is consistent with presented material	1	**classifying** determining that something belongs to a category	2	**differentiating** distinguishing relevant from irrelevant parts or impor-tant from unimportant parts of presented material	3.5	**checking** detecting inconsistencies of fallacies within a process	4.5	**generating** coming up with alternative hypothesis based on criteria	6
	recalling retrieving relevant knowledge from long-term memory	1.5	**inferring** drawing a logical conclusion from presented information	2.5	**organising** determining how elements fit or function within a structure	4	**decision-making (simple)** choosing between multiple options where reasoning is clear or errors have insignificant consequences	5	**planning** devising a procedure for accomplishing a task	6.5
			comparing detecting correspondences between two ideas, objects, and the like	3			**decision-making (difficult)** choosing between multiple options where reasoning is unclear or errors have significant consequences	5.5	**producing** inventing a new solution	7
activity type	**Perception**									
operator	**Visual Search** find elements, e.g. in the surgical field, on the navigation screen or in a CT image	rel. workload	**Visual Identification** recognize elements, e.g. in the surgical field, on the navigation screen or in a CT image	rel. workload	**Haptic Discrimination** recognise differences between elements based on haptic information, e.g. tissue stiffness	rel. workload	**Haptic Interpretation** asses properties of elements or interactions based on haptic information	rel. workload		
reference operators	localise cranial sutures on an exposed skull	2.1 (±1.2)	detect a meningioma (<2 cm diameter)	2.5 (±1.3)	manual palpation of carotid artery	1 (±0)	estimate the necessary cutting force and depth for cutting skin with a scalpel	2.1 (±1)		
	localise an arterial bleeding	3.6 (±1.5)	identify a non-infiltrating, displacing tumour with a clear boundary	2.6 (±1.5)	recognise the difference between drilling in cancellous and cortical bone	4.3 (±1.2)	estimate the necessary cutting force and depth for cutting muscle with a scalpel	3.2 (±1.3)		
	localise a venous bleeding	4.4 (±1.1)	detect adhesive and slightly infiltrating metastases	4.3 (±0.9)	palpation with a hook of a stenosis in the neuroforamen/spinal canal	5.2 (±1)	estimate the necessary contact force when sawing bone	4.5 (±1.2)		
	find structures in fat tissue, e.g. peripheral nerves	5 (±1)	identify an infiltrative growing brain tumour (degenerated brain cells)	6.6 (±1)	manual palpation of jugular vein	5.5 (±1.9)	estimate the appropriate feed rate when drilling in bone	5.1 (±1)		
	find a carotid-T aneurysm (intracranial)	5 (±2)					estimate the necessary force for milling bone	5.1 (±1.3)		
activity type	**Action**									
operator	**Primarily Physical Actions** simple movements that do not require practice and involve physical exertion	rel. workload	**Primarily Coordinative Actions** complex movements that require practice and fine motor skills					rel. workload		
reference operators	remove bone screw	2.8 (±1.7)	probe artificial landmarks with pointer (e.g. during registration)					2.1(±0.8)		
	reposition patient	3.4 (±1.6)	probe anatomical landmarks with pointer (e.g. during registration)					2.2 (±0.9)		
	hammer in implant (knee, hip)	4.1(±1.5)	position an instrument at a desired point with desired orientation (e.g. find start position for drilling)					4.4 (±0.9)		
	hold a soft-tissue retractor (spine, knee)	5.7 (±1.6)	follow a trajectory with an instrument (e.g. drilling along a trajectory, milling path to remove bone)					4.7 (±1.2)		
			remove material in a confined plane (e.g. sawing task TKA, milling task laminectomy)					5.1(±0.9)		
			remove material in a confined volume (e.g. remove tumour/cystic neoplasm)					5.5 (±0.9)		

Table 2. Task decomposition and workload assessment of four common tasks in posterior cervical spine fixation using S-TAWL. Reference workloads determined using Surg-TLX method (bar height corresponds to raw TLX values, bar width to weighting factors).

posterior cervical (C7) spine fixation - pedicle screw placement									
surgical task	**surgical activity**	**activity type**	**operator**	**reference operator**	**surgical task**	**surgical activity**	**activity type**	**operator**	**reference operator**
non-navigated drill guide alignment	check pedicle and drill guide position within the surgical site in relation to anatomical	perception (visual)	visual search	find structures in fat tissue, e.g. peripheral nerves (5)	navigated drill guide alignment	check pedicle and drill guide position on the navigation screen	perception (visual)	visual search	localise cranial sutures on an exposed skull (2.1)
	verification of the pedicle position in the lateral x-ray image (in one plane).	perception (visual)	visual ident-ification	detect adhesive and slightly infiltrating metastases (4.3)		(supplementary) verification of drill guide alignment using anatomical landmarks	perception (visual)	visual search	find structures in fat tissue, e.g. peripheral nerves (5)
	cognitive activities necessary to perform the surgical task	cognition	various	recognising (1), inferring (2.5), comparing (3), differentiating (3.5), decision-making (difficult) (5.5), planning (6.5)		cognitive activities necessary to perform the surgical task	cognition	various	recognising (1), recalling (1.5), inferring (2.5), checking (4.5), decision-making (simple) (5), planning (6.5)
	hold drill guide in position	action	primary physical action	hold a soft-tissue retractor (spine, knee) (5.7)		hold drill guide in position	action	primary physical action	hold a soft-tissue retractor (spine, knee) (5.7)
	align drill guide	action	primary coordinative action	follow a trajectory with an instrument (e.g. drilling along a trajectory, milling path to remove bone) (4.7)		align drill guide	action	primary coordinative action	position an instrument at a desired point with desired orientation (e.g. find start position for drilling) (4.4)
non-canulated pedicle screw insertion	check screw position within the surgical site	perception (visual)	visual search	localise a venous bleeding (4.4)	canulated pedicle screw insertion	check screw position within the surgical site	perception (visual)	visual search	localise cranial sutures on an exposed skull (2.1)
	monitor screw depth	perception (visual)	visual search	localise cranial sutures on an exposed skull (2.1)		monitor screw depth	perception (visual)	visual ident-ification	detect a meningioma (<2 cm diameter) (2.5)
	position and alignment control using haptic feedback during screw insertion	perception (haptic)	haptic inter-pretation	estimate the appropriate feed rate when drilling in bone (5.1)		position and alignment control using haptic feedback during screw insertion by sliding the K-wire back and forth	perception (haptic)	haptic inter-pretation	estimate the necessary force for milling bone (5.1)
	cognitive activities necessary to perform the surgical task	cognition	various	recognising (1), recalling (1.5), inferring (2.5), comparing (3), differentiating (3.5), checking (4), decision-making (difficult) (5.5), planning (6.5)		cognitive activities necessary to perform the surgical task	cognition	various	recognising (1), inferring (2.5), checking (4.5), decision-making (simple) (5), planning (6.5)
	screw insertion	action	primary physical action	hold a soft-tissue retractor (spine, knee) (5.7)		screw insertion	action	primary physical action	hold a soft-tissue retractor (spine, knee) (5.7)
	maintain screw alignment	action	primary coordinative action	follow a trajectory with an instrument (e.g. drilling along a trajectory, milling path to remove bone) (4.7)		maintain screw alignment	action	primary coordinative action	follow a trajectory with an instrument (e.g. drilling along a trajectory, milling path to remove bone) (4.7)



same identified workload (5.1). Regarding cognition type activities, all four tasks require recalling (1), inferring (2.5) and planning (6.5). For navigated drill guide alignment and canulated pedicle screw insertion decision-making (simple) (4.5) is chosen, while for non-navigated drill guide alignment and non-canulated pedicle screw placement decision-making (difficult) (5.5) is chosen. For non-canulated screw placement 8 reference operators are chosen, while for canulated screw placement only 5 are chosen. Regarding action type activities, primarily physical actions were rated high (5.7), while workloads for primarily coordinative actions were rated medium (4.4-4.7) for all four tasks. In applying the method, the surgeon reported that they struggled most with assigning cognitive reference operators.

DISCUSSION

As human factors are a significant contributor to preventable adverse events in surgery, accurate and reliable workload assessment is key for safe and successful surgery. However, surgical workload assessment is challenging due to task variability and a large number of interdependent influencing factors. While performance shaping factors indicate sources of workload, assessment of compound workload magnitudes of individual activities is challenging [Heard et al., 2018]. In this paper a prospective workload assessment method based on rating scales composed of reference tasks was proposed. The limited scope of the formative evaluation study with only one participating surgeon does not allow for final conclusions about reliability or validity of the proposed method. However, some general conclusions about the design of the method can be drawn for future considerations.

Comparing the assessed workloads using Surg-TLX and S-TAWL is challenging due to differences in workload components and the current lack of a method to compute compound workloads with S-TAWL. Nonetheless, some results show similar tendencies: Both methods rate non-canulated pedicle screw placement to be more demanding than canulated pedicle screw placement. With Surg-TLX ratings are higher for complexity and mental demands, while S-TAWL shows increased workloads for visual perception activities. However, there are also some disparities: Surg-TLX reports higher raw ratings for physical demands in pedicle screw placement compared to drill guide alignment, while S-TAWL rates physical demands similarly high for both tasks. However, for Surg-TLX, differences in raw ratings do not affect compound workloads because the determined weighting factor is 0.

By enabling a more detailed assessment of workloads related to perceptual, cognitive, and motor demands S-TAWL facilitates the identification of resource conflicts and excessive workloads when combined with existing model-based risk analysis methods [Dell'Anna-Pudlik 2022]. However, computation of compound workloads with S-TAWL remains an open research question. To compare workloads across multiple operators weighting factors may be added [Virtanen et al., 2022]. Furthermore, operator interferences could be considered using a conflict-matrix as proposed by Wickens [2002]. Finally, researching limits for acceptable compound workloads with respect to human performance capacity is crucial to determining excessive workloads.

When using S-TAWL's rating scales, which are composed of reference operators, workloads are assessed through relative comparison. Studies indicate that relative rating methods, such as paired comparisons, appear to have greater validity and reliability than absolute rating scales, such as the NASA TLX [Vidulich and Tsang 1987]. However, the presented evaluation study showed that adaptation of the proposed rating scales is necessary. The proposed rating scales for perception and action operators exhibit limited reliability as indicated by high standard deviations in the determined relative workloads. Measurement sensitivity is affected by scale non-linearity, a limited scale span, and varying numbers of scale steps. Additionally, there are potential limitations in the measurement range due to scale attenuation effects. Regarding cognition operators, further research is necessary to validate the proposed linear rating scale, which is based on Bloom's taxonomy, originally developed to describe student learning.

For the assignment of reference operators to surgical activities, the optimal choice of reference operators is an open research question. Highly specific reference operators from the user's field of expertise may improve the assignability, while more general operators, such as those form a surgical training curriculum [Acosta et al., 2018], may increase the method's application scope. During the study, the participating neurosurgeon reported having the most difficulty with the assigning cognitive operators. This may be either because cognitive activities were not further specified or because cognitive reference operators were not selected from clinical examples. In addition, when multiple operators were selected it was unclear whether the assigned reference operators referred to separate cognitive activities. Due to the hierarchical structure of Bloom's taxonomy higher-level reference operators include lower-level operators.

CONCLUSION

Human factors play a significant role in preventable adverse events, highlighting the importance of accurate and reliable workload assessment to proactively identify risks arising from excessive workloads. The proposed task decomposition and operator definition in S-TAWL offer valuable insights into the workloads associated with perceptual, cognitive, and motor demands of surgical tasks. However, determining compound workloads still presents a challenge. Future research is essential to incorporate task interrelationships, resource utilization, and all relevant performance shaping factors in the evaluation of surgical task workloads. Extending existing model-based risk analysis methods with an accurate and comprehensive workload analysis can support evidence-based design of assistance systems and promote safe and successful surgery in the future.

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