ACTIVATION OF MUSCLES IN THE PIG FORLIMB USING A LARGE DIAMETER MULTIPOLAR NERVE CUFF INSTALLED ON THE RADIAL NERVE IN THE AXILLA

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Abstract – *Stimulation of trunk nerves using multipolar cuff electrodes for muscle activation in FES systems is an alternative to the use of epimesial, intramuscular, interfascicular and transcutaneous approaches [1]. In this paper we describe the development of an animal model which uses the pig forelimb as a means to characterize the ability of multipolar cuff electrodes to achieve well graded, selective activation of forelimb muscles. Preliminary results are presented indicating that satisfactory muscle recruitment curves can be obtained and that some degree of selective muscle activation is possible with the present cuff design. The utility and limitations of the pig model are also discussed.*

Keywords: FES, Neuromotor prostheses, Nerve cuffs, Selective stimulation

1. Introduction

The functionality of FES systems that restore grasp in quadriplegia could be enhanced if more muscles could be activated. That is difficult to achieve if intramuscular or epimesial electrodes are employed because separate lead wires are needed for each added muscle; because some of the muscles are small in relation to the size of the electrode; and because some muscles might be difficult to access surgically. In particular, with regard to the thenar muscles (which are important for thumb function), lead wires would have to traverse the wrist joint and there is little space for this. Other difficulties include: the occurrence of “spill over’’ wherein stimulus current intended for a given muscle “leaks’’ sufficiently within the tissue to activate a neighboring muscle with undesirable consequences; and contraction or length dependent recruitment effects caused by mechanical distortion of the electrode muscle interface.

A proximally located nerve stimulation cuff presents some formidable problems of its own, however, and this mainly centers on the need to develop means to separately activate the individual muscles served by a multifasicular nerve. Building on prior work by McNeal and Bowman [2], Veraart and his colleagues, demonstrated the use of a spiral cuff containing 12 addressable contacts. This design works well when the fascicles of the trunk nerve are morphologically and functional divided into large component groups, such as the tibial and peroneal divisions of the sciatic nerve in the cat (as shown in refs. [3] and [4]. A question remains, however, how well the multipolar design concept functions when the cuff is applied to larger trunk nerves of 5 or 6mm dia such as exists in the human arm, and where the fascicular divisions are not well segregated either morphologically or functionally. Another, limitation of the prior studies by Grill et al., for example, is that the contraction data obtained pertained to short evoked twitches, and the studies need to be extended to include sustained contractions that will be required for FES applications.

In light of the above, we sought to develop an animal model with which to study the recruitment and selectivity characteristics of multipolar cuffs on large nerves. The pig was selected because the median, radial and ulnar trunk nerves of the forelimb are of comparable sizes with their human analogs. Furthermore, common farm pigs are relatively inexpensive, and their use in research is not as controversial as some more popular laboratory animals. Our strategy was to assess the selectivity and recruitment characteristics of the cuff interface by directly measuring the tendon forces developed by the activated muscles.

2. Methods

Preparation – Acute experiments were performed on six pigs (approx. wt 60 kg.) under gas anesthesia (Isoflurane). After performing exploratory examinations of the muscles and tendons of the forelimb in pilot studies, we decided to use 6 extensor tendons to the toes on the dorsum of the foot and the wrist extensor tendon from the extensor carpi radialis muscle. These tendons can be isolated relatively easily (in contrast to the system of flexor tendons on the palmer aspect of the foot). The locations of the selected tendons are shown in **Figures 1 and 2**. The animal is placed on its back and the left elbow, wrist and toes are secured in a frame After isolation, the tendons are each transected and tied via sutures and stainless steel wires to individual strain gauge tension transducers anchored to an overhead frame.

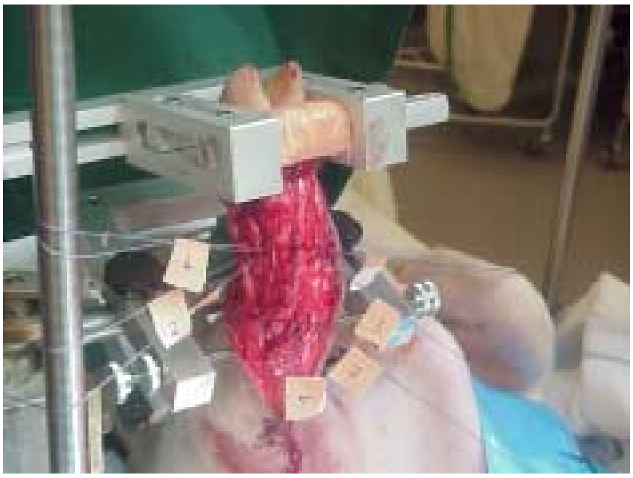


Fig. 1 Showing exposure of extensor tendons and limb fixation

Nerve stimulation cuff – The studies utilized a hybrid design cuff consisting of platinum electrode facings deposited on polyimide ribs. The rib structure

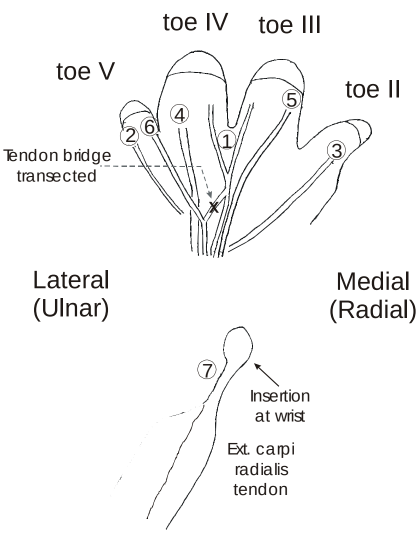


Fig. 2 Dorsum of Pig left forelimb (wrist and foot) showing principal extensor tendons

was laminated between two sheets of silicone one of which was pre-stretched to cause the final structure to be self coiling (for additional details see ref [5]). **Figure 3** shows

a photograph of the 6mm dia. cuff.

The bracial plexus was exposed via an incision in the Axilla. The component from which the radial nerve derives was mobilized over 30mm for installation of the cuff, and the median and ulnar nerve components were transected. In the early experiments we transected several branches of the radial n. component distal to the cuff that innervated the triceps, lattismus dorsi and scapularis muscles. We did this to ensure that activation of the shoulder muscles would not cause mechanical interference with the registration of the contractions of the foot extensor muscles. In the later experiments, however, we were confident that the limb fixation was robust enough to preclude such mechanical artifacts. We then allowed this innervation to remain intact and placed EMG electrodes (bipolar pairs of coiled wires) into these shoulder muscles to monitor their activation by the cuff stimulation as well.

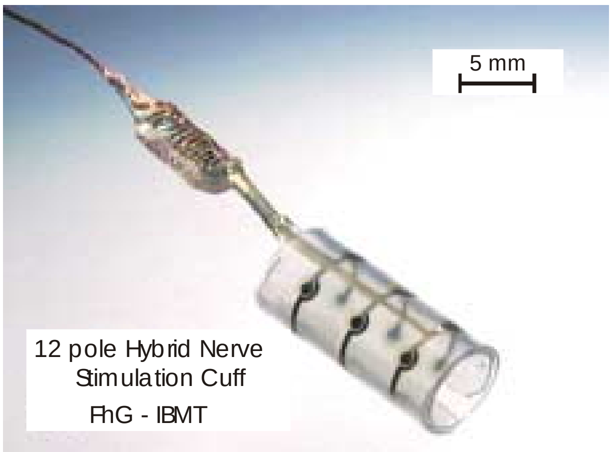


Fig. 3 Photograph of a Hybrid cuff formed from polyimide and from silicone sheeting

Radial nerve morphology – Figure 4 shows a cross section of the pig radial nerve in the region where the cuff was applied. The nerve is oval shaped (5mm x 6mm) and consists of numerous small fascicles.

Fig. 4 Cross section of Radial N. division at Brachial Plexus

Recording - The contraction forces were sampled at 600 Hz and stored digitally. The EMG signals were amplified, band pass filtered between 20 and 500 Hz before being sampled at 1KHz and stored. During offline analysis the EMG signals were full wave rectified and integrated using a 50ms sliding window (+/- 25 pt moving average).

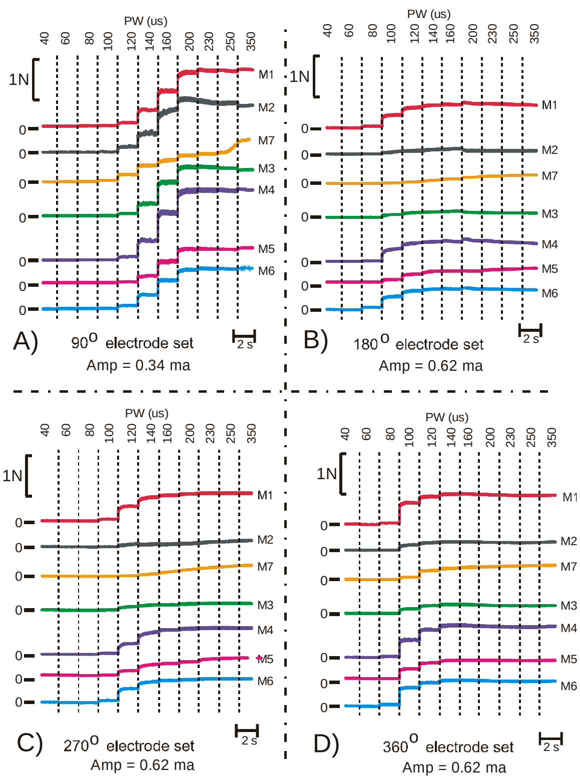
Stimulation – Stimuli consisted of biphasic charge balanced constant current pulses delivered to sets of electrodes within the cuff as follows: The outer electrodes in each longitudinal set of three were connected to each other and driven as anodes while the center electrode of each set was driven cathodically during the primary stimulus phase. The primary phase and recharge phases had relative current amplitudes in the ratio of 10:1. The impedances between longitudinal contacts within the cuff after being installed were in the range of 1.4 to 1.8 kOhms (1000Hz). To test the spatial selectivity characteristics of the multipolar cuff the responses of the monitored muscles were compared when the stimulation was switched from one set of electrode contacts to the others in succession. The 12 contact cuff afforded 4 different combinations of electrode sets (each at 90 degree intervals circumferentially around the nerve). In different sets of trials, the stimulus pulse width was changed stepwise over the range 40 to 350us at a fixed amplitude. After all four electrode combinations were tested, the current was increased and the process repeated. The effect of stimulus current was studied from below threshold (usually about 0.2ma) until 1.0ma. In rare instances (where the muscle responses were weak) we continued to increase the amplitude up to 2.0ma. After the pulse width modulation studies, we investigated the effect of frequency on modulation of the muscle contraction forces. The effect of frequency was studied with steps from 15 to 55 Hz.

In the first studies each stimulus level was presented for 2s, but this was later reduced to 0.5s in order to reduce the possibility of fatiguing the muscles. All sequences of the stimulation were computer programmed.

3. Results

Figure 5 shows the contraction results for each of the 4 electrode sets on the Radial N. in Pig#4. It can be seen that the 90^{o} set (A) produced the greatest magnitude contractions in all of the 7 muscles compared to the other 3 site combinations (B, C and D). Moreover, the current at which this occurred was lower then with the other sets (0.34 vs. 0.62ma). In comparing (A) with (C), the reduction in contraction strength is about half for M1 but the reduction is much more pronounced for M2 and M3. It is not know why the set at (A) was more sensitive.

Figure 6 presents mixed data where two toe extensor muscles responded (M4 and M5) and two shoulder muscles (latisimus dorsi and scapularis) were activated by the cuff with Pig#6. The figure represents a matrix of responses where the columns are the four sets of electrode sites and each row corresponds to a different stimulus amplitude. The stimulus freq. was fixed at 25Hz. Each matrix element contains four traces: the upper two are contraction forces from toe extensors M4 (black) and M5 (grey); and the lower pair of traces are the integrated EMG activity evoked in the latisimus dorsi (black) and scapularis (grey) muscle. The scales (Newtons and microvolts) are the same throughout the figure. The abscissa is time in seconds, and the stimulus pulse width was increased stepwise from 40 to 350us. Of the toe extensor muscles, only M4 and M5 showed any activation over the current range



tested (1 ma), therefore the other toe extensor muscles are not displayed.

- a high level of selective activation is seen for the scapularis verses latisimus dorsi. The electrode set 90° and 180° activate the former and the electrode set 0 and 270° activate the later. This is seen in comparing [a] or [b] with [d] or [f].
- sets 90° and 180° are able to activate M4 and M5 at low current, whereas the 0° and 270° sets are not (see [c], [d], [e] and [f].
-

Fig 5

- equal activation of M4 and M5 can be obtained over a large range using the 90° electrodes and 0.45ma as seen at [e], but greater activation of M4 relative to M5 can be obtained using higher current (see[i], [j] and [k]).

- activation of M4 and M5 can be obtained without Latisimus dorsi (but with Scapularis) using the 90° electrodes (see [c], [e], [g], [I] and [m].

- it was not possible to activate either M4 or M5 without co-activating Scapularis.

- the relative activation of Latisimus dorsi verses Scapularis could be reversed by selecting the pulse width. For example, in [m] Scapularis is higher at low PW but Latisimus dorsi is higher at high PW. A point of equality is possible at intermediate PW (and note that M4 and M5 are at saturation over most of this stimulus range).

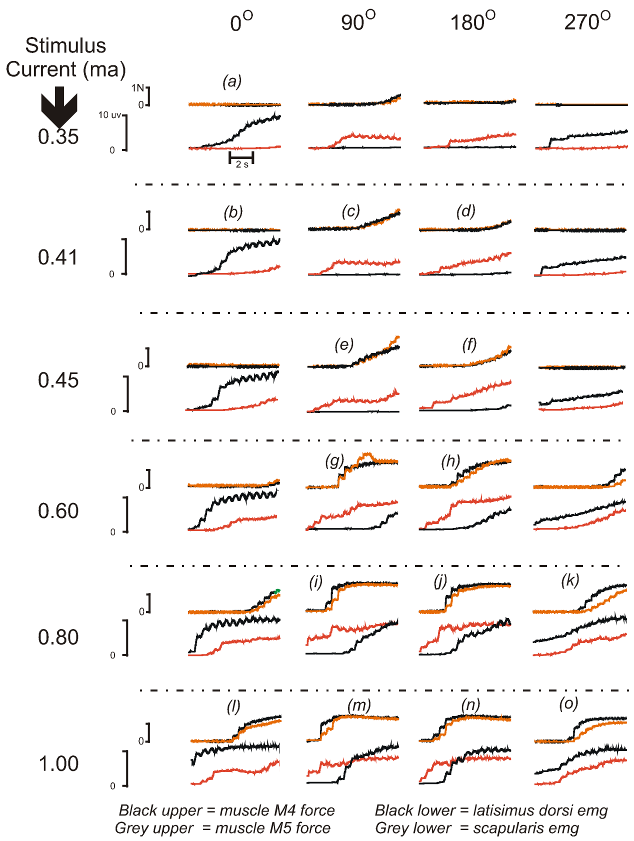


Fig. 6

4. Discussion

The results thus far indicate that different contraction patterns can result from the use of different electrode sets, however, it will be difficult to be able to select any arbitrary muscle and activate it to the exclusion of other muscles.

We have not seen any problems with recruitment curves being too steep. If a muscle was able to be activated at all, then we could always find a combination of stimulation parameters that could produce graded contractions.

The paradigm of transecting the tendons and tying them to force transducers has two main drawbacks: Once the tendon has been severed, it is difficult to know where the muscle length is relative to its physiological length. Thus, a stronger contraction by one muscle may reflect a more optimal initial length rather than greater activation by the stimuli. Another difficulty is that the muscle and tendon system yields continuously throughout the experiment. Thus, it is necessary to check that the tendons do not become ‘slack’ and this can occur in just 30 minutes or so. If comparative data are gathered by rotating swiftly from each electrode set to another, the comparisons are valid, but comparisons between results obtained at the start of the day and at the end of the session would be questionable. It might be useful to employ the ‘’belt buckle’’ transducer for these studies.

We found it useful to apply exploration gel over the muscles and tendons to keep them from drying out during the session.

We also noted high sensitivity of the cuff interface to mechanical disturbance. When the shoulder muscles contracted it could apply pressure to the chest area, which in turn coupled to the cuff. We were able to eliminate this by abducting the forelimb, and presumably, a chronically implanted cuff would be less sensitive to pressure. This issue will, however, need to be addressed.

The use of EMG as a measure of muscle activation was very satisfactory and has the advantage that it could be applied during studies with chronic preparations since it can be done with minimal invasiveness.

In summary, we feel that the pig forelimb is a useful model to test novel cuff designs. Furthermore, by placing cuffs on the median nerve to activate wrist flexor muscles and a similar cuff on the radial nerve for wrist extension, it should be possible to perform studies of closed loop systems to control the position of the ankle joint for example.

5. References

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