A REALISTIC SIMULATION STUDY OF A MULTI-UNIT MULTIPATH NEURAL SIGNAL TRANSMISSION SYSTEM

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Abstract. The functions performed by the multiplicity of units and paths in neural signal transmission are examined by computer simulation of the afferent limb of the monosynaptic spinal reflex (MSR). The simulation incorporates, in particular, the distributions of the spindle stretch thresholds and afferent conduction speeds, "spatial and temporal" summation at the motoneuron, statistical dependence between system parameters such as afferent conduction speed and spindle stretch threshold, and the so-called granularity (noise) introduced by the sensory encoding process. Results of the study indicate that the multiplicity of units and paths is essential for achieving fidelity of signal transmission in the afferent limb of the MSR.

Introduction. Information in the nervous system is transmitted and processed simultaneously along many paths and through the simultaneous coordinated action of many units. Thus it has been generally recognized that this multi-unit multipath characteristic must perform essential functions in the representation, transmission, and transformation of information. However, investigation of such multi-unit multipath neural communication so far has had limited success, because of experimental difficulties (as in the simultaneous recording of individual activities of interconnected neurons), and conceptual difficulties (as in the representation of information by pulse trains in multiple channels). For simple reflex systems these difficulties are not as great. With reasonable simplifying assumptions, the author recently has deduced by mathematical analysis some of the functions performed by the multi-unit multipath characteristic of the afferent limb of the monosynaptic spinal reflex (MSR)(1). In the present paper, results of a realistic computer simulation study of this system are presented to confirm and extend the analytical results.

The Neural Signal Transmission System. In the afferent limb of the MSR, information is transmitted from the muscle to a pool of α-motoneurons (α-MN's). As a communication system, the complete afferent limb can be considered to comprise many communication links such as the one shown in Fig. 1. The applied stretch and the α-efferent pulse trains produce change of muscle length, which is coupled mechanically to the spindles, while the γ-efferent pulse trains stimulate the spindles directly. Some dynamic function of these three input signals is encoded by the spindles into pulse trains which are conducted to the α-MN by the afferent fibers. In the α-MN, these pulse trains are converted into excitatory postsynaptic potentials (EPSP's) and then summated "spatially and temporally". For the present study, this summated EPSP at the pulse generating site of the α-MN is considered to be the output of the communication link(2).

In the communication link there are as many transmission paths as the presynaptic fibers arising from the Ia afferent axons. Each of these has its own intrinsic properties different from its neighbours. The spindles have different stretch-thresholds and different degrees of innervation by γ-efferents, while their different output pulse trains are conducted to the α-MN at different speeds(3). Further, there is evidence that the synaptic knobs are scattered throughout the soma-dendritic complex of the α-MN and that the miniature EPSP's produced at the pulse generating site by single synaptic inputs located at different points on the α-MN membrane are different(4,5). In other words, the "neuronal transfer dynamics" relating a single presynaptic neural pulse to the resulting postsynaptic subthreshold neuronal response at the pulse generating site, vary with the paths.

Simulation and Results. In the computer simulation, the muscle length is assumed to vary with a small amplitude about a suitable mean length so that the spindle output pulse frequency is linearly related to both the γ-efferent input and the change in muscle length(6,7). The neural encoder of the spindle is represented by a generalized integral pulse frequency modulator(1) which functionally resembles the neural pulse generating mechanism, while the miniature EPSP's are assumed to summate linearly at the pulse generating site of the α-MN. The simulation incorporates the various intrinsic properties of the multiple transmission paths and their statistical dependence. Variations of these properties across the paths are described by random parameters which obey appropriate statistical distributions. For example, variation in the size and shape of miniature EPSP's is described by the parameter x in the following expression representing the miniature EPSP.

$$h(t) = b(e^{-t/T_1} - e^{-t/T_2}),\ t \geq 0;$$

$$b = 500 - 0.159\pi x;\quad T_1 = 1/b\ ;\ T_2 = T_1/16$$

where x is the distance (in microns) between the synaptic location and the pulse generating site of the α-MN. Here the distribution of synaptic inputs with respect to x is based on the data given in Ref. 4. The values of the parameters and the inputs are adjusted so that the afferent pulse frequencies lie within the range of from 0 to 120 pulses/sec.

The results generally confirm and extend the conclusions deduced from mathematical analysis using simplifying assumptions(1). Variations in the properties of the multiple transmission paths all tend to reduce the noise content (introduced by the sensory encoding process) of the summated EPSP, as demonstrated by the typical results shown in Fig. 2. In Fig. 2a the summated EPSP (points designated by "x") is compared with a sinusoidal change in muscle length (curve composed of "0") for the hypothetical case in which all paths are identical. Fig. 2b shows that the summated EPSP has a greatly improved signal-to-noise ratio when both the spindle stretch threshold and afferent conduction speed vary with the paths. However, the spatial distribution of synaptic inputs, and the correlation between afferent conduction speeds and spindle stretch thresholds, both have relatively little effect on the noise content of the received signal at the α-MN. From the results of the simulation study and mathematical analysis, we conclude that the multi-unit multipath characteristic provides the essential filters for demodulating the afferent pulse trains to achieve fidelity of signal transmission in the afferent limb of the MSR.

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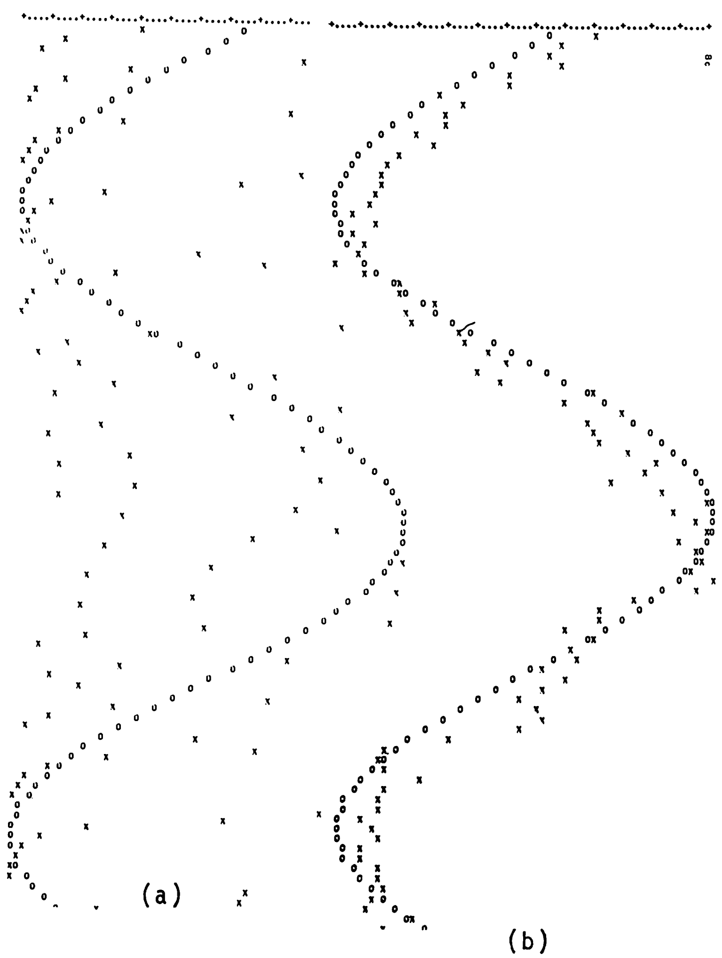

Fig. 2. Summated EPSP for different transmission characteristics of the MSR; (a) All paths are identical; (b) Spindle stretch threshold and afferent conduction speed both vary with the paths.

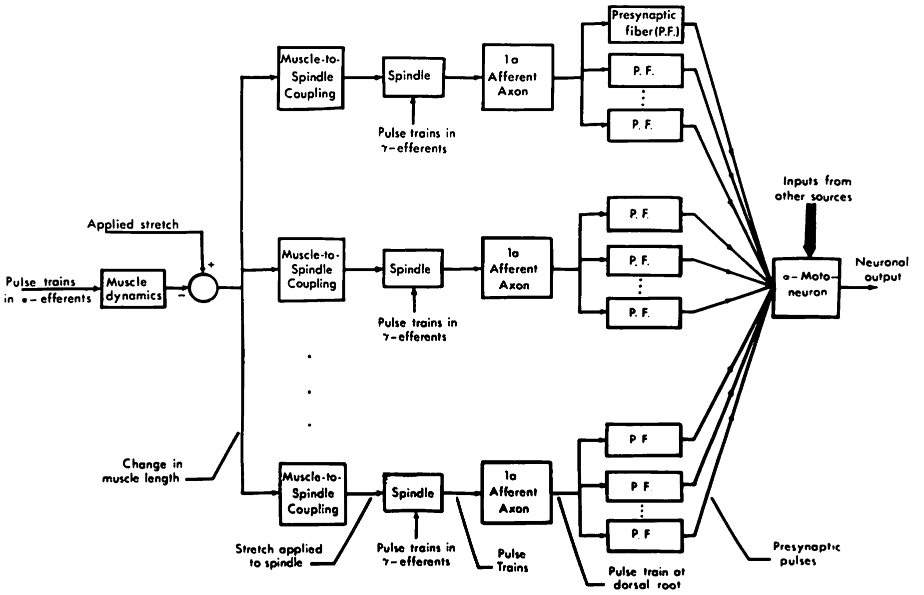

Fig. 1. Information flow in a typical communication link of the afferent limb of the MSR.