

Research Article

The capability of haptic feedback as additional sensory quality for robotic heart surgery

Eva U. Schirmbeck^{1*}, Constanze Haßelbeck¹, Hermann Mayer^{1,2}, Alois Knoll², Franziska K. B. Freyberger³, Stephen M. Wildhirt¹, Rüdiger Lange¹, Robert Bauernschmitt¹

¹German Heart Center Munich, Dept. of Cardiovascular Surgery, Munich, Germany

²Fakultät für Informatik, Institute for Robotics and Embedded Systems, Technische Universität München, Munich, Germany

³Human Factors Institute, University of the Bundeswehr Munich, Munich, Germany

GMS CURAC 2006;1:Doc12

provisional PDF

Abstract

The implementation of telemanipulator systems into cardiac surgery enabled the heart surgeon to perform sophisticated minimally invasive and endoscopic procedures with high precision under stereoscopic view. At present, the commercially available robotic surgical systems do not provide force feedback for the operating surgeon. The lack of tactile feedback may cause damage of tissue and bending or breaking of suture material. For further improvement of telemanipulated systems, we implemented haptic into a realistic experimental platform. Force-feedback is evaluated in a model of robotic heart surgery. The robotic scenario offers an impression very similar to usual and open procedures with high immersion. It enables the surgeon to palpate arteriosclerosis, to tie surgical knots with delicate suture material and to feel the break of suture material. The aim of this study was to analyse the effect of haptic feedback in typical cardiac surgical procedures and the influence on the fatigue of surgeons.

Keywords: telemanipulator, heart surgery, haptic feedback

Introduction

Minimal invasive and endoscopic cardiac surgery does not only minimize the collateral surgical trauma but also results in quicker recovery. The hospital stay and the infection rate of the sternum can be reduced.

In heart surgery the introduction of endoscopic techniques were promising, but not satisfying like the application of robots in other surgical disciplines [1], [2], [3]. Complex cardiac surgery had to be performed by long instruments without tremor filter or adequate freedom of movement, so satisfactory results were missing. In heart surgery, pure endoscopic techniques have not been established since the demanded high precision in this speciality was not achieved with endoscopic instruments only. The promise of telemanipulated endoscopic assistance was to eliminate many of the beginning impediments, with the concurrent enhancements of motion scaling, tremor filtration, 3-dimensional vision and fulcrum effect. The surgeon could now operate with a surgical mechatronic assist system in a comfortable, dextrous and intuitive manner [4], [5], [6].

The solution for the initial problems was the implementation of telemanipulators that offer as much degrees of freedom in movement as the hand of the surgeon in conventional open surgery, thus

*Corresponding author: Dr. med. Eva U. Schirmbeck, German Heart Center Munich, Dept. of Cardiovascular Surgery, Lazarettstr. 36, 80636 Munich, Germany, eMail: schirmbeck@dhm.mhn.de

performing 6 degrees of freedom instead of four in conventional endoscopic instruments. Furthermore, the telemanipulator provided a 3D-optic and a filter of tremor [7]. The new system has been a telesystem controlled remotely by the surgeon. The implementation of totally endoscopic heart surgery was realised ten years later [8] with the telemanipulator Da Vinci[®] (Intuitive Surgical, Inc., USA) after introducing endoscopic surgery in abdominal surgery.

Nevertheless technical limitations still exist, limiting the application to special heart diseases and surgical indications in expert medical centres only.

This telemanipulated technology is available for a minimal part of heart surgical patients only since the technical inconvenience and clumsiness of the system prevents to safely perform valve surgery, congenital heart surgery and a bigger part of bypass surgery.

The necessity of haptic feedback is discussed controversially by robotically working surgeons and haptic engineers [9], [10], [11], [12]. The postulate, that the integration of a supplementary haptic channel in addition to the visual channel improves the quality of surgical work and enhances the immersion for the surgeon in a remote system, has not yet been demonstrated and evidenced.

Current available robotic surgical systems do not provide haptic or tactile feedback to the surgeon. The manipulation of delicate tissues and suture material still remains a challenge. The hypothesis, that haptic feedback in form of sensory substitution facilitates the performance of surgical tasks, is evaluated on an experimental platform of a robotic surgery system (Figure 1).

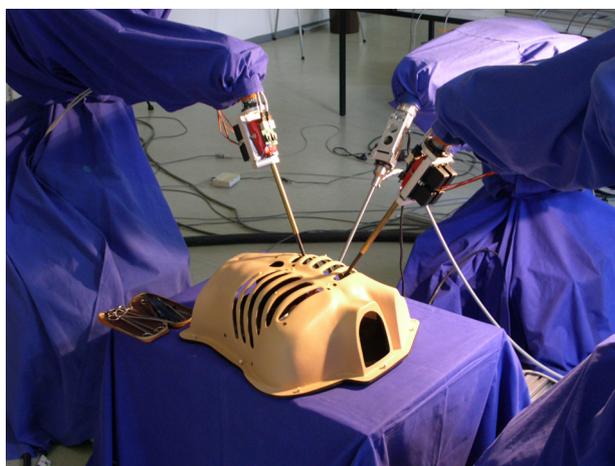


Figure 1: Experimental robotic platform: Two endoscopic instruments and one endoscopic 3D-camera

This study analyses the benefit of haptic feedback as additional sensory quality for operating more precisely without damage of soft tissue and without breakage of fine suture material. The change of amount of forces with haptic feedback is analysed. Furthermore the surgeon's fatigue arising during operation is investigated in special examinations.

For virtual and artificial scenarios tactile sense and haptic feedback is an essential part [13], [14], [15], but in the research of surgical telepresence for remote real scenarios the necessity of haptic feedback is still discussed very intensely. The breaking of surgical suture material and the damage of tissue are basic and unsolved problems in telemanipulated surgery. A further hypothesis is not yet explored: The especially high fatigue of the surgeon during and after robotic operations may be caused by visual compensation of the skills and movements [16].

In our study, haptic feedback is built up in the experimental setup of a surgical telemanipulator system as technical modification [17], [18], [19]. The application on surgical skills is analysed and evaluated.

Methods

The study intended basic surgical and cardiac surgical procedures. Knot tying, breaking suture material (Figure 2, Figure 3) and detection of arteriosclerosis had to be performed in a defined cycle with double blinding. These tasks imply at least basic knowledge in surgical principles. The participants dealt with three different levels of haptic feedback: no haptic, actually fed back forces (1:1) and doubled enhanced force feedback (1:2). The *no-haptic-level* do not feed back any forces or

collisions to the surgeon. The *actually fed back forces-level* transmits the really existing forces while manipulating. In the *doubled force feedback-level* the occurring forces are transmitted and presented after duplicating the forces. During the entire experiment, the used forces were recorded. The statistical tests used for the evaluation were the analysis of variance for normal curve of distribution. Mean forces and mean differences of forces are indicated for the results in the graphs. The conformity of four raters added up to minimum 0.8.

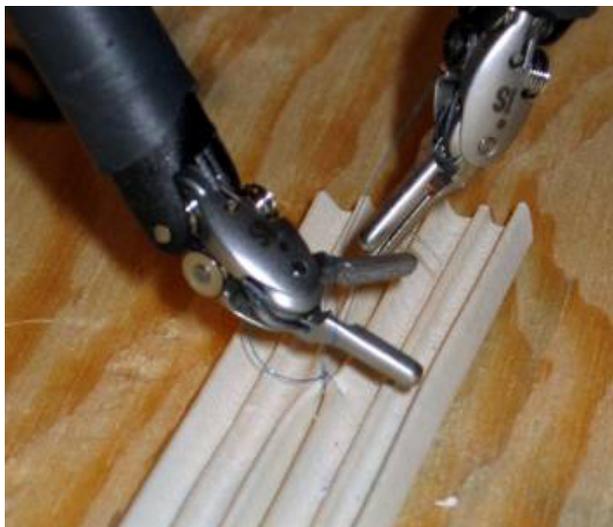


Figure 2: Surgical task: Knot tying with haptic instruments

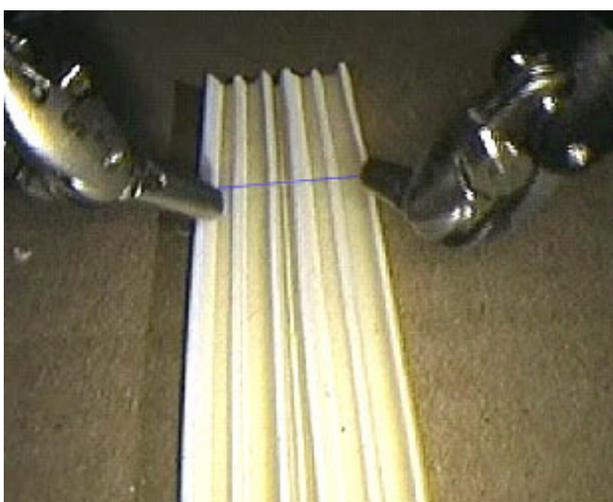


Figure 3: Surgical task: Breakage of surgical suture material with haptic instruments

Human subjects

The human subjects of this study included 25 heart surgeons in different levels of surgical training and age. Three groups of surgeons were defined: One group of 8 with young surgeons, the second group with 12 experienced surgeons and the third group of 5 with robot-trained surgeons. The study intended basic surgical and cardiac surgical procedures. Knot tying, breaking of suture material (the rate for telepresence of the system) and the detection of arteriosclerosis had to be performed in a defined cycle with double blinding.

Experimental telemanipulating system

The system is based on two manipulators, which are controlled by two input devices. Each manipulator is composed of a KUKA KR 6/2 robot that bears a modified surgical instrument of Intuitive Surgical®. A customized adapter is linking the robotic arm with the instrument. For security reasons all flange adapter are equipped with magnetic security couplings.

The position and orientation of the manipulators are controlled by two PHANTOM[®] (SensAble Technologies Inc.). The shaft of the surgical instruments is made of carbon fibre, which is equipped at the distal end with strain gauge sensors as full bridges. This application permits the feedback of forces in two directions while surgical manipulation.

The force sensors were applied directly on the distal end of the instrument's shaft as full bridges. One full bridge of sensors is used for each direction. The signals of the sensors are amplified and transmitted via CAN-bus to a PC system. Sensor readings are blurred with noise; digital filters are applied to stabilize the results. Since we know the position and orientation of the instruments, we can transform occurring forces back to the coordinate system of the PHANTOM devices. Therefore the user has the impression of direct haptic immersion.

For proper and precise telemanipulation a 3D-display is indispensable. This setup is equipped with a fixed head mounted display and a stereoendoscopic camera to provide a realistic scenario for the surgeon.

Breaking of suture material

The breaking of suture material represents the amount of telepresence and immersion of the robotic system for the surgeons and was considered to be the evaluation of the technical quality of force feedback. The surgeons had to tension the thread until the supposed breaking point and had to mention this point before breaking. The difference of force between the supposed and the real breaking of a surgical thread was measured in Newton. The human subjects performed this breaking of suture material once in each haptic level to prevent a recognition of the haptic mode. The used surgical suture material Prolene[®] 6-0 (ETHICON Inc., USA) is in heart surgery a common and frequently used non-absorbable thread made from polypropylene.

Knot tying

The human subjects had to tie surgical knots with two surgical instruments equipped with haptic feedback. The surgeons had ten minutes to perform precisely as much knots in alternate way (left and right taught knots) as possible. The total number of knots, the applied forces, the breakage of suture material and the speed of motion during knot tying were recorded.

Detection of arteriosclerosis

The surgeons had to detect possible stenosis with one haptic instrument in artificial arteries made from polymer precisely and at the same time rapidly.

The errors in detecting short (0.5 cm), long (1 cm) or no stenosis in three arteries were counted. The applied forces while detecting were recorded in Newton and the time of detecting in seconds.

The critical flicker fusion frequency CFF

The critical flicker fusion frequency (CFF) is an individual part of the Wiener Testsystem (Schuhfried GmbH, Austria) analysing the progression of fatigue during the evaluation [20]. The CFF is regarded as an indicator for the central-nervous function capacity, the activation level and the progression of fatigue during practical tasks [21].

The CFF is defined as median of the flicker and the fusion frequency presenting a flickering red light five times in ascending and descending intensity. The course of fatigue during the experiment was measured in between three blocks of tasks.

Results

Surgical knot tying

Force feedback influences the application of forces significantly ($p < 0.05$) in surgical knot tying. In increasing the force feedback the applied forces are reduced significantly ($p < 0.05$, Figure 4). The experience of the surgeons does not influence the amount of applied forces ($p > 0.05$). Haptic feedback

does not show any influence on the quality of surgical knot tying ($p=0.05$) like number of knots, breakage of suture material or speed of motion.

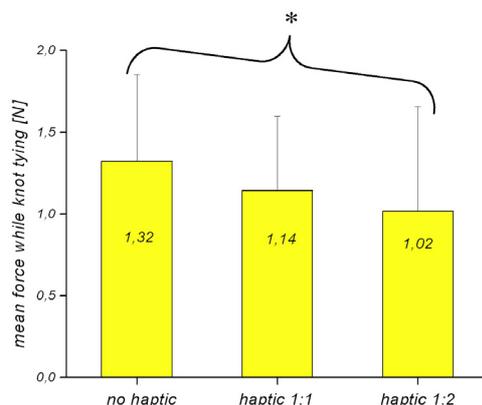


Figure 4: In increasing the force feedback the applied forces are reduced significantly while knot tying.

Breaking of suture material

The difference of forces was calculated where the thread was breaking supposed by the surgeon and the force where the thread was actually breaking. Haptic feedback showed a significant effect of the force difference ($p<0.05$). In increasing the haptic feedback the difference decreased ($p<0.05$, Figure 5), which signifies the precision of the estimated force when the thread was breaking and the high grade of telepresence of the telemanipulator system.

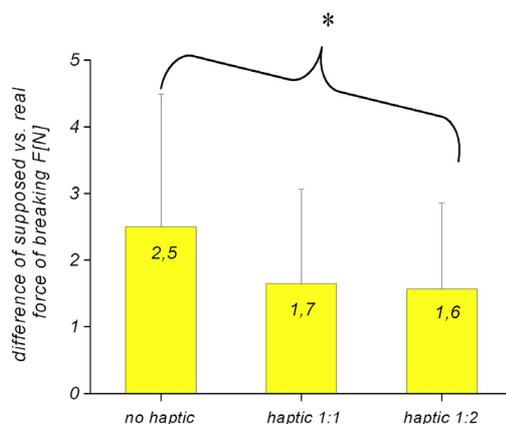


Figure 5: The force difference of the supposed versus the real force of breakage decreases significantly with increased haptic feedback.

Detection of stenosis

Haptic feedback influences significantly the amount of applied forces while detecting arteriosclerosis ($p<0.05$). In increasing the force feedback the applied forces decrease significantly ($p<0.05$). This effect is independent of the surgical experience ($p>0.05$).

Haptic feedback does not increase the number of correctly detected stenosis (Figure 6, right).

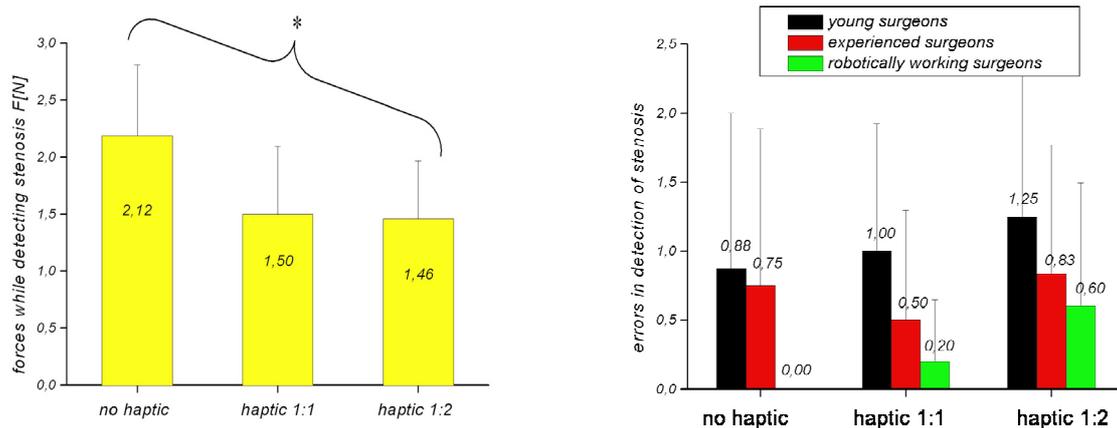


Figure 6: Results in detecting arteriosclerosis. The applied forces decrease significantly ($p < 0.05$) with the increase of haptic feedback (left). Haptic feedback does not decrease the errors in detecting stenosis (right).

Fatigue of the surgeons

The visual fatigue decreases while operating with haptic feedback. Haptic feedback decreases the visual stress and fatigue ($p < 0.05$, Figure 7).

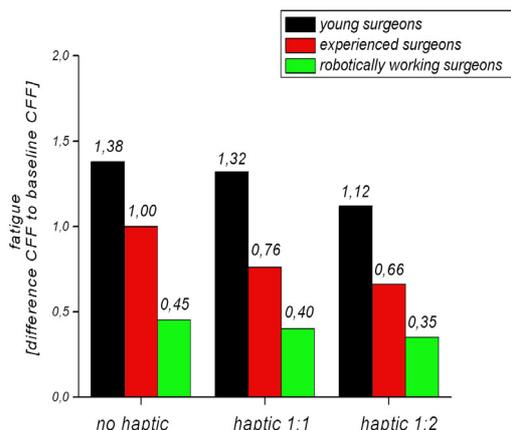


Figure 7: The visual fatigue decreases while operating with haptic feedback.

Discussion

The haptic feedback is currently limited to interact with rigid structures, such as tool-on-tool collisions, not soft tissues. This requires the surgeon to rely on visual feedback in tasks such as suturing. The basic consideration in our work is to offer the heart surgeon an accessory sensory channel in addition to the visual channel not only to avoid breakage of surgical suture material and tissue, but also to decrease visual fatigue.

Following experimental aims were fulfilled: The surgeons broke significantly less suture material and got significantly more immersion, the system reduced the fatigue of surgeons with force feedback. Nevertheless, not all experimental tasks showed significant differences, but statistical tendencies.

The applied forces decrease significantly with force feedback, but we could not find significantly less tissue trauma. This is likely due to the fact, that artificial tissue and arteries even close to real tissue do not represent the genuine violability and the bleeding component of natural tissue.

Therefore, the next step is to implement the system in animal testing as planned and scheduled by the working group.

The results of detecting arteriosclerosis were satisfying, but artificial tissue and arteries being even close to real tissue do not replace human tissue. Visual cues might be less obvious in genuine tissue.

The new system feeds back force in two directions. It is quite possible that force feedback applied in three directions (x, y and z) would intensify the perception of haptic feedback. A subsequent evaluation of detecting stenosis with force feedback in three directions could reveal steps forward and could explain differences in detecting differentiated impressions. The question is the necessity of three fed back dimensions in surgical tasks. Thus, the next important technical consideration is the implementation of the teleoperated robotic surgical instrumentation with strain gauge sensors in three directions.

One time consuming procedure during robotic operations is the knot tying. Fact is, an experienced surgeon performs more knots per time unit in conventional surgery than in robotic surgery. This might be due to the fact, that the range motion of the input devices is obviously inferior to the human hand. The number of knots did not increase within the experimental platform with haptic feedback as expected. Furthermore, the quality of the visual display was criticised by the surgeons and needs to be ameliorated.

Haptic feedback resulted particularly to decrease the visual stress in young surgeons. The working time at the system might be too short for the young surgeons to distinguish significant effects.

The milestones that could be achieved by implementing force feedback in surgical tasks were significantly reduced forces while knot tying and detecting arteriosclerosis as well as significantly less violating of tissue for robotically working surgeons. Potential harmful mistakes can be averted for patient's safety. A heavy collision of instruments in the patient's thorax and with anatomical structures can be avoided by the working surgeon. Furthermore, the immersion and telepresence was higher and enhanced with haptic feedback.

Conclusions

The goal of these experiments was to examine claims about necessity of force feedback for robot-assisted surgical procedures in cardiac surgery. We present an approach of evaluating haptic feedback with a novel robotic system for minimally invasive and endoscopic surgery.

Haptic feedback is needed for surgical tasks since less force are applied by the surgeon. The experiments showed that haptic feedback can be employed to prevent the surgeon from potentially harmful mistakes like breaking of suture material and consequently losing of the surgical needle. The fatigue of surgeons is decreasing and the perception of telepresence by the surgeons is increasing. The safety for patients operated with a telemanipulator with integrated haptic could be increased.

Haptic feedback is an indispensable feature for surgical telemanipulators, in particular for operations with delicate suture material like in heart surgery. The future benefits of force feedback may enhance the safety of patients and increase the quality and number of indications for endoscopic heart surgery. Future surgical systems with integrated haptic feedback could be used to train young surgeons for exercising and teaching critical and difficult steps of surgical operations by the system as simulator.

Acknowledgement

This work is supported by the German Research Foundation (DFG) within the Collaborative Research Centre SFB 453 on "High-Fidelity Telepresence and Teleaction".

References

1. Bholat OS, Haluck RS, Murray WB, Gorman PJ, Krummel TM. Tactile feedback is present during minimally invasive surgery. *J Am Coll Surgeons*. 1999;189(4):349-55.
2. Gutt CN, Oniu T, Mehrabi A, Kashfi A, Schemmer P, Büchler MW. Robot-assisted abdominal surgery. *Brit J Surg*. 2004;91(11):1390-7.
3. Mitsuishi M, Tomisak S, Yoshidome T, Hashizume H, Fujiwara K. Tele-micro surgery system with intelligent user interface. In: *IEEE International Conference on Robotics and Automation ICRA 2000 April, Vol. 2*. 2000. p. 1607-14.
4. Falk V, Jacobs S, Gummert J, Walther T, Mohr FW. Computer-enhanced endoscopic coronary artery bypass grafting: the da Vinci experience. *Semin Thorac Cardiovasc Surg*. 2003;15(2):104-11.
5. Falk V, Jacobs S, Gummert J, Walther T. Robotic coronary artery bypass grafting (CABG)-the Leipzig experience. *Surg Clin North Am*. 2003;83(6):1381-6.
6. Falk V, Mintz D, Grunenfelder J, Fann JI, Burdon TA. Influence of three-dimensional vision on surgical telemanipulator performance. *Surg Endosc*. 2001;15(11):1282-8.
7. Suematsu Y, Del Nido PJ. Robotic pediatric cardiac surgery: Present and future perspectives. *Am J Surg*. 2004;188(4A):98S-103S.
8. Kappert U, Cichon R, Schneider J, Gulielmos V, Tugtekin SM, Matschke K, Schramm I, Schueler S. Closed-chest coronary artery surgery on the beating heart with the use of a robotic system. *J Thorac Cardiovasc Surg*. 2000;120(4):809-11.
9. Bethea BT, Okamura AM, Kitagawa M, Fitton TP, Cattaneo SM, Gott VL, Baumgartner WA, Yuh DD. Application of haptic feedback to robotic surgery. *J Laparoendosc Adv Surg Tech*. 2004;14(3):191-5.
10. Fager PJ. The use of haptics in medical applications. *Int J Med Robot Comput Assisted Surg*. 2004;1(1):36-42.
11. Hu T, Tholey G, Desai JP, Castellanos AE. Evaluation of a laparoscopic grasper with force feedback. *Surg Endosc*. 2002;18(5):863-7.
12. MacFarlane M, Rosen J, Hannaford B, Pellegrini C, Sinanan M. Force-feedback grasper helps restore sense of touch in minimally invasive surgery. *J Gastrointest Surg*. 1999;3(3):278-85.
13. Darggahi J, Najarian S. Human tactile perception as a standard for artificial tactile sensing - a review. *Int J Med Robot Comput Assist Surg*. 2004;1(1):23-35.
14. Van Beers RJ, Sittig AC, Gon JJ. Integration of proprioceptive and visual position-information: An experimentally supported model. *J Neurophysiol*. 1999;81(3):1355-64.
15. psychologie.uni-bonn.de [homepage on the Internet]. Bonn, Germany: Psychologische Online-Dokumente in Deutschland, Österreich und der Schweiz; [updated 2003 April 23]. In: Zwisler R. *Virtuelle Realität und die Rolle von Haptik*; 1998. Available from: <http://www.psychologie.uni-bonn.de/online-documents/literat.htm>
16. Thompson J, Ottensmeier M, Sheridan T. Human factors in telesurgery: effects of time delay and asynchrony in video and control feedback with local manipulative assistance. *Telemed Journal*. 1999;5(2):129-37.
17. Nagy I, Mayer H, Knoll A, Schirmbeck EU, Bauernschmitt R. The endo[pa]r system for minimally invasive robotic surgery. In: *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS 2004*. p. 3637-42.
18. Mayer H, Nagy I, Knoll A, Schirmbeck EU, Bauernschmitt R. Integration of force feedback in a system for robotic surgery. In: *IFMBE e-Proceedings Xth Mediterranean Conference on Medical and Biological Engineering MEDICON and Health Telematics 2004, Ischia, Italy, Vol. 6*.
19. Bauernschmitt R, Schirmbeck EU, Knoll A, Mayer H, Nagy I, Wessel N, Wildhirt SM, Lange R. Towards robotic heart surgery: Introduction of autonomous procedures into an experimental surgical telemanipulator system. *Int J Med Robot Comput Assist Surg*. 2005;1(3):74-9.
20. Wiemeyer J. Flimmerverschmelzungsfrequenz und zentralnervöse Aktivierung. *Neurol Rehabil*. 2002;8(1):29-34.
21. Johansson A, Sandström M. Sensitivity of the human visual system to amplitude modulated light. *Arbetslivsrapport Nr. 2003:4*. Arbetslivsinstitutet, National Institute for Working Life 2003. Umeå, Sweden.