The Essential Human–Machine Interface for Surgery: Biological Signals Transmission

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The concept of a machine-augmented surgeon will become a widespread reality only after the barrier of harnessing the "computer as a tool" has been successfully accomplished. The prospects of surgical robots for computer-assisted surgery, for telemedicine, and for teleoperation–cybersurgery–will be greatly enhanced when computers are no longer considered a separate component that links a system together; they must lose their identity, becoming "transparent." The ideal human-machine interface for surgery is one juxtaposed between surgeon and patient that derives digital biosignals directly from both bodies, transmitting them transparently without perceptible delay, and distributes them bilaterally into afferent (sensory) and efferent (operator or effector) limbs.[1] This ideal human-computer interface will be based upon biosignal processing and will "optimize the technology to the physiology," in what has been called "biocybernetics."[2] Applications of biosignal interfaces are being developed in entertainment, medicine, commerce, defense, and in sales and distribution (Table 1).

CURRENT STATE OF THE ART

Fortunately for the current revolution in surgical therapy, the development of minimal access surgery, the above objective has recently been reached; a biosignals recorder/transmitter has been designed and tested, and is commercially available.

Named the BioMuse™ because of its original development for music applications, the product with its eight recording/controller channels is now recognized as an important development bed for use in a variety of medical applications, including surgery. As clinical information flow becomes increasingly more digitized, many areas of medical practice will benefit (Table 2), and biosignals will play an important role. For example, in Rehabilitation Medicine practice, the BioMuse™ system is being used for enabling physically disabled individuals to explore and control their immediate environments, including the operation of word processors by quadriplegic persons. The great strength of the biosignal technology is the direct acquisition of digital, albeit filtered signals, with only milliseconds transfer time, for immediate interaction with appropriate software-managed applications. A listing of potential medical applications of digital biosignals, most of them currently transmitted by the BioMuse™ and the electro-oculogram (EOG, EyeCon™) systems, appears in Table 3. Even alpha waves of the standard EEG are recoverable for use as a brain-wave controller of peripheral objects.

VIDEO-MONITOR IMAGES: THE MAIN AFFERENT LIMB IN ENDOSCOPIC SURGERY

Currently in video-endoscopic surgery, the primary afferent or sensory limb reaching the surgeon is the visual image captured by a camera and projected onto the video monitor. Even this video signal is not *real* but is a digital image rendition. These days, electronic image enhancement of magnified fields of surgical interest provide augmented video visualization, superseding that possible at open surgery. This essential visual cue would be greatly enhanced by the addition of superimposed data sets, such as from ultrasound, real-time MRI, or reflectance/transmission spectroscopy projected onto the physical images during surgery.[1] Such data sets could be from the patients' pathology (confirmed or

Table 1. The multiple uses of biocontrol technologies

ARENA	*APPLICATIONS*	*EXAMPLE*
Medicine		
Rehabilitation	Diagnostic & Therapeutic	Testing muscles & nerves, rehab. incentives (quadriplegics),music therapy
Communication	Augmentation Products	Environment control (lights, TV, etc.), computers, games
Endoscopic Surgery	Establish databases, Control Instruments	Camera location & 3D-focus, micro-, & macrorobots
Ophthalmology	Diagnostic & Therapeutic	Diagnosis of eye control (strabismus), field perimetry, feedback
Entertainment		
Virtual Reality	Controller, sounds	Fly-through views (without joystick), movement capture
Entertainment Centers	Music generator, game sounds, dance	'Air' piano, violin, drums, etc., movement capture
Computer Graphics	Cartoon generator	Character movements generation and display
Video Games	Controller	View & hand/arm/leg movements
Commercial		
Workman's Compensation	Diagnosis & Prevention	Low back strain/pain Carpal tunnel compression
Automotive	Design & Testing	Ergonometrics, sobriety & fatigue testing
Robotics	Controller	Hazardous materials, volcano and deep sea exploration
Training & Simulation	Databases, controller	Automobile & truck safety, power equipment safety, engineering, architecture, airplane design, etc.
Criminal Justice Diagnosis	Polygraphic fingerprinting	
Defense		
Bioelectric sensors	Diagnosis	Combat health & fatigue assessment
Weapons, simulation & telesurgery	In-helmet controller, war games simulation, remote surgery	Guiding weapons, missiles Performance efficiency & safety Controller for surgical robots in mobile pods
Sales/Distribution		
Synergistic corporations	Imbedded controllers in manufactured products	Video games, virtual reality kiosks, automobiles, endoscope robots, etc.

identified by any of the above methods, all of them providing digitized data), an anatomically correct digital image, or at least the opposite-side structure(s) of the individual patient. This type of enhanced visual sensory input for endoscopic surgeons has become a reality with MRI for neurosurgical and orthopaedic applications.[3,4]

Tactile sensations are present during minimal access surgery, but they are obtunded compared to traditional, open surgery. The remoteness of the instrument tips and the smaller movements contribute to the reduction. Another digital sensory input now possible, but not yet perfected for endoscopic surgery, derives from the muscular system of the surgeon: the haptics (touch) biosignal that is derived from the small electromyographic (EMG) voltage. For the training of surgeons, this performance-based information obtained from the work of master surgeons is being evaluated for its aid as an instructional database matched with synchronized images, either on video or simulated images. An envelope of appropriate forces that may be safely applied to the surgical instrument handles can be experimentally defined as an instructional, reference database to be correlated with the tissue effects observed on the video monitor. Cautionary prompts, utilizing "fuzzy logic" that permits the exercise and/or evaluation of surgical judgment, can be provided as the established envelope of safety is violated, and assessments of surgical performance can be made objectively. Even cardiac rate, eye-blinking frequency, breath holding, and perspiration can be monitored as indicators of the degree of "stress" felt by the operator.

In order to enhance further the teaching and learning of surgical manipulations, the introduction of sensory reinforcement is possible with BioMuse™ technology. By harnessing MIDI (Musical Instrument Digital Interface) signals generated by the digital EMG biosignals, the sensations of muscular action can be transformed artificially into vibratory/tactile feedback into the arms and hands of surgical trainees. Thus, cutaneous or osseous sensory tactile reinforcement can be generated by artificially transforming the coordinated muscular effort of surgery into tactile perceptions. The potential value of this sensory feedback augmentation on the rate or accuracy of learning video-endoscopic surgery is under current investigation. The addition of auditory cues that indicated proximity to target objects–the normal visual images during simulation of laparoscopic cholecystectomy–significantly enhanced the performance of manipulations observed on a standard two-dimensional monitor.[5]

In summary, the afferent limb of currently available interface technologies interposed between surgeon and patient, including digital cameras, electronic image enhancement, and recently, tactile sensing and reinforcement, all seem to contribute to improved performances in both the conduct and the learning of video-endoscopic surgery. These digital inputs to the physician of the future are among an increasing set that are enabling efficient, and therefore lower cost, surgical services of high quality.

THE EFFERENT LIMB IN ENDOSCOPIC SURGERY

The effector features of interface systems perform the actual manipulations/maneuvers with the output or terminal components, those usual operating instruments of surgery. Currently,

Table 2. Clinical information flow

DIGITAL INPUT =>		***DIGITAL OUTPUT =>***
Patient Record	**P**	Augmented Patient Record
Vital Signs & Physical Findings	**H**	Diagnostic Interpretations
Laboratory Data	**Y**	Diagnosis Confirmation
Radiologic Images	**S**	**Diagnostic Studies: micro-robots endoscopy**
Real-time Videos	**I**	**Therapeutic regimen:** **• parental home therapy** **• biofeedback**
Virtual Environments	**C**	**Telepresence:** **• house calls** **• clinical consultations**
Medical Literature (NLM, Journals, CD-ROMs PDR, etc.)	**I**	
	A	**Teleoperation:** **• surgeon (or pathologist)** **• consultations & assistance**
	N	**Patient Education**

*Items in **boldface** feature biosignal transmissions.*

man–machine interfaces have been designed and are being sold as computer-assisted robots for assisting in the performance of open surgery (installation of hip and knee prostheses), and for endoscope or retractor manipulation during video-endoscopic surgery. Still, these interfaces are both cumbersome and expensive, as they rely on complex 3-D registration systems for attaining accurate alignment,[4] and they are unnatural for endoscopic surgery, as they require the direct positioning of instruments by foot pedals, buttons, roller balls or joysticks, or even touch screens or voice controls (the latter in development).[6]

The dexterous hand and arm movements that operate these instruments can now be recognized by their EMG biosignal patterns, and transmitted in real-time from the operating surgeon, either collecting them into databases for educational value, or soon, utilizing them on-line to conduct or facilitate telesurgery. Furthermore, for surgical simulations with "real" virtual reality systems, EMG biosignal databases constitute an envelope of safe, masterfully performed manipulations of skilled surgeons that students seek to emulate as they practice with the instruments. In "true" virtual reality surgical simulation, in which the surgeon (or make-believe surgeon) wears a head-mounted display (HMD) of the "virtual operative site," the EMG biosignals may direct surgeon avatars ("virtual surgeons") that conduct the "virtual surgery." The developing technology that underlies the latter may become the future basis for conducting telesurgery without intervening, electromechanical devices.

However, in the near future, macro- and mini-robots that grasp and manipulate tissues or needles will represent a new type of operating terminal. These will be able to extend the surgeon's expertise and skills to remote operative sites for either conducting emergency life-saving procedures, as on the battlefield where the remote surgeon assists corpsmen working on frontlines, or to provide real-time, surgical assistance to a surgeon colleague in another place (teleoperation). Of course, such sites must be equipped in advance for such on-line interactions.

Indeed, laparoscopic cholecystectomies have been safely and efficiently performed by a surgeon operating in a surgical theater wherein the patient lay anesthetized, but the teleoperated movements of the robotic arm holding the laparoscope within an umbilically placed cannula were controlled, with a remote joystick and two push-button switches, with a separate video image screen in an adjacent room.[7] And much more remarkably, the satellite transmission of surgical manipulations conducted at a workstation site in the United States has operated mechanized, robotic surgical instruments in an experimental operating theater in Italy, with only a one-second delay in visual signal transmission time.[8]

The above demonstrations are solely based on video transmission for the

Table 3. Potential medical applications of digital biosignals

DATA ACQUISITION		APPLICATION CONTROLLER
EMG: (multiple skeletal sites)	**B I O M U S E ™**	• Haptics Constraint & • Instruction Systems for Video-endoscopic Surgical Simulation
ECG: • pulse rate • QRS complex		• Intraoperative assessment • Home monitoring
PHONOCARDIOGRAM: • adult • fetal		• Palpation of cardiac murmurs & • fetal pulse
EMG: (uterus) **RESPIRATION:** • rate		• Palpation of contractions for: • diagnosis of labor • monitoring of labor • Home monitoring
TEMPERATURE EEG: • viability assessment		• Postoperative home monitoring • Robot position
SKIN MOISTURE • Intraoperative assessment		• (tbd)
EYE MOVEMENT: • position • focus • blink	**E O G**	• Endoscopic position • Region of interest • Magnification • Signaling

images, the latter by satellite; however, electromechanical interfaces that sense pressures placed on the instruments by the surgeon's grasp, responding with feedback, are also being developed to provide remotely the tactile component of video-endoscopic surgery. These, too, can be transmitted wirelessly if the signals are digital, as with EMG biosignals. One recognizes that electromechanical interfaces for tactile sensing are indirect and impose nontransparent equipment factors between man and machine,[9] in contrast to the desired digital biosignal approach.

ELECTRO-OCULO-GRAM (EOG) IN ENDOSCOPIC SURGERY

The harnessing of the electro-oculogram (EOG) as an intuitive, biosignal controller of an endoscope-guiding device (a robot arm) offers great promise. The EOG biosignal was developed initially as a controller to be used by disabled persons for operating energized items within their proximity (e.g., electric switches, modified computer keyboards, motorized toys, etc.). A milli-voltage change across the ocular globe, it is also likely to be useful for operating surgical robots that have multiple functions. Such computerized robots have built-in memory that allows repetitive activities, once set, to be repeated without the interruption of resetting the device. These are currently being directed by keyboard, roller ball, or joystick, but voice commands are also being developed.

In addition to the direction of the gaze, a unique advantage of the EOG biosignal is its response to convergence upon looking at objects near from afar, and vice versa. The ability to focus on an image allows one working in 3-D environments to zoom in or out upon a region of interest identified on the monitor. Just as a quadriplegic individual can operate a motorized wheelchair or the modified keyboard of a computer, a surgeon can operate the robot-held endoscope, moving it intuitively by eye motions to the region of surgical interest, and with 3-D systems, at whatever magnification is desired, all without touching the instrument. The headband and electrodes that are worn comfortably around the head are illustrated in Figure 1.

Enhancing this EOG controller capability, the signaling of other desired manipulations is also possible through the pickup of EMG signals derived from the facial muscles, such as clinching the masseter muscle of the mandible or even twitching the nose. A code of three consecutive blinks of the eyelid (an EOG signal, the voltage across the globe being changed by the closure of the lid) could be utilized to advance the laser wattage or turn off the biopolar electrocautery, etc.

Figure 1. Headband with electrodes as an EOG controller. Another "drop-down" electrode, on the left side of the face, is necessary for three-dimensional eye controllers.

BIOMETRICS: ANOTHER APPLICATION OF BIOSIGNALS IN SURGERY

Identifying the biosignal patterns of an individual provides unique biological information as specific as fingerprint patterns–a static, morphologic feature well known as a tool in genetics and law enforcement. However, biosignals are not static, since they reflect physiological processes, and are therefore much richer in information about the person's clinical status. Such variables in clinical condition may include one's degree of rest or sleep deprivation, amount and type of food or fluid ingestion (e.g., coffee or other stimulants, or frustration and satisfaction quotients). Indeed, when coupled with the ECG signal (QRS complex), the respiratory pattern (whether breath-holding or smoothed rates), or galvanic skin response (GSR) and the EMG signals of the arms and face, these constitute a polygraphic pattern of high reliability for stress and fatigue factors. Biometric analysis is feasible and may be useful as a method for the self-diagnosis of surgical proficiency, perhaps in conjunction with simulation exercises, for establishing one's safety and comfort characteristics. This versatile biosignal technology also has merit for use by the Armed Forces as a remote identification system and as a monitor of the personal status (PSM) of soldiers and sailors in battlefield conditions, for enabling life-saving triage and emergency surgical interventions when appropriate. STI

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