AL/CF-SR-1995-0014

ARMSTRONG LABORATORY

FUNCTIONAL TRANSCUTANEOUS ELECTRICAL STIMULATION OF THE VESTIBULAR SYSTEM (U)

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AUGUST 1995

FINAL REPORT FOR THE PERIOD DECEMBER 1991 TO DECEMBER 1994

AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6573

NOTICES

TECHNICAL REVIEW AND APPROVAL

AL/CF-SR-1995-0014

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

KENNETH R. BOFF, Chief
Human Engineering Division
Armstrong Laboratory

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1995	Final Report, Dec 1991-Dec 1994

4. TITLE AND SUBTITLE

Functional Transcutaneous Electrical Stimulation of the Vestibular System

5. FUNDING NUMBERS

PE 62202F
PR ILIR
TA CH
WU 20
F41624-94-C-6000

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Armstrong Laboratory, Crew Systems Directorate
Human Engineering Division
Human Systems Center, Air Force Materiel Command
Wright-Patterson AFB OH 45433-7022

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AL/CF-SR-1995-0014

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The research described in this report is being conducted to support the development of a new technology. This technology builds on prior research and existing technology in which humans and machines work synergistically to control self motion in situations that are demanding because of limitations to sensory or motor systems. Significant improvement in the simulation of self motion could be made if there were a means to control independently the stimulation of the vestibular system. A related need in the domain of sensory prosthetics is for a device that could enhance or restore vestibular function as a conventional "hearing aid" restores auditory function. Such a vestibular prosthesis could have a significant impact on the lives of people with balance disorders. We chose to develop the technology for transcutaneous electrical stimulation because of its potential for independently controlling stimulation of inner-ear structures (EVS) and because of the existence of supporting technology and research. We replicated the results of other investigators in that we have produced sensations of self motion and manipulated them with EVS. The central issues involved in the development and use of EVS in aerospace and prosthetic applications are discussed in this report.

14. SUBJECT TERMS

Electric Current, Stimulation (Physiology), Vestibular Apparatus, Roll Motion, Flight Simulation

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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PREFACE

This report is similar to one submitted by the first author as the final report for his Air Force Office of Scientific Research Summer Faculty Research Program with the Armstrong Laboratory during the summer of 1994. It does, however, summarize research performed under the In-House Laboratory Independent Research workunit (ILIRCH20) which was jointly conducted by all four authors.

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INTRODUCTION

Technology Need

The research described in this report builds on prior research and existing technology in which humans and machines work synergistically to accomplish some function that is difficult or impossible with human or machine alone. Two important categories of such human-machine technology are aerospace systems and prosthetic systems. In the former, machines enhance human sensory and motor capabilities so that people can function in unusual or otherwise disabling environments. In the latter, machines enhance human sensory and motor capabilities so that people with physiological disabilities can function in the activities of daily living. Our approach to human-machine systems considers the similarities between these two situations to be much more important than the differences. The similarities between aerospace and prosthetic applications of human-machine systems reveal possibilities for technology development in each domain. Such possibilities include but are not limited to situations in which technology in one domain can be taken "off the shelf" and transferred with little or no modification to another domain. We believe that important developments also can be made in multiple domains of human-machine systems by considering "dual use" early in the process of technology development. One way to facilitate this is to encourage an interplay between the abstract and the particular in the research that supports or stimulates technology development.

A useful level of abstraction in our current research is the general problem of controlling self motion in situations that are demanding because of limitations to sensory or motor systems (Riccio, 1993, in press). Many of the problems of controlling self motion are common to vehicular locomotion and pedal locomotion. These problems generally have to do with producing, monitoring or dealing with the consequences of changes in the velocity vector for self motion. Variation in the velocity vector produces informative and task-relevant differences between the reference frames provided by the visible surroundings, the tangible surroundings and the forces due to gravity and acceleration (Riccio & Stoffregen, 1988, 1990, 1991; Riccio, 1993; Stoffregen & Riccio, 1988, 1991). Multiple sensory systems allow us to keep track of the multiple environmental reference frames that are relevant to purposeful self motion. Limitations in one sensory system can be compensated by another sensory system but only under highly restricted conditions because self motion is fundamentally a multimodal phenomenon. In general, cooperative use of multiple sensory systems, or "multimodal perception," is crucial to the achievement of adequate levels of performance on the nested tasks involved in or made possible by self motion.

The importance of multimodal perception in self motion is evident when there are limitations to one of the sensory systems that play a primary role in this activity (e.g., the visual, somatosensory or vestibular systems). In the aerospace domain such limitations are problematic in the simulation of self motion (i.e., in virtual environments). High fidelity can be achieved with visual display systems and moderate fidelity can be achieved with g-suits, g-seats, centrifuges, and other motion platforms; however, it is difficult to simulate variations in the inertial environment. More specifically, the mechanical consequences of linear and centripetal acceleration are difficult or even impossible to simulate with existing technology (Riccio, 1993, in press). Significant improvement in the simulation of self motion could be made if there were a means to control independently the stimulation of the vestibular system (the primary system for sensing the mechanical consequences of self motion). A related need in the domain of sensory prosthetics is for a device that could enhance or restore vestibular function in a manner analogous to the role of a conventional "hearing aid" for people with auditory impairments. Such a vestibular prosthesis could have a significant impact on the lives of people with balance disorders. The prosthesis would not be limited to people with vestibular impairment as such. It could be useful, more generally, in reoptimizing the vestibular system for the unique characteristics of an impaired or otherwise modified postural control system.

Technology Pull

One way to pursue technology transfer from a particular domain, such as the aerospace industry or from the federal laboratories, is to search for new applications of a technology in a domain that is different than the domain in which the technology was developed. This sometimes is referred to as "technology push," and technology generally must be pushed by people with expertise in the domain in which the technology is developed. A major problem with this approach is that it is difficult for the experts to identify applications outside their domain of expertise. The problem is exacerbated in "biobehavioral" technology transfer because of problems of translation from engineering to medicine and biology. Perhaps a more significant problem with technology push is that, almost by definition, it is difficult to allocate resources in a way that is influenced appropriately by the likelihood of successful technology transfer. This can be done only by a priori consideration of the need or the market for various technologies. Such a strategy, sometimes referred to as "technology pull," seeks to pull technologies from any available source domains into economically viable domains of application. While technology pull is believed to be more desirable than technology push it also is plagued by the problems of domain-specific expertise and translation between different domains of development and application.

Our approach to the development of a new human-machine technology is based more on technology pull than on technology push. We have spent a considerable amount of time in the systematic identification of technology needs within particular domains (Brown, Cardullo, McMillan, Riccio, & Sinacori, 1991; Riccio, 1993). This has led us to identify a generalized need for a device that can restore, enhance, or otherwise modify vestibular function for the purpose of controlling self motion. We have strategically avoided an a priori investment in particular technologies, and at the same time we have considered a wide range of specific technologies. This strategy has fostered a continual interplay between the abstract and the particular which has led to the serendipitous identification of "dual use" for the developing technology. Relatedly, abstraction to the general problem of controlling self motion has alleviated some of the problems we otherwise would have encountered when trying to translate between domains (e.g., aerospace and prosthetic applications).

Most methods for stimulating the vestibular system involve movement of the body and they result in stimulation of other sensory systems (e.g., sensory receptors in the skin, muscles, and joints). We needed a method for stimulating the vestibular system independently of other sensory systems (Riccio, 1993, in press). We chose transcutaneous electrical stimulation because of its potential for independently controlling stimulation of inner-ear structures and because of the existence of supporting technology and research. We are not the first to stimulate the inner ear transcutaneously with an electrical source (e.g., Volta, 1800; Stevens, 1939; Dzendolet, 1963). This research has been useful to us but it is limited in that most of it employed DC stimulation and all of it involved use of single-channel open-loop stimulation. We must rely on other research to ensure safety and to enhance the technology with AC stimulation, encoding in complex patterns of stimulation, multichannel stimulation, and closed-loop stimulation. Research on transcutaneous electrical stimulation of the muscles, for example, has involved the development of complex stimulating waveforms to balance the potentially conflicting demands of energy transfer, neural coding and safety. Research on electrical stimulation of the cochlea and auditory nerve provides us with analogical guidelines for development of multichannel and multimodal stimulation (Riccio, 1982). It also is the richest source of data on acute and long-term physiological effects and related safety issues. Another key to our development of this new technology is our own research on closed-loop human-machine interactions that was conducted in the context of aerospace systems (e.g., Martin et al, 1986; Riccio, Cress, & Johnson, 1987; Warren & Riccio, 1985). Thus, to some extent, we can view the technology for vestibular stimulation as another component with which to simulate self motion.

METHODOLOGY

Apparatus

Components in all configurations.

We have used gold cup-electrodes (Grass) that are often used for recording electrical potentials at the scalp. Electrode paste and tape have been used to affix electrodes to the scalp and to lower impedances. Electrode impedances typically were between 1,000 and 5,000 Ohms. Electrodes were approximately 9.5 mm in diameter. We plan to use larger electrodes in the future in order to lower the current densities. We always placed one electrode on the mastoid process at the level of the auditory meatus. The purpose of this placement is to concentrate current in the vicinity of the body labyrinth. Electrically-induced motion sensation depends on this. In prior research, we examined a variety of placements for the secondary (return or ground) electrode and found only subtle differences between locations. In the current research we place the secondary electrode either at the back of the skull in the vicinity of inion or at the contralateral mastoid. The stimulator is a current source. The current output is linearly related to the voltage input to the stimulator. The maximum output of the stimulator is 10 mA and 70 volts.

Ancillary devices.

Several additional devices have been used in various phases of the investigation. A signal generator (Bafco, Model 916) has been used to test components of the system and for open-loop electrical stimulation of the vestibular system when continuous on-line modification of the signal has been necessary. The signal generator limited us to the use of sinusoidal, square or triangular waveforms. A computer program was developed in our laboratory to create more complex signals, inject them into our electrical stimulation system, and to collect time-locked data on the output from the system. We have used this program primarily to create pseudo-random sum-of-sines waveforms and to collect data for calibration and verification of the system's function. The primary limitation of the digital input is that the signal has to be created off-line; thus it was not used for rapid or routine data collection. An oscilloscope (Tektronix, model 2215) and chart recorder (Gould, model 220) have been used to collect data for rapid or routine calibration and verification of the system and its components. A force-platform system (Neurocom, Equitest System) has been used to collect data on postural sway with and without EVS. The Equitest System has a platform and visual surround that can move either as a function of an external disturbance or as a function of postural sway (i.e., change in the center of pressure on the platform). Most of the data analysis have been done on a Macintosh (Centris 650) using Systat 5.2.1.

Data Collection From Human Subjects

Safety and precautions.

We have taken every precaution possible in the development of this technology. Our precautions fall into a variety of categories: (a) prior experience of other investigators with transcutaneous electrical stimulation of the inner ear, (b) data on the likelihood of pathological macroscopic physiological activity induced by transcutaneous electrical stimulation, (c) data on the likelihood of localized damage to cells and tissues due to electrical stimulation of any kind, (d) comparisons between electroneural activity and natural neural activity, (e) observation on ourselves (i.e., investigators) only, (f) subjective evaluation of undesirable side effects, (g) observation of short-term effects on postural control, (h) observation of long-term effects of intermittent (infrequent) electrical stimulation.

A number of investigators and clinicians have explored electrical stimulation of the vestibular system (see e.g., Sekitani & Tanaka, 1975; Watanabe et al., 1987). Subjective effects typically are observed in the milliamp range, and stimulation rarely has exceeded 5 mA (or 50 Volts). No side effects have been reported for these magnitudes of electrical stimulation. A class of potential side effects of electrical current is the disruption of macroscopic physiological processes that are mediated or controlled by the nervous system. These side effects include "likelihood of muscular contractions and difficulty in breathing, reversible disturbances of formation and conduction of impulses in the heart, including atrial fibrillation and transient cardiac arrest without ventricular fibrillation" (IEC, 1984). The likelihood of these side effects increases with current magnitude and duration. The minimum threshold in 99.5% of the population asymptotes at 10 mA for durations of AC current (15 to 100 Hz) longer than 10 s, and the threshold can be as high as 500 mA for durations less than 20 ms. Beyond 40 mA for durations greater than 10 s, and beyond 500 mA for durations less than 20 ms, the probability of ventricular fibrillation increases to 5%. The probability of cardiac arrest increases rapidly at still higher values of current. The threshold for such physiological side effects are higher, by a factor of about four, for DC current. Our currents are limited to a maximum of 10 mA (typically settings have been 2 mA).

Another class of potential side effects is related to current density (or charge density) rather than current (or voltage) and involves the microscopic destruction of tissues, cells or membranes. Nonreversible processes are to be avoided. These include: (a) physically damaging gas bubbles released by the electrolysis of water, and (b) toxic oxidation-reduction products that leave the vicinity of or are not created at the surface of the electrode. Reversible processes are favored by charge-balanced biphasic pulses of limited charge density. The theoretical nongassing limits for noble-metal electrodes in simulated cerebral spinal fluid has been estimated at around 300 $\mu C/cm^2$ (Brunner and Turner, 1977). Subtle chemical effects such as local changes in pH are more difficult to measure. Consequently an important source of data is histopathology and the deterioration in function that may be caused by chronic electrical stimulation. For example, nonreversible processes driven by DC stimulation result in destruction of nerve tissue (Lilly et al., 1955). Thus, while DC stimulation has higher thresholds than AC stimulation for macroscopic physiological effects (e.g., ventricular fibrillation), it is much more dangerous than AC on a microscopic level. It should be noted, however, that microscopic damage has been observed in cats after chronic stimulation with charge-balanced biphasic pulses of high charge density. Most of these data come from chronic stimulation with cochlear implants (i.e., internal electrodes). These data indicate that the spatial concentration of charge delivered <u>per pulse</u> must be limited to avoid neural damage (Prudenz et al., 1975). Transcutaneous stimulation involves the use of relatively large electrodes and, by definition, remote sites of stimulation. Thus, our method of electrical stimulation is relatively safe with respect to charge densities when current is limited to the milliamp range (especially when AC stimulation is used).

Electrical stimulation of the nervous system requires the transfer of energy from a metal to an electrolyte. The former is an electronic conductor while the latter is ionic. The loss of loosely bound electrons at the surface of a metallic conductor results in a net positive charge that attracts the negatively-charged ions of the tissue fluids. The resulting "ionic double layer" creates an electrical potential. Current will be driven by the potential difference between the electrode surface and <u>any</u> other electrically charged structures (e.g., electrodes) in the physiological environment. Both the potential difference and the current stimulate active (nonlinear) membrane processes including changes in the ionic permeability of membranes. This method of inducing electrophysiological activity probably is very similar to natural electrotonic interaction at synapses and between parallel fibers (cf., Schmidt, 1975; Scott, 1977). It is useful to know how our artificially induced potential differences compare to physiological levels. Our stimulator is a current source that is limited to 10 mA and 70 Volts, and our electrode spacing can be as small as several centimeters. Our highest average voltage gradient would be on the order of 20 V/cm (although the average voltage gradient in our trials is a couple of orders of magnitude smaller than this). While microscopic structures (cells, membranes, and components of membranes) vary in electrical impedance there is a fairly uniform distribution of such structures in macroscopic tissue (nerve bundles and organs); thus, the macroscopic impedance of the head is relatively uniform.

Given uniform impedance our highest average voltage gradient can be assumed to be on the order of 2μV/mμ. This is well below the range of normal physiological potential gradients: for example, typical values for a nerve cell are a potential difference of 90 mV across a membrane that is 10 mμ in thickness (Schmidt, 1975).

As a final safety measure, we have been using only the investigators in our laboratory as subjects in the research on EVS. By far, most of the data has been collected on subject GER. We have been very careful to note any unusual acute or chronic physiological symptoms or unusual experiences during the period over which we have been subjects in the EVS experiments. In addition, the Equitest System that we use in this research is used widely as a precision diagnostic tool for vestibular pathology and other balance disorders. We should be able to detect any subtle changes in vestibular function and balance over the period of participation in the experiments. By analogy to clinical practices for exposure to radiation we also (a) have been careful to limit exposure over the long term and (b) have tried to allow for extended periods between trials or bouts of stimulation. We check blood pressure and pulse rates before and after stimulation.

Phenomenology

Subjects were queried about their experiences during EVS. Subjects were asked whether they experienced a clear sense of motion including such things as awareness of a direction of motion, to what extent experienced motion was rotational, axis around which the body seemed to rotate, whether the surfaces (e.g., walls, floor, chair) in the environment also moved, and whether the electrically-induced sense of motion was like any natural motion they had experienced. They also were asked about any feelings of discomfort.

Behavior

Postural movements were observed during EVS in trials in which subjects were not restrained. Postural movements were observed in several ways: (a) videotape, (b) head mounted accelerometers, and (c) effects of such movements on forces at the support surface. Subjects were seated in some conditions and standing in others. When subjects were restrained, they were sometimes asked to move a hand-mounted accelerometer in a way that was synchronized with the electrically-induced sensation of motion. Overt behavior sometimes was used as an alternative way for subjects to describe their experiences of motion; for example, subjects were asked to reproduce, through actual movement of the head and torso, their immediately preceding experience during EVS. This allows us to determine "magnitude matches" between EVS natural motion (cf., Riccio & Cress, 1986; Stevens & Marks, 1980).

RESULTS AND DISCUSSION

Phenomenology

Psychophysical thresholds for EVS ranged from 0.2 to 2.0 mA across subjects. Thresholds are typically below 1.0 mA. Discomfort levels can be as low as 1.0 mA in some subjects. The range between threshold and saturation in particular subjects varies between one and three octaves. As the magnitude of EVS is increased from threshold subjects experience a nonspecific sensation of self motion, followed by a specific direction of motion, and finally, perception of a specific relative mix of rotary and translational motion with a concomitant sense of an axis of rotation at a particular point in the body. A typical experience at above threshold sinusoidal stimulation is oscillating side-to-side rotational (roll) motion with the axis of rotation somewhere in the torso. The experienced axis of rotation (e.g., head, torso, seat) varies within subjects. While the causes of such within-subject variation are not well understood it is influenced by posture, visual stimulation, and experience with EVS. In addition, subjects may or may not experience motion of the visible or tangible surroundings (e.g., walls or chair) that is correlated with perceived self motion.

Roll motion is the clearest sensation elicited by EVS and it occurs when stimulation of the left and right vestibular systems is not identical (i.e., asymmetrical). Occasionally, in some subjects, rotational motion in the horizontal plane (yaw) is experienced in such conditions. Asymmetrical stimulation results either from unilateral stimulation or from bilateral stimulation when the electrodes on the left and right mastoids are out of phase (e.g., opposite in polarity). One way to interpret this common finding is (a) to consider that EVS probably stimulates most of the nerve fibers in the vestibular nerve including afferents from both the otoliths and semicircular canals, and (b) to speculate about the forces and motions that naturally result in such patterns of vestibular nerve stimulation. Actual translational motion and rotational motion in the pitch axis result in symmetrical bilateral stimulation. Only roll and yaw motion naturally result in asymmetrical stimulation. Roll motion naturally results in greater or more comprehensive bilateral asymmetries than does yaw motion because of changes in tilt as well as acceleration.

We hypothesized that it would be possible to induce an experience of pitch motion with EVS using identical (bilaterally in-phase) stimulation to the left and right vestibular systems. The reason is that actual pitch motion results in symmetrical stimulation of otoliths and semicircular canals (i.e., the most comprehensive bilateral symmetry). We have attempted only a few trials with bilaterally symmetrical stimulation without a highly salient experience of pitch motion. The result with these few exploratory trials has been a more diffuse sensation of motion. Roll motion is not experienced under bilaterally symmetrical EVS. Further research and development of bilaterally symmetrical EVS should be conducted because of the potential value of multi-axis control of EVS.

Behavior

EVS produces postural sway including movement of the head when seated or movement of the whole body when standing. This effect has been quantified with the Equitest System for perturbing and measuring postural sway. EVS has effects that are comparable to the postural effects induced by motion of the visible surroundings. We have replicated the findings of other investigators in that our effects generally are in medio-lateral (m-l) sway with bilaterally asymmetrical EVS. The effects of EVS on m-l sway are consistent with phenomenological effects in the roll axis (both refer to motion in the frontal plane). The effects are "head centric" in that sway generally is relative to the m-l axis of the head. Anterior-posterior (a-p) sway is generated by bilaterally asymmetrical EVS if the m-l axis of the subject's head is nearly aligned with the a-p axis of the torso (i.e., if the subject "looks" over her/his shoulder). This postural manipulation is useful in that it provides a way to control for the biomechanical confound in the relative postural stability in the m-l axis versus the a-p axis. Control for the biomechanical confound will be necessary to evaluate multi-axis effects of EVS (e.g., head-centric pitch and roll) if and when we develop this capability.

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U. S. Government Printing Office 1995 750-071/00146