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Towards Intelligent Virtual Environment for Training Medical Doctors in Surgical Pain Relief

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Abstract

Chronic pain is a serious health problem affecting millions of people worldwide. Spinal cord stimulation is one of the most effective methods of easing the chronic pain. For most patients, a careful selection of weak electric currents drastically decreases the pain level. Engineering progress leads to more and more flexible devices that offer a wide variety of millions of possible simulation regimes. It is not possible to test all of them on each patient, we need an intelligent method of choosing an appropriate simulation regime. In this paper, we describe the need for an intelligent virtual environment for training medical doctors in surgical pain relief; specifically, we show that the design of such a system will drastically speed up the doctor's training and enhance their training skills.

1 Introduction

1.1 Chronic pain: a problem

Pain is unpleasant, but it serves an important goal: it signals to the brain that something is wrong with a certain part of the body. The intensity of pain is usually proportional to the importance of the signal: severe pain indicates a life-threatening situation that needs an immediate help (like chest pain during the heart attack), while a minor pain (e.g., caused by a small cut) usually indicates a relatively minor problem.

Unfortunately, the pain-generating mechanism itself is as prone to mis-perform as any other physiological mechanism in our bodies. Ideally, we should get a pain signal in the presence of damage, and no pain signal if there is no damage. If the pain mechanics mis-performs, we can get one of the two errors:

- there is a damage, but no pain is felt;
- there is no serious damage, but a severe pain is felt.

Situations of the first type mainly require caution, frequent tests, etc. (e.g., people with diabetes, usually, do not get any indication of the low sugar count until it may be life-threatening, so they must continuously monitor their sugar count). In short, these situations are manageable.

Situations of the second type are much more serious: they lead to a continuous strong pain (*chronic pain*) that is not an indication of any physiological damage. Chronic pain is a serious health problem that affects up to 10% of the world population (more than 25 million of people in the United States only). Chronic pain may not be perceived as such a threat as cancer or heart diseases because, unlike these diseases, it does not kill. However, chronic pain disables more people than cancer or heart disease. It costs the US economy more than $90 billion per year in medical costs, disability payments, and lost productivity.

To ease the suffering of the patients suffering from the chronic pain, it is desirable to stop the pain signals from being received by the brain. This is a very difficult task because, although we can monitor the signals coming through the neurons, the existing technology is not capable of differentiating between neuron impulses that correspond to pain and other types of neural impulses. Since the physiology of pain is still at its infancy, we need some indirect *heuristic* methods to get rid of the pain.

1.2 Easing chronic pain: a brief history

Since pain signals are simply electric signals, it is natural to use electricity to treat chronic pain.

The use of electricity to treat chronic pain has its roots in the ancient world: Roman physicians prescribed the use of "electric fish" in the treatment of their first century patients. The modern use of electricity to treat pain began in the 1750's, when European researchers experimented with newly-invented mechanical devices capable of producing static electricity. The invention of the electrochemical battery in 1800 led to improved treatments. By 1826 guidelines for the use of direct current in medical treatment had been published. The use of electrostimulation gradually diminished after 1900, when the credibility of the treatment was undermined by unsupported claims of earlier researchers.

1.3 Easing chronic pain: the idea of spinal cord stimulation (SCS) and its current achievements

The problem of easing chronic pain is made somewhat easier by the fact that all the pain signals, no matter where they originate, go through the *spinal cord* before they reach the brain. So, the idea is to surgically insert electrodes attached to different points on the spine, and then apply a trial-and-error method to find the combination of signals that would eliminate or at least ease this pain.

This idea was known for quite some time, but it was only implemented in the 1960's, because the implementation of this idea is not easy at all: we want to target the pain in a certain area and so, we need to find the place on the spine that corresponds to this very area of the body. This place is usually very small and difficult to find.

The first clinical trials of this idea were not always successful: Following the *gate control* theory, by Melzack and Wall in 1965, Shealy *et al.*, and Wall and Sweet published first clinical reports of pain relief by direct spinal cord stimulation in 1967. Many inappropriate patients were subsequently implanted and large numbers of failures resulted.

During the 1970's significant improvements in technology occurred, resulting in greater success. In 1973, Cook published favorable responses in multiple sclerosis patients. Shimoji developed a catheter type electrode in 1974. Waltz developed a laminotomy type electrode for clinical applications. In 1979 quadrapolar electrode catheters were introduced.

In the 1980's technology continued to advance, as did the types of conditions identified for treatment using SCS. Surgical instruments were refined and better radiological imaging equipment led to the procedure becoming more widely used. The first multiprogrammable electronics were introduced in 1980, and totally implantable neural stimulator systems were introduced in 1981. Eight-channel multiprogrammable electronics and the first eight-electrode catheter were developed in 1986. In 1988 the noninvasive programmable implantable pulse generator that also had radio frequency capabilities was introduced.

In the 1990's as patients with more complex conditions were identified, use of multi-lead electrode arrays was adopted. As a result, implantable programmable pulse generators, implantable radio frequency receivers, and more sophisticated objective patient screening methods have led to improved outcomes (for detailed surveys, see, e.g., [2, 3, 4, 6].

1.4 Easing chronic pain by SCS: main problems

In spite of the successes of Spinal Cord Stimulation in easing chronic pain, there are still several unsolved problems:

- First, there are, currently, only a few medical doctors knowledgeable and qualified enough to perform these procedures. It is desirable to use the knowledge of these doctors for creating a software helping tool that will help other doctors apply similar techniques. One of the possibilities is to design a computer-based simulator to help the doctors learn this technique.

- Second, the current adjustment procedures take too long. In the academic environment, where a doctor can spend dozens of hours with each patient, the success rate is very high: in the majority of cases, there is a drastic pain relief. However, in the clinical environment, we cannot afford to spend that much time with each patient. It is, therefore desirable to design a special computer-based tool that would speed up this adjustment phase. Since each adjustment requires a feedback from the patient, we need, therefore, a computer-based simulation tool that would help the patient to speed up the learning process.

- Finally, although the existing combinations of signals help to ease the pain in the majority of the patients, with some patients, there is no drastic pain relief, and even if there is, it is desirable to eliminate the pain altogether. For that purpose, medical engineers are currently developing a new generation of implanted tools that would enable us to drastically increase the variety of different signals sent to the spine and thus, hopefully, increase the possibility that some combination of these signals will help every patient.

But with this variety comes a problem: we cannot any longer test all possible combinations of these signals (there are more than 40 million possible combinations), so we need to design an intelligent method of finding the best combination without going through all of them.

1.5 What we are planning to do

In this paper, we describe a new argument in favor of designing a Virtual Environment (VE) for training medical doctors. Namely, we will show that the design of such a system will drastically speed up the doctors' training and enhance their training skills.

Our arguments about the speed up will be reasonably general, and therefore applicable to other learning situations as well.

2 Virtual Environment Can Drastically Speed Up Medical Training

2.1 Basic assumptions about the training speed

In order to determine the training time, let us make some (simplifying but realistic) assumptions about training.

In principle, there are many different types of situations; let us denote the total number of these types by T. For simplicity, we assume that acquiring skills necessary for each of these situations takes the same number of training situations s (be it real patients or simulated patients in VE training). So, to learn all possible types, a doctor needs at least $T \cdot s$ situations. If we denote, by T_0, the time necessary for handling each situation, then the total time for training a doctor for all such situations is equal to $T_0 \cdot T \cdot s$.

For pain relief, the number T of possible types is large, so the above time of total training is unrealistically large. Therefore, we cannot expect every single doctor to be skilled in every possible situation type.

Since we cannot train a doctor to be skilled in every possible situation type, i.e., we cannot train a doctor that is able, without any help, to handle *any* medical situation of desired class, it is therefore necessary to train a doctor in such a way that this doctor will be able to handle *the largest possible number* of such situations, and ask for help in *the smallest possible number* of them.

Some of these situations are more frequent, some are less frequent. So, if we know that a doctor can only learn t different situation types, and we have to choose which of these types the doctor has to learn, we should choose t most frequent ones.

A *skill* of a medical doctor can be thus characterized by the number t of the situations in which this doctor is well skilled.

Some situations types are more frequent, some are less frequent. To estimate frequencies of different situations, we can use a general (semi-empirical) law discovered by G. K. Zipf (see, e.g., [5, 7]), according to which, if we order types from the most frequent to the least frequent one, then the frequency f_i of i-th type is proportional to $1/i$: $f_i = c/i$ for some constant c. The value of this constant can be determined from the fact that the sum of all these frequencies should be equal to 1: $f_1 + \ldots + f_T = 1$. Since $1 + 1/2 + \ldots + 1/T \approx \ln(T)$, we thus conclude that $c \cdot \ln(T) = 1$, $c = 1/\ln(T)$, and

$$f_i = \frac{1}{\ln(T) \cdot i}. \quad (1)$$

2.2 Traditional training

In traditional training (internship), a medical doctor is trained on the real-life flow of patients.

Let us denote by I the time allocated for training. Since handling each patient takes time T_0, during this training time, the trainee will see $N = I/T_0$ patients. According to our assumption about the training time, the doctor will be trained only in those patient types i for which he has seen at least s patients of this type. Out of N patients, the doctor will see $N \cdot f_i$ patients of i-th type; so, the doctor will be trained in all the types for which $N \cdot f_i \geq s$. Substituting Zipf's expression (1) for f_i, we conclude that the doctor will learn all the types i for which

$$\frac{I}{T_0} \cdot \frac{1}{\ln(T) \cdot i} \geq s,$$

i.e., for which

$$i \leq \frac{I}{T_0 \cdot \ln(T) \cdot s}.$$

Therefore, the resulting doctor's skill level t (i.e., the total number of types in which this doctor will be skilled), will be equal to

$$t = \frac{I}{T_0 \cdot \ln(T) \cdot s}. \quad (2)$$

This formula describes the skill level acquired during a given training time I.

We can also consider the inverse problem: we want a doctor to be trained for a certain skill level t, and we need to know the time I required for this training. From the formula (2), we can conclude that

$$I = t \cdot T_0 \cdot \ln(T) \cdot s. \quad (3)$$

2.3 VE training

In VE training, we *simulate* patients. If we want a doctor to be trained on t different types, then we need to simulate exactly s patients of this type.

If we fix the total training time I, then during this time, we can simulate and process $N = I/T_0$ simulated patients. Since learning each type requires s patients, the total amount of different types in which a doctor can get skilled is equal to $t = N/s = (I/T_0) \cdot s$. Thus, after this training, the doctor will acquire the skill level

$$t = \frac{I}{T_0 \cdot s}. \quad (4)$$

This formula describes the skill level acquired during a given training time I.

We can also consider the inverse problem: we want a doctor to be trained for a certain skill level t, and we need to know the time I required for this training. From the formula (4), we can conclude that

$$I = t \cdot T_0 \cdot s. \quad (5)$$

2.4 Conclusion: VE training is faster and better

By comparing the formulas (2) and (4), we conclude that during the same training time, the skill level acquired during the VE training is much higher ($\ln(T)$ times higher) that the skill level acquired in traditional training.

Similarly, by comparing the formulas (3) and (5), we conclude that the training time necessary to acquire a given skill is much shorter ($\ln(T)$ times shorter) for the VE training than for traditional training.

2.5 Auxiliary issue: how to optimally combine VE and traditional training

Designing a virtual environment requires a lot of computer work and a lot of programming. At first, therefore, VE training will not be available for the whole training; realistically, we should expect that only a part of the training is done on a VE, and after this basic training, a trainee goes into a traditional internship training. How can we best organize this combined training?

Let us denote the time that we can allocate for VE training by $I_{\rm VE}$, and the training time for the follow-up traditional training (internship) by $I_{\rm tr}$. During the follow-up training, the doctor encounters $N_{\rm tr} = I_{\rm tr}/T_0$ patients. Of these patients, $N_{\rm tr} \cdot f_i$ are of type i.

If this number of patients is $\geq s$, then for patients of this type, the doctor acquires necessary skills during the follow-up internship, so there is no need to simulate patients of this type during the VE training. Thus, we get all types from 1 to

$$t_{\rm tr} = \frac{I_{\rm tr}}{T_0 \cdot \ln(T) \cdot s} \quad (6)$$

covered.

For each type $i > t_{\rm tr}$, we get

$$f_i \cdot N_{\rm tr} = \frac{I_{\rm tr}}{T_0 \cdot \ln(T) \cdot i} < s$$

patients covered during traditional training. So, if we want the doctor to get the necessary skills, we must simulate the remaining number of patients

$$n_i = s - \frac{I_{\rm tr}}{T_0 \cdot \ln(T) \cdot i} \quad (7)$$

during the VE training.

We want to learn as many new types as possible. How many situation types can we thus learn? During the time $I_{\rm VE}$, we can only simulate $N_{\rm VE} = I_{\rm VE}/T_0$ patients. Since learning type i requires n_i patients, the skill level t acquired by a doctor can be determined by the formula

$$\frac{I_{\rm VE}}{T_0} = N_{\rm VE} = \sum_{i=t_{\rm tr}}^{t} n_i.$$

Substituting the above expression for n_i, we conclude that

$$\frac{I_{\rm VE}}{T_0} = s \cdot (t - t_{\rm tr}) - \frac{I_{\rm tr}}{T_0 \cdot \ln(T)} \cdot \sum_{i=t_{\rm tr}}^{t} \frac{1}{i}.$$

Since $1 + 1/2 + \ldots + 1/i \approx \ln(i)$, we can rewrite this equation as

$$\frac{I_{\rm VE}}{T_0} = s \cdot (t - t_{\rm tr}) - \frac{I_{\rm tr} \cdot (\ln(t) - \ln(t_{\rm tr}))}{T_0 \cdot \ln(T)}. \quad (8)$$

So, we can make two conclusions:

- If the training times $I_{\rm VE}$ and $I_{\rm tr}$ are given, then the resulting acquired skill t can be determined from the equation (8), where $t_{\rm tr}$ is determined from the equation (6).

- Vice versa, if we know the training time $I_{\rm VE}$ for VE training, and the required skill level t, then we must find $t_{\rm tr}$ for the equation (8), and then use the formula (6) to determine the necessary internship period as

$$I_{\rm tr} = t_{\rm tr} \cdot T_0 \cdot \ln(T) \cdot s. \tag{9}$$

In both cases, the number of patients of different types $i = t_{\rm tr}, t_{\rm tr} + 1, \ldots, t$ simulated during the VE training is determined by the formula (7).

2.6 Possible application of SCS to other medical problems

The success of SCS as a method of treating chronic pain has led to the successful suggestions of using the electrical stimulation of the spinal cord to treat other neuron-related diseases such as motor system malfunctions (spasticity, dystonia, tremor, etc.), ischemia and ischemic pain of the heart and blood vessels, etc. The corresponding research is currently at different stages of investigation.

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