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A Model of the Hoffmann Reflex

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Abstract –**The Hoffmann reflex which has applications in assessment of nervous system damage in stroke, spinal injury, Parkinson's disease and other conditions is studied here both practically and theoretically. Using recorded Hoffmann reflex data a model is proposed that captures the qualitative behaviour of the phenomenon and allows investigation of how different waveform morphologies and patterns of recruitment can be related to underlying physiological variables.**

Keywords- **Hoffmann Reflex, Neural modelling, EMG.**

I. INTRODUCTION

Models of nerve fibre recruitment allow deeper understanding of nerve phenomena. In particular some additional special studies carried out in EMG laboratories such as late responses can be understood in terms of such recruitment. Late Responses consist of two separate procedures called Hoffman-responses (or simply the H-reflex) and F-waves. Both responses involve nerve impulses travelling up to the spinal cord and back causing a late response to be measured with suitably placed recording electrodes. F-waves can be elicited from any motor nerve and involve only motor nerve fibres; unfortunately as a diagnostic tool the F-wave has found little success. The H-reflex on the other hand has found application in many clinical situations and therefore it is this late response that will be under investigation here.

II. THE H-REFLEX

The H-Reflex is an electrical response of the triceps surae muscle (the "calf" muscle) to electrical stimulation of the posterior tibial nerve in the popliteal fossa (the hollow at the back of the knee) (Fig. 1). It was first described by Hoffmann [1] in 1918. He showed two facets: a short latency or instantaneous response and a delayed response (Fig. 2). Both responses are compound muscle action potentials. The delayed response is relatively low threshold requiring a smaller stimulus to evoke it than the instantaneous response and gradually disappears as the stimulus increases. This late response represents a spinal reflex as evident by the fact that if the stimulus site is moved distally the latency increases and as such it is the only spinal monosynaptic reflex that can be readily elicited by electrical stimulation.

When the nerve is stimulated initially the larger sensory fibres at the stimulation site are recruited first as they have the lowest threshold. The action potentials that are set up travel both orthodromically and antidromically. The APs travelling antidromically are not picked up with the recording electrodes because their amplitiude is very small and the recording electrodes are neither configured or positioned appropriately for such responses. However the APs that travel orthodromically along the sensory fibres reach the S1 segment of the spinal cord where they are passed on to S1 motor fibres which travel back down to the triceps surae muscle and activates some of those muscle fibres, the activity of which is picked up by a suitably positioned electrode as a response. Responses generated in this way are termed H-responses.

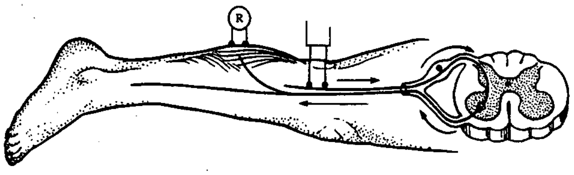

Fig. 1: *The H-reflex procedure.*

As stimulation increases, an increasing number of sensory nerves become recruited and so the amplitude of the H-response increases. However at some stimulation level there will be direct recruitment of the motor nerve fibres under the stimulating electrodes. When this happens two CMAP responses are recorded. The direct motor response is short in latency and is known as the M-response. As stimulation intensity increases further the amplitude of the M-response increases and that of the H-response diminishes as a result of collisions between APs carried via the sensory fibres and APs travelling antidromically along the motor fibres.

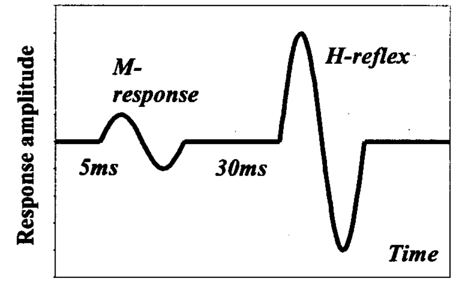

Fig. 2: *Typical H-reflex responses.*

One of the important measures taken during H-reflex experiments are recruitment curves. Such curves are loci of peak response amplitudes versus stimulation intensity and vary in character as a function of muscle temperature, state of contraction ,age, etc. Nevertheless typical curves do exist such as those shown in Fig. 3 for a control position, half-way through stance and half-way through swing.

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The control position is a supine one, i.e. the subject lies prone on their back. As obvious from this figure the H-reflex varies over the gait cycle and it is these variations that make the H-reflex particularly useful as a diagnostic tool. It has been shown [2] that the excitability of the H-response decreases by 60% in mid-swing while in mid-stance an increase of up to 85% has been found demonstrating that the reflex is inhibited during the swing phase of walking. From such measurements it has been found that for healthy people the ratio hc/hs is greater than unity, while for spinal-injured people, in which the inhibitory pathway responsible for h-reflex reduction during swing is damaged, this value diminishes towards unity. It is apparent then that this ratio hc/hs provides some measure of the function of the neurological control system and with sufficient data an empirical function could be obtained that relates this measure to some scale of severity of injury that would aid in rehabilitative monitoring. It should be noted that in order to compile or use such a scale, standardisation of the measurement procedure is required. One such protocol is the Hugon protocol [3] and it is this protocol that is used for the measurements shown here.

The dynamical behaviour of the response can yield diagnostic and prognostic information concerning spasticity, Parkinson's disease and spinal injuries and as such is an important tool in rehabilitation studies.

Section III shows typical data as recorded during a H-reflex experiment along with representative recruitment curves, while in sections IV and V a tentative model for H-reflex generation will be presented. Results for this model are shown in section V.

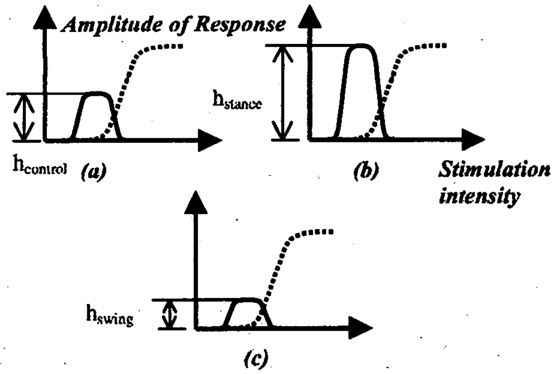

Fig. 3: *M- and H-response recruitment curves for (a) control (b) 50% stance and (c) 50% swing.*

III. EXPERIMENTAL DATA AND RECRUITMENT CURVES

Fig. 4 shows recordings of M and H responses in a supine healthy subject (control) taken using the Hugon protocol (for more details concerning the measurement procedure, see [4]. The dual responses are clearly visible.. Fig. 5 shows the recruitment curves for these traces along with H-reflex curves for 50% stance and swing. In this figure the variation in excitability of the H-reflex is clearly visible. Only the control M-response is shown.

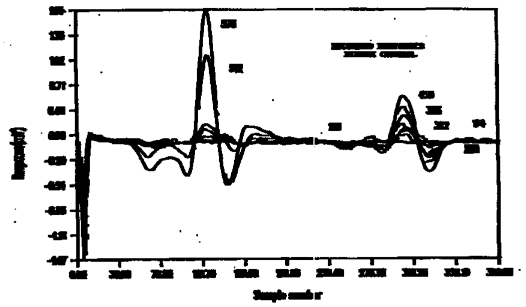

Fig. 4: *Experimental H-reflex results.*

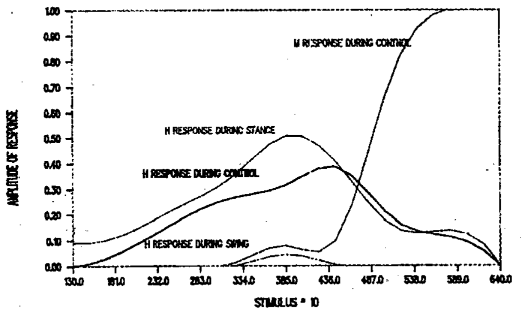

Fig. 5: *Experimentally derived recruitment curves.*

IV. NERVE FIBRE RECRUITMENT

A model will now be proposed that captures the qualitative behaviour of the H-reflex experiment for a subject in supine position. One considers a mixed nerve, with both sensory and motor fibres having a diameter profile R(ϕ) as in Fig. 6. The distribution of the nerve fibre diameters does have a bearing on the exact shape of the exact shape of the recruitment curves therefore some distribution must be assumed initially. Physiological studies seem to suggest a double gaussian distribution about two distinct mean diameter sizes with the larger mean diameter distribution being associated with the sensory fibres. The nerve trunk is then decomposed into N bins based on a histogram of diameter measurements, with these individual fibres dispersed uniformly through the nerve bundle.

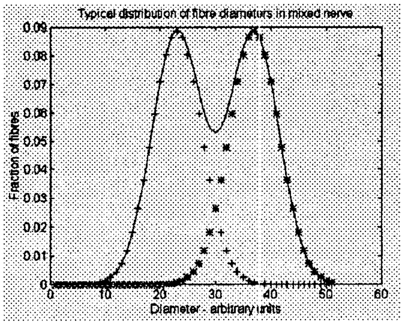

Fig. 6: *Diameter distribution.*

The nerve trunk is considered to have a circular cross-section with a homogeneous spatial distribution of the different nerve fibre sizes. Of course arbitrary spatial distributions and geometry can be considered, but only in exchange for more complex expressions for the recruitment curves.

Nerve recruitment is governed by the size principle, which states that during electrical stimulation the larger fibres are recruited first.

The relationship between the electrode-axon distance and threshold level will be another important factor to take into account as the diameter of the posterior tibial nerve can be quite large. This implies a spatial variation in nerve excitation for similar threshold fibres. In fact it is known [5] that for the excitation of a single myelinated nerve fibre from a point current source I_0 the applied potential field is

$$E = \frac{I_0}{4\pi\sigma r} \qquad (1).$$

To elucidate more clearly what happens as electrical stimulation is increased from subthreshold it is best to consider a nerve bundle containing *N'* fibres with an applied potential threshold φ_t. If the nerve fibres are distributed evenly across the bundle, then as Fig 7 shows, increasing stimulation entails a moving front of depolarisation across the nerve bundle. The problem of expressing recruitment in this case therefore can be reduced to the geometric problem of finding a expression for the area A enclosed by an advancing chord across a disc of radius r.

This function can be calculated and is found to be [4].

$$A = r^2\left[\cos^{-1}\left(\frac{r-z'}{r}\right)-\frac{1}{2}\sin\left\{2\left[\cos^{-1}\left(\frac{r-z'}{r}\right)\right]\right\}\right] \qquad (2)$$

z' goes from $0 \rightarrow 2r$

(As complicated as this expression appears a graph of A(z') yields a simple sigmoidal curve as one would intuitively imagine for the process.). The spatial variable z' can now be replaced by sgn(k(φ-φ_t)) in an approximation to equation (1) to yield a spatial recruitment expression.

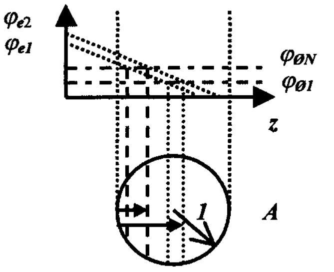

Fig. 7: *Recruitment as a function of spatial and temporal variables.*

More physiologically realistic activation functions could have been invoked at this stage such as those due to Rattay [6] and others, but the simpler expressions used here serve to elucidate the phenomena in a clearer and more concise manner.

To complete the picture of recruitment for this model one must pull together the size principle and the spatial principle to form a compound activation function. As equation (2) expresses recruitment for a single diameter bin only, the formula must be parameterised by fibre diameter such that the smaller diameters displace the curve to higher stimulation intensities (Fig. 7). Therefore one gets a family of curves, one for each diameter bin. These curves express the fraction of each bin recruited for a given stimulation intensity, therefore if one weights each fraction by the actual nerve fibre diameter histogram results one obtains values for the number and sizes of fibres recruited for a given stimulus intensity. Fig. 8 shows the results of this procedure for the double gaussian distribution used earlier.

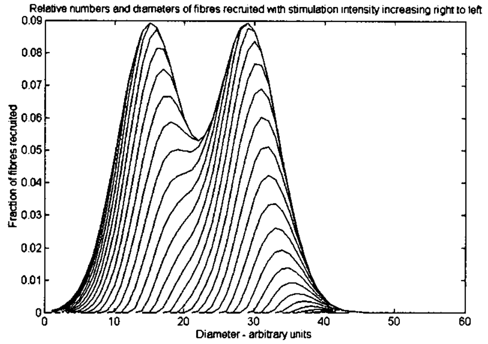

Fig. 8: *Recruitment as a function of diameter distribution*

As stimulation increases sensory nerves are recruited first. Then both types of nerves are recruited until finally stimulation picks up the smallest motor fibres.

V. MODEL STRUCTURE

Fig. 9 gives the model structure in terms of generation of responses. Two types of recruitment are distinguished - direct, and indirect. The M-response is due to direct recruitment of the motoneurons, its exact waveform being a function of the number and diameter of the participating fibres and the stimulation intensity ***v***. These parameters are related to the stimulation intensity according to equation (3).

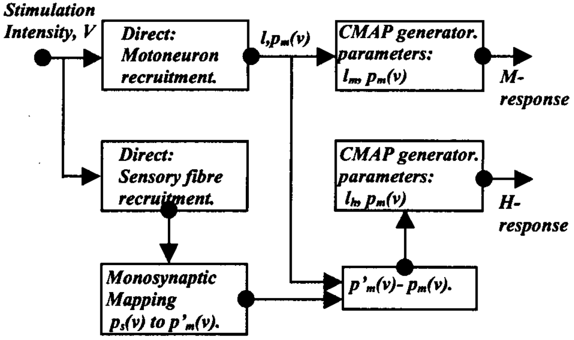

Fig. 9: *Model structure.*

$$p_m(\phi,v)=\sum_{i=1}^{N} R_m(\phi_i)A_{\phi_i}(v) \qquad (3).$$

For a given stimulation level then, this equation provides a diameter-based distribution of fibres, which together with the distance between the cathode and the recording electrode (l_m), can generate a CMAP. The CMAP function uses the fact that there is a linear relationship between axon diameter and velocity [7] to calculate the dispersion of the motor unit responses (MUR). The MURs are modelled as damped sinusoids and the CMAP generator is based on the volume conductor model [4].

The H-response is due to indirect recruitment, modelled by a one-to-one mapping of nerves from the sensory bundle onto the motor bundle. This is to model the monosynaptic reflex. The sensory fibres are directly recruited with number and diameter profile according to:

$$p_s(\phi,v)=\sum_{i=1}^{N} R_s(\phi_i)A_{\phi_i}(v) \qquad (4).$$

This distribution of fibres maps onto a distribution of motoneuron fibres p'_m based on size, i.e. the largest sensory fibres are mapped onto the largest motoneurons and so on. From the literature there have been no physiological studies that support or discredit this mapping hypothesis, possibly due to the technical difficulty in performing such studies. Nevertheless the mapping used here seems intuitively appropriate and although other mappings were used quite successfully it was this size-based mapping that was adopted for the results to be shown here.

Motor fibres that have been directly stimulated are unavailable to participate in the H-response due to collisions with antidromic APs and refractory period considerations therefore it is possible to derive the numbers and sizes of motoneurons fibres available to generate a response using

$$p_h(\phi,v)=p'_m(\phi,v)-p_m(\phi,v) \qquad (5).$$

Again this diameter distribution can be fed into a CMAP generator along with the appropriate conduction length l_h to produce a response.

Responses of this model for increasing stimulation are shown in Fig. 9. M and H recruitment curves can now be compiled by noting peak amplitudes to give plots such as Fig. 10. Despite the idealisations these correspond at least qualitatively with typical recruitment curves.

VI. CONCLUSION

The Hoffman reflex, which has applications in assessment of nervous system damage in stroke, spinal injury, Parkinson's disease and other conditions, has been studied here both practically and theoretically. It is hoped that the methodology will have wider applicability in mono-synaptic arc reflex studies. This simple model of the H-reflex can be used to investigate how different waveform morphologies and patterns of recruitment can be related to the underlying physiological variables. As more knowledge of these underlying physiological variables emerges it is hoped that the output of this model can be matched up with real data such that deeper measures of nervous system integrity can be obtained. Even as the model currently stands it could provide an invaluable tool for education purposes in physiology courses.

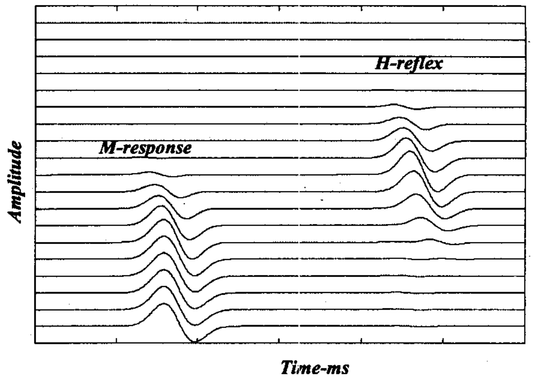

Fig. 10: *Model output.*

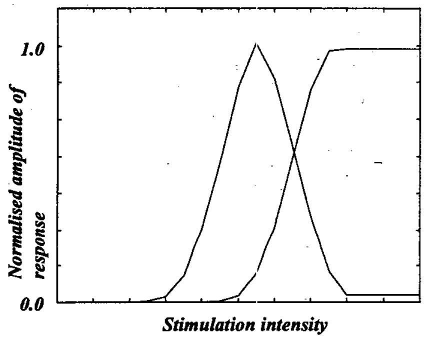

Fig. 11: *Model generated recruitment curves.*

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