PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Experiments on the Restoration of Paralysed Muscles by means of Nerve Anastomosis. Part II. Anastomosis of the Nerves Supplying Limb Muscles

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II. *Experiments on the Restoration of Paralysed Muscles by Means of Nerve Anastomosis.** Part II.—*Anastomosis of the Nerves Supplying Limb Muscles.*

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[Plates 3 and 4.]

Contents.

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1. Introduction.

In the Preface published with Part I* of this research the historical development of the subject has been shortly detailed. As there stated, the first experiments on anastomosis of nerves were those conducted on the nerves of the muscles of the limbs, namely, on the wing of the cock. Although the functional restoration in the case of FLOURENS' experiment was described as being so satisfactory, it apparently failed to convince investigators, and, subsequently, when the possibility of functional cross union came to be inquired into, various explanations of the result in FLOURENS' experiment were put forward. Thus there was the objection that sufficient precaution was not taken to prevent confluent reunion of all four ends, and that this might have occurred and permitted restoration of the old paths. There was the allegation again of SCHIFF that the description of the extent of the recovery was deficient, and the suggestion of CUNNINGHAM (5)† that the recovery might have been vicarious, due to the tensors of the patagium, whose supply remained intact.

The next contribution to the subject in the form which is here under consideration was that by RAWA (2) in 1883–85. There are two parts in RAWA's research, namely, the cross union of nerves of different function, namely, the vagus and hypoglossal, and the cross union of nerves of similar function in the limb in dogs. In the latter, which alone require consideration here, the nerves which he crossed were the posterior tibial and the peroneal. His idea here was to form a cross between the nerve supply of the flexor and that of the extensor muscles of the paw. He, however, found difficulty in getting isolated unions, and thus preventing confluent reunion of the nerve ends, with danger of reunion of corresponding ends. To avoid this he adopted a method of reunion which could not lead to functional restoration of the limb in any circumstances, namely, the laying down of but one crossing, the other central and peripheral segments being excised. Thus only one set of muscles remained in a position to recover function, while the other group was left to be permanently unsupplied. The consequence was that in all his animals contracture had of necessity to develop, and to become more pronounced with the recovery of the muscle group to

* 'Phil. Trans.,' B, vol. 202, pp. 93–163.

† The numbers in brackets refer to the Bibliography, p. 73.

which the nerve supply had been conducted. RAWA, however, deduced from his work that recovery of function of the group of muscles took place under the new conditions, as he found recovery of flexion in the case where the peripheral segment of the posterior tibial was united to the central segment of the peroneal, and of extension when the peripheral segment retained was that of the peroneal, and these conclusions were confirmed by physiological examination. One of his conclusions also was that a period was required for re-education to the altered conditions.

In the year following the full publication of RAWA'S results STEFANI (3) contributed some valuable experiments on the limb muscles of dogs. His experiments are free from the objection of RAWA'S in that they formed conditions which made recovery of functional use of the limb a possibility. Thus they consisted of cross unions between the median and musculo-spiral, or of the combined median and ulnar with the musculo-spiral. Recovery of function took place, and a physiological examination showed in most of his experiments that the recovery was not due to reunion of the severed trunks, but to the cross union. In some of his experiments he exposed the cerebral cortex to ascertain how the cortical centres were affected by the new arrangement of the nerve trunks, but his observations led him to the conclusion that under such circumstances the cortical centres lost their excitability, as he failed to get responses on stimulating the cortex.

HOWELL and HUBER (4) followed with experiments in crossing the median and ulnar in dogs, but their conclusions, while leading them to believe in the possibility of recovery of the muscles through crossed nerves, were inconclusive by reason of the fact that the nerves which they crossed supplied muscles of similar function instead of those of antagonistic action.

The correct conditions were more nearly approached by CUNNINGHAM (5), who published his results a few years later. CUNNINGHAM, after having repeated the experiments of HOWELL and HUBER, *i.e.*, cross union of the median and ulnar, with similar findings, namely, that the operation was productive of little disability to the animal, performed a series of crossings involving the median and ulnar with the musculo-spiral, as had been formerly done by STEFANI. In four, in which the conditions had been successfully established, he found that no proper functional recovery had occurred. Thus, at one year and five months, in one of the experiments, although there was practically no atrophy of the muscles, there was in-coördination, which prevented proper use of the limb. His examination of the condition of the cerebral cortex showed that the flexion centre had become an extension and *vice versâ*, thus differing from the conclusions of STEFANI. He concluded that "it is evident that the central nervous mechanisms do not, as RAWA has claimed, adjust their impulses to suit the altered peripheral innervation, and by practice supply exactly what is required of them by the peripheral organs with which they become connected."

In 1900 I (7) published a contribution to this subject in which the experiments took the form of a crossing between the entire nerve supply of the flexor group with that of the extensor group in the fore-limb of the dog. Previous experiments (6) which I had made on the hind-limb of the dog had led me to regard the hind-limb as less suitable for this form of investigation, as even with all the muscles of the hind-limb paralysed, the dog can use the leg for walking, the chief indication of the defect being flexion of the paw, the animal thus standing on the dorsum of the foot, and the toes pointing backwards. In the case of the fore-limb, however, there is no possibility of the leg being used for walking if the whole of the muscles supporting the wrist joint are paralysed, and, therefore, in the case of the fore-limb, ability to use the fore-limb is evidence of recovery of the muscles. In order to involve all the muscles, not only the median, ulnar and musculo-spiral were cut, but also the musculo-cutaneous, as in the dog this nerve sends fibres to muscles below the elbow. Two experiments of this type were performed, together with a control experiment, in which the same nerves were similarly divided and accurate reunion made. In both cases in which crossing was effected, recovery of function of the limb was efficiently restored on the 45th and 90th day respectively after the operation, and was maintained thus in a state of efficiency till the end of the observations, namely, on the 105th and 177th day respectively. The same was the case with the control experiment. Thus, at the 94th day, when the last observation was made, the degree of recovery was not markedly different from that present in the cases where the crossing had been done. Two other important points were ascertained with reference to these experiments. First, as to the excitability and condition of the cortical representations of the affected muscles, it was found that they had not lost their excitability, but, if anything, were more excitable, and that in the case of the crossing experiments, they had interchanged their position. In one the flexion centre was found where, normally, the extension centre should have been, and extension centre where the flexion centre should have been, and in the other experiment the same was also indicated. This agreed with the observations of CUNNINGHAM, and was opposed to those of STEFANI. The second point was with reference to the comparison between the experiments and the control, as "it was found that the fact of the divided nerves being united in their old position without any crossing, did not result in a recovery of function any sooner than in the experiments where nerve crossing had been done" (*loc. cit.*, p. 146) and "the course of restoration was not markedly different from that of the cases in which the same nerves were divided and united in a crossing" (*loc. cit.*, p. 147).

In 1905 KILVINGTON (8) published four experiments which were designed to elucidate the conditions under which one group of cells in the central nervous system normally associated with the supply of one of two antagonistic groups of muscles could be induced to innervate both groups. This had been shown to be possible in the case of the cell groups associated respectively with the spinal-accessory and the facial nerves, in the case of spino-facial anastomosis, which I published in 1900, along with the research referred to above. KILVINGTON, however, investigated this in the case of the nerves supplying antagonistic groups in the limbs. He chose for this purpose the hind-limbs of dogs, the nerves being the internal and the external popliteal in the popliteal space. In two of the experiments he made the internal popliteal innervate not only the flexor group but also the extensors, by excising the central stump of the external popliteal, so as to prevent reunion with its own peripheral end. In the other two he made the external popliteal subserve the double function, and cut out the central segment of the internal popliteal. In all he conducted a physiological examination at periods of about four months from the date of the initial operation, and with one exception was able to record the restoration of conductivity of both peripheral segments by their junction to the single trunk. He also records that in each of the three cases the electrical stimulation of the proximal single trunk produced muscular contractions in both extensor and flexor groups. He omits, however, to record whether or not he applied electrical stimuli to the central end of the nerve which had been cut out, to ascertain whether any nerve fibres reached the anastomotic junction from that source. Thus when the external popliteal had been cut off short, and the distal end of the external popliteal had been attached to the internal popliteal, there is no record of stimuli having been applied to the central stump of the external popliteal, and *vice versâ*. It is true that he states that no strands of tissue could be seen descending to the seat of junction from the central end of the eliminated nerve trunk except in one case, and in that case he subjected the cord to microscopical examination, and was satisfied that the nerve fibres did not reach the junction.

It is in my view impossible to exclude the possibility of such reunion by any way other than by stimuli applied to the nerve, so as to show the absence of participation of the nerve trunk in the supply of the muscles. A microscopic examination may fail to discover nerve fibres, and the naked eye examination for strands connecting a severed nerve is inconclusive, although it may, in certain cases, render the probability of such connections remote.

As regards the recoveries in KILVINGTON'S animals, he puts forward as evidence chiefly the ability of the animal to walk on the plantar surface of the foot. Where he had retained the external popliteal for the supply, the result was unsatisfactory, but where he had made the internal popliteal the nerve of supply, he reported the recovery as satisfactory. In 139 days one of the dogs did not walk on the dorsum of the foot at all, and a similar result was recorded in his other experiment of the same kind.

In connection with this it is important to bear in mind how difficult it is to judge of recoveries of voluntary movements in the case of the hind limb. This is due to the fact that, although the entire hind-limb below the knee is completely paralysed, the animal continues to make use of the limb for walking. This I found to be the case in a former research (6), in which the sciatic nerve was divided at the level of the trochanter. Practically the only indication of paralysis which is in evidence is the

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turning back of the paw, so that the animal rests on the dorsal surface of the paw, and, having no sensation, scrapes along until the skin of this part of the paw is rubbed off. If precautions are taken to fix the paw in position with a bandage, the defect does not occur. In some dogs the paw, even soon after the section, is not invariably placed with the dorsal surface down. This was also KILVINGTON's experience. Thus, in one of his experiments, he states 38 days after the operation "only occasionally treads on the dorsal surface of the foot," and of another experiment at 16 days he says "animal constantly uses left leg in walking, and the plantar surface is placed on the ground, though very rarely the dorsal is used." It cannot be supposed that so early an improvement could have occurred, and yet the chief defect which results from the nerve lesion is recorded in these cases as very rarely showing so soon after the nerve section. The conclusion which is evident is that the hind-limb of the dog is not well suited for giving definite information on this subject, as the results which follow are difficult to interpret with certainty.

KILVINGTON counted the nerve fibres in the transverse section of the proximal nerve, and those in the two distal nerves, and concluded that this gave evidence of branching of the axons. He attributed to this supposed axon branching the phenomenon of association movements after nerve crossing, *i.e.*, the simultaneous contraction of the two groups of muscles when the volition is only for the contraction of one. He assumed that this was due to and caused by one branch going to one muscle and the other branch to one of its antagonistic muscles. Thus an impulse descending the parent axon would cause simultaneous contraction of the antagonists. He brings forward experimental evidence in proof of this view. Thus he refers to the "axon reflex," or a contraction in a muscle supplied by one of two distal segments, each of which has been joined to one central trunk, when the stimulus was applied to the proximal end of the other distal segment, previously severed for the purpose of this part of the experiment. In Part II of the same paper he publishes additional experiments bearing on this aspect of the subject, where he endeavoured to establish conditions which would obviate the difficulties which he regards as the outcome of axon branching. Thus in an experiment in which he divided both external and internal popliteal nerves, and attached both to the central segment of the internal popliteal, he prepared the central segment for the reception of the two distal segments by first splitting it into two unequal portions, one (the larger) for the internal popliteal and one (the smaller) for the external popliteal, taking care in splitting to damage as little as possible the contained nerve fibres. In this experiment he states that a markedly good result was obtained. Of the condition in seven weeks he says: "Dog walked fairly well and nearly always on the plantar surface of the foot; no ulcers had formed on the dorsum." He opened up the wound and found that two separate unions had occurred, these not being in contact with each other. In four and a half months the function was practically perfect. His contention as to this result being better owing to the prevention of the branches of one axon being distributed to each of two antagonistic sets was confirmed by a physiological examination, which showed absence of "axon reflex." It is to be noted, however, that here, as in his other experiments, no note is made that the proximal segment of the external popliteal had been stimulated to prove the absence of reunion of this with its own distal segment.

In commenting on his results he says: "In facio-accessory anastomosis it would be wise to split the latter nerve into two strands, injuring the actual nerve fibres as little as possible. One of these should be attached to the distal cut end of the facial, and the other to the whole of its own distal end. This would abolish associated movements of the shoulder, or, at any rate, reduce it to a very small amount, for a few fibres at the angle of splitting would possibly be injured, resulting in their growing down the nerves to both sets of muscle." In this connection it may be pointed out that this prediction, founded on theoretical explanations of the experimental findings, has been refuted by the fact that the association movements are found to be present, although the whole of the spinal-accessory was attached to the distal segment of the facial, as in a case published by CUSHING (11), making it thus impossible that the associated movements were the consequence of this alleged axon splitting, as in such circumstances there could be no possibility of axon branches reaching the distal segment of the spinal-accessory.

The principle involved in nerve crossing may be tested, not by disturbing the actual nerve trunks themselves, but by altering the attachments of the muscles to which these nerves are distributed. This has been carried out as a remedial procedure in the human subject, in order to bring about improvement where one of an antagonistic pair of muscle groups has become paralysed by a lesion of its nerve supply. Such a condition is commonly brought about in man by a lesion in the anterior horns of the cord, causing a flaccid paralysis of the muscles supplied by the affected cells (infantile paralysis). The first to suggest and carry into practice this method was NICOLADONI (12), of Innsbruck, who was able to publish in 1881 a success by this procedure. The case in which he performed this operation was one of Pes calcaneus in a boy of 16 years of age, who developed this condition in his right foot when 3 years old. Before the operation there was in the right foot well marked Talipes calcaneus. Thus the foot could be strongly extended, but could not be flexed at all. Also the great toe was unable to be flexed, and in the case of the second toe there were only inefficient tremors on attempted flexion. The three outer toes could be flexed imperfectly. In these attempts he first extended with a jerk the tarsus, and flexed, then, the peripheral parts of the foot, the tendons of the peronei standing out visibly. In walking he placed the foot down on the heel, being unable to bring the entire sole on to the ground. The electrical examination showed prompt responses to the faradic current in the tibialis anticus, extensores longus hallucis and longus digitorum and in both peronei, absence of responses in both layers of the calf muscles, and very weak reaction in the muscles of the sole, causing very slight movements of flexion of the toes. Owing to the evident defect in the gastrocnemius he came to the conclusion that improvement might be attained by detaching the peronei tendons from the bone and attaching them to the tendo Achillis. This tendon transplantation was done on April 15, 1881, and in the following way:—Along the anterior border of the peronei a 12-cm. incision was made down to the external malleolus, and from this at right angles passing backwards over the Achillis tendon a 6-cm. incision was made. These two cuts formed a rectangular flap whose right angle lay under the tip of the malleolus externus. After dissecting back the flap there were exposed the two peronei tendons, and the Achillis tendon right up to the beginning of the muscular substance. The muscular substance of the gastrocnemius appeared to be fatty. Next the two tendons of the peronei were raised from the bone, saving as much as possible of the adhering soft parts. The tendons were then cut just under the tip of the malleolus. The tendons were exposed only at the cut surfaces, elsewhere being covered not only by their sheaths, but also by surrounding soft parts. These tendons were then drawn to the tendo Achillis with a gentle traction, and the point of meeting of each on the tendo Achillis marked on the latter. Then the tendo Achillis was transfixed at this level about its middle, and a flap about 8 cm. long cut upwards terminating in a blunt point. The peronei tendons were then stitched to the tendo Achillis. The wound was closed and healed without much trouble. NICOLADONI gives the progress of the case as follows, but states that it is only on the examination of another, communicated to him by letter. The report was made two months after the operation. The faradic current applied to the peronei caused distinct flexion of the foot by their action on the Achillis tendon. The patient tried to go about in the end of June for the first time, and Prof. ALBERT, who examined the patient in the second half of July, states: "Dass Pat. bereits willkürlich mit den Peronealmuskeln die Plantarflexion selbständig ausführen konnte, was früher total unmöglich war, und dass er fühle, wie sein Tritt mit jedem Tage sicherer werde." At the date of publishing the case not much improvement had occurred in the mode of walking. He concludes his paper by indicating the suitability of this form of treatment in other forms of paralytic club-foot, and in a footnote he states that his case was shown at a meeting of the Naturforscherversammlung in Salzburg on September 21, 1881, at which meeting the strong voluntary plantar flexion was demonstrated, as also much improvement in the deformity of the foot, as compared with that shown by a plaster cast taken before the operation. Although published so long ago, this mode of operating for paralytic club-foot has not been generally practised until within the last 10 or 12 years, when it came more prominently before surgeons.

It is important to note that NICOLADONI calls attention to the voluntary power to produce flexion of the foot by means of the contraction of muscles whose normal function was to produce eversion of the foot. It is therefore evident that this presents for consideration problems analogous to those which are presented when nerve crossing has been performed between nerves supplying muscles of antagonistic function. The exact form of this operation does not present an experiment so distinct as if two antagonistic muscles had been transplanted, but this has been done in operations of a similar kind subsequently published. Within recent years considerable attention has been paid to this method of treatment under the name of tendon grafting, and it has become a recognised procedure for certain cases of paralysis, where antagonistic groups are sufficiently strong to permit of part of them being taken to substitute for the paralysed muscles. In many of the published cases it is evident that there is not sufficient indication that the new muscle formed by the grafting is capable of contracting voluntarily so as to produce the movement opposite to that which by nature it was intended to produce. It would appear that, instead, the tendon grafting has merely resulted in the formation of a tense band, which passively holds the limb in an improved position. When, however, it can be proved that the new muscle is under the control of the patient's will, and that it can be voluntarily thrown into contraction so as to produce a movement, the case comes to have a physiological interest identical with that of experiments on nerve anastomosis.

This result has occurred in the following case, in which part of the gastrocnemius muscle was grafted on to the tendons of a paralysed group in the front of the leg, and in which care was taken as far as possible to exclude sources of fallacy, in judging as to the result.

A girl aged 7 years was admitted to my wards at the Royal Infirmary on May 20, 1912, suffering from paralytic Talipes equinus of the right foot. The condition dated from the time the patient was one year old, at which age she was seized with infantile paralysis, which affected the right lower extremity. Partial recovery resulted, but the limb was left permanently in the following condition. By passive movement it was not possible to bring the foot to right angles with the leg, owing to contracture of the gastrocnemius. She walked on the toes of the affected foot. There was no power whatever to extend the foot, which was held in the position of Talipes equinus. There was not any very marked atrophy of the leg, and the measurement round the bulkiest part of the calf showed that the affected limb was less by half an inch than that of the sound limb. Electrical examination showed that there were normal responses in the gastrocnemius, and in the peronei, but that there was an absence of responses both to faradic and to galvanic stimuli in the muscles of the front of the leg, including the tibialis anticus, no contraction in any of these muscles being felt and no movements of the foot or toes being produced by the application of strengths of current far in excess of those necessary to produce contractions in the gastrocnemius. The strength of current was increased until it commenced to evoke contraction of the posterior groups, although the electrode was being applied to the point of the leg at which the extensor muscles would have been easiest stimulated.

On May 14, 1912, the operation was performed, consisting of the following procedure. The parts were exposed by an incision commencing at the os calcis close to the outer border of the tendo Achillis, and extending upwards for $5\frac{1}{2}$ inches along the tendon, till the muscular belly of the gastrocnemius was exposed almost to the upper end of the leg. One-third of the thickness of the tendo Achillis was then separated, the separation extending from the os calcis upwards well into the substance of the gastrocnemius. The separated third was then detached from the os calcis. Next the tendon representing the remaining two-thirds of the tendo Achillis was divided obliquely, and united by a suture in such a way as to lengthen the tendon, so that the foot could be passively extended quite to the normal extent, thus overcoming the contraction. Next, a short incision was made over the tendons of the anterior group of muscles, just above the level of the anterior annular ligament, and a passage under the deep fascia was tunnelled between the anterior and posterior incision. This tunnel extended obliquely from the anterior incision upwards and outwards and backwards to the upper part of the leg, and through it was drawn the separated third of the gastrocnemius and tendo Achillis. With the foot held in extreme hyperextension, the segment of the Achillis tendon was attached to the anterior tendons by a silk suture, and the wounds closed. The limb was then fixed in this position of hyperextension of the foot in a plaster of Paris casing, in which it remained till union occurred.

On August 1, 1912 (69 days after the operation), the child was able to walk on the sole of the foot well, and had the power voluntarily to extend the foot at the ankle joint, and in doing so the foot was extended in a plane directed upwards and outwards in consequence of the movement being the result of the action of the new muscle coming round from the outside of the leg.

On September 4 (103 days after the operation) the case was investigated by electrical examination. There were no responses in the extensors of the foot to galvanic or faradic stimuli. On the posterior aspect of the limb, the gastrocnemius showed two parts, both excitable to galvanic and faradic currents. Both contracted at 70 mm. in the case of the faradic, and at 6 ma. in the case of the galvanic, but in the case of the two heads different results were shown. When the inner part was stimulated, flexion of the foot was exhibited, and when the outer was stimulated, extension was produced. During the voluntary effort at extension, it was seen that the external portion of the gastrocnemius stood out in contraction, and traceable from that was a cord passing downwards and forwards, representing the course of the new muscle to the anterior aspect of the foot. A photograph of the extreme flexion effort of the child was taken, and also one of the extreme extension effort. These two plates were superimposed, and a new photograph taken of the two combined so as to show the total range of flexion and extension (Plate 3, fig. 1). Although every effort was made to obtain the full extent of the movements represented, nevertheless, the photographs do not represent the full extent of the possible movements, as it was found impossible to induce the child to maintain the state of extension movement sufficiently long to enable the photograph to be taken.

The electrical reaction was again tested on October 31, 1912 (161 days after the operation). This confirmed the previous observation that no recovery had taken place in the extensor muscles, and the extensors were further tested by making a puncture through the skin into the muscle substance, and inserting a platinum electrode into the muscle substance. Faradic responses were obtained in the gastrocnemius at 75 mm., and at 6 ma. the galvanic current evoked contractions in the gastrocnemius, the K.C.C. > A.C.C. Over the external popliteal of the other leg 6 ma. of current gave contractions in the extensors, but no contractions on the right side could be obtained by any currents.

In this case the muscle substance acting on the tendo Achillis has been made to perform the double function of flexion and extension, so as to restore the lost function of extension. There was no doubt as to the absence of the function of extension before the operation, and there was also no doubt as to its restoration after operation. The recovery of voluntary extension could then be due either to a recovery, in the interval between the operation and the examination, of the normal function of the extensor muscles, or to a substitution for their function of the action of the separated part of the gastrocnemius. The former supposition was unlikely from the history of the case, which showed that the paralysis had lasted for six years, nearly the entire lifetime of the patient. It was improbable, therefore, that spontaneous recovery had taken place subsequent to the operation. This history, however, did not absolutely exclude the possibility of the extensors having recovered and being prevented from functioning by means of the contracted gastrocnemius. The probability of no recovery having taken place was confirmed by the result of the electrical examination of the anterior group of muscles, which was on more than one occasion made, and found to be negative. Also the movement of extension was ascertained to be the result of the action of the outer part of the gastrocnemius, not only by the results of electrical stimulation of the outer part of the gastrocnemius, but also by the appearance presented during voluntary efforts on the part of the patient to extend, showing in the first place a tense cord in the line along which the detached part of the tendo Achillis had been led to the front of the leg, and in the second place the movement of extension always in a plane directed upwards and outwards, *i.e.*, in the direction in which a muscle led round the outside of the leg, and attached in front, would necessarily pull the foot. As far as could be ascertained, therefore, the conclusion was inevitable that the gastrocnemius muscle, with perhaps the soleus, was performing a double function, the two parts of which were antagonistic, namely by the outer part the function of extension, and by the inner that of flexion. As the gastrocnemius normally only performs one of these functions, it follows that the nerve supply of this muscle was able to perform a double function, so that the case was explicable only by the same principles which can explain restoration of function after nerve anastomosis.

Within recent years there have been published a considerable number of cases of infantile paralysis, in which operations on the principle of nerve anastomosis have been performed. In almost all, if not in all of these, the published results have not been satisfactory, either in the way of having shown no recovery at all, or because the reported recovery has not been proved by satisfactory methods of examination. In these cases the chief obstacle to the possible recovery is the length of time which has elapsed between the date of operation and the onset of the paralysis. This complicates the issue very materially, for in the first place it is possible that after a certain interval paralysed muscles are irreparable, and therefore that a nerve-crossing operation supplying them with a new nerve would come too late, and in the second place it has been proved that delay in restoring the nerve supply in a muscle means great delay in the recovery of the function, after the nerve supply has been restored.

It is desirable before proceeding further with such operations to have investigated fully the probabilities of recovery under conditions which are as closely as possible similar to those which are met with in the human subject affected with infantile paralysis. Experiments on nerve crossing do not fulfil these conditions, for in such experiments both of the nerve centres are retained, the only difference being that they are brought into relation with the group of muscles which oppose the action of that which formerly they supplied. There is still merely one function for each centre to perform, both being still retained, and in a former paper (7) it was demonstrated that under such conditions those centres were interchanged as far as concerned their function.

To approximate to the ordinary conditions and requirements in a case of infantile paralysis, it would be necessary to cut out completely from action one of the cortical centres, and then to split the action of the remaining centre, so as to cause it if possible to perform both of the two antagonistic functions. This can be done by dividing the two nerves concerned or the two groups of nerves or the nerve and group of nerves, and then, after excising widely one central end or ends, to unite all the peripheral ends to the one central segment or group of central segments, and thus to cause the one nerve supply to be distributed to the muscles of both groups. In applying this principle to a case of infantile paralysis, this is all that can be done, for in such a case the one of two antagonistic muscles or groups of muscles is paralysed, and its nerve supply is thus abolished, and cannot be reclaimed. Therefore it is only by borrowing from the neighbouring nerve supply of the antagonistic muscle or group of muscles that any communication with the centres can be secured. It has been seen that in the case of the face this method has succeeded, but it is necessary to find out if such can also succeed in the case of the limb. These conditions were in KILVINGTON's work satisfactorily arranged, but I have already indicated that experiments of the kind carried out in the hind-limb are unsatisfactory, because of the trivial apparent defects which are produced in the hind-limb of the dog by section of the sciatic in the thigh, and the great difficulty of interpreting the real significance of improvements, *e.g.*, the walking on the sole of the foot. Apart from this, it is impossible to study the effects on the cerebral cortical areas in the case of the hind-limb, as only one area represents in the dog the entire movements of the limb. In the case of the fore-limb, however, there can be no possibility of the animal walking on the unsupported leg, until recovery of the muscle groups has taken place. In addition, the usually clearly demarcated centres for flexion and extension enable an investigation into the condition of these to be made, before the death of the animal.

I have, therefore, performed in dogs experiments of this nature, the histories of which will now be related.

2. THE AUTHOR'S EXPERIMENTS.

(1) Experiment I.—*Anastomosis of Musculo-cutaneous, Median, and Ulnar with the Musculo-spiral, the Central Segment of the Musculo-spiral being Prevented from Reuniting.*

On October 16, 1909, a young fox-terrier dog was anæsthetised with 0·2 grm. morphia sulphate and chloroform-ether. After the skin had been shaved and disinfected, an incision was made on the inner aspect of the right fore-limb, extending from the fold of the axilla downwards to the olecranon. On the inner aspect of the anconeus internus muscle the median, ulnar, and musculo-cutaneous nerves were defined, and each tested by stimulation with the faradic current, causing flexion movements of the paw. The musculo-spiral nerve was next found above the origin of the anconeus internus, where it leaves the other nerves to wind round the humerus. Traction was made on the nerve, and its continuation thus found distal and external to the origin of the anconeus internus, and at this point it was hooked up and drawn inwards to the surface of the wound at the lower edge of the origin of the anconeus internus. The nerve was tested by stimulation with the faradic current, causing strong extension of the paw. The musculo-spiral was then cut through at a point midway between the upper and lower limits of the origin of the anconeus internus, and therefore on the outer aspect of that muscle. The branches of the musculo-spiral to the muscles above the elbow came off from the central segment, those to the forearm muscles from the peripheral segment. The peripheral segment was then pulled inwards, *i.e.* to the surface of the wound, and therefore to the mesial aspect of the anconeus internus muscle. This peripheral segment was brought into apposition with the musculo-cutaneous, median, and ulnar, and the point at which these three must be divided to permit of a union without tension was determined. A catgut thread on a needle with two flattened surfaces, designed for nerve suture, was passed through the three nerves of the flexor group immediately above and below the point at which section was to be made. The catgut was then also passed through the peripheral end of the musculo-spiral. Then the musculo-cutaneous, median, and ulnar were sectioned between their two points of transfixion and the single suture tied. This produced a union of seven ends, three central, namely, the musculo-cutaneous, median, and ulnar, and four peripheral ends, namely, the musculo-cutaneous, median and ulnar, and musculo-spiral, and the junction was separated from the termination of the musculo-spiral central segment by the whole thickness of the anconeus internus muscle and at a point midway between the upper and lower limits of its origin from the humerus. The wound was then sutured with silkworm gut and a dressing applied. Next a plaster of Paris bandage was applied from the toes up the limb and round the body so as to maintain the now paralysed limb in the straight position, and to give rigidity to this plaster casing a stout wire was incorporated with the bandage.

October 17: The plaster of Paris not having quite dried, an additional 0·2 grm. of morphia sulphate was given in order to keep the animal at rest until the plaster should dry.

November 10, 1909 (25 days after): The plaster was removed to-day, and the wound was found soundly healed, and the stitches were removed. The leg was not used by the animal in running about, but was held up, the paw being semi-flexed. There was no contracture, the joints being flaccid. Up till the time that the plaster was removed the dog had been using the plastered leg in standing, in walking, and in running. The leg was protected by an ordinary flannel bandage, and the animal allowed to run about.

November 15 (30 days after): Since the last note it had sometimes appeared as if the dog laid down its paw on the ground, but this was thought to be accidental, as it just as often landed on the radio-carpal joint, with the paw flexed, and as a rule held the limb up. There was no evidence of sensation to be found. The limb was to-day again put up in plaster, but this time merely extending from the toes up to the elbow, so as to keep the radio-carpal joint and the paw extended.

December 6 (51 days after): The animal till now had been running freely about, making use of the plastered limb. To-day the plaster was removed, and when allowed to run about he held the limb up, not allowing it to touch the ground. The affected joints were flaccid, not showing any contracture. There was no discoverable sensation. Percutaneous faradic stimulation gave no contractions. The continuous current, however, gave muscular contractions both in the flexor and in the extensor groups of the forearm. This took place both when the muscles were stimulated directly and when they were stimulated indirectly through the nerve supply, by placing the one electrode over the anastomotic junction, and the other on the opposite paw. The movement produced then was flexion of the paw, not extension. It was ascertained that A.C.C. > K.C.C.

January 20, 1910 (96 days after): To prevent the formation of a flexion contracture, another plaster splint was applied like the previous one, the leg being fixed in the straight position.

February 1 (108 days): The dog has been using the leg in walking, running, etc., since the splint was applied.

February 19 (126 days): To-day the plaster was removed, and it was at once ascertained that the animal had regained voluntary control over the limb. He was seen both flexing and extending the paw. He was able to walk with the leg, apparently in a perfectly normal manner, and run and jump about. When he stood the leg was kept on the ground in a perfectly normal manner. He also was seen pawing the ground as is customary with dogs, using the affected leg quite as well as the left one.

February 20 (127 days after): To-day the animal, although he has been running about since yesterday with the limb unsupported, has lost none of the power which had been regained. Sensation was found to have been regained in the paw. To-day photographs were taken of the animal using the leg in standing (Plate 3, fig. 2). A flannel bandage was applied as a support from the toes up to the elbow.

March 10 (145 days): It is impossible at a glance to tell which leg was the one which had been experimented with. The dog, for a week or two, has been running about without any supporting bandage, and has been using the right fore-leg just as he does the left. Voluntary flexion at the wrist and of the toes, and extension of the same, can be observed, and the dog paws in a natural manner and gives the affected paw on request, holding it out in extension. When standing, the limb presents the normal degree of hyperextension at the wrist joint. On comparison the muscular development of the forearm can be felt to be less than in the case of the left side.

April 30 (196 days): The recovery has remained and the two legs are practically indistinguishable in movements and in bulk. For a considerable time past the dog has been taken out in the streets for exercise, as he presents no peculiarity. To-day the two fore-limbs were measured, and at a point one inch below the olecranon the measurement round the forearm is the same on both sides, namely four inches.

May 29, 1910 (225 days after). There has been no falling off from the very perfect recovery attained to date. To-day a physiological examination was made at 11.45 A.M. The animal had 0·15 grm. morphia sulphate administered, followed by chloroform-ether. The examination was then made in the following order :—

A. *Examination without Disturbing Skin of Forearm.*

1st. Exposure of the seat of suture—

(a) *Exposure of the Central Segment of the Musculo-spiral Nerve.*—This was taken at the upper part of the limb before the nerve passes outside of the anconeus internus. Stimulation here by the faradic current caused contractions of the extensor muscles of the brachium and extension movements at the elbow, but no movement of the paw or at the wrist. This was proved by fixing the elbow, so that it could not move, and applying the stimulus, when no movement at all of the joints below the elbow occurred, and the latter was prevented from moving by the fixation.

(b) *Exposure of Central Segments of Musculo-cutaneous, Median, and Ulnar.*—Stimulation of these with the faradic current caused strong palpable contractions of the forearm muscles and flexion of all the joints below the elbow. Each nerve was then separately stimulated, but the resulting movement was always flexion, although extensor contractions were distinctly palpable. Next the weakest possible faradic current which would evoke a contraction was taken, and the three nerves were each stimulated with the minimal current round the circumference in the hope of finding a point which would evoke pure extension movements, but no such point could be found, in every case the same result being got, namely, contraction of both groups of muscles, and flexion movements.

(c) *Exposure of Peripheral Musculo-spiral Segment and Stimulation with the Faradic Current.*—The result of this was strong contractions palpable in the extensor group, and strong extension of the paw.

2nd. Exposure of the brain—

(a) *Stimulation of the Right Cortical Areas.*—On the post-crucial gyrus a distinct hind-leg centre was found near the longitudinal fissure. Further out on the gyrus there was found a wide area for flexion of the left fore-limb, and no point could be found where pure extension of the left fore-paw was produced, although at the external part of the gyrus opposite the extremity of the crucial sulcus a point was found at which stimulation caused contractions of the extensor muscles in the left forearm.

(b) *Stimulation of the Left Cortical Areas.*—A distinct hind-limb centre was found on the post-crucial gyrus in a position corresponding to that of the right side. Stimulation carried out external to the hind-limb centre right out to the external limit of the gyrus could find no centre in which pure extension movements of the right forearm could be produced, but the extensor group of muscles was felt to contract distinctly, when stimulation was made in any part of the area corresponding to the position of the flexion centre of the right side of the cortex, but these contractions were accompanied by flexion contractions also.

B. Examination with Removal of the Skin from the entire Fore-limbs, and Exposure of Flexor and Extensor Groups of Muscles on Both Sides.

1st. Stimulation of the brain—

(a) *Right Side of Brain.*—Stimulation in the normal position of the flexion centre as previously stimulated, again, also shows that the centre is one of pure flexion, and is exceptionally wide, and no signs of contractions are shown in the other muscles. Still farther out, as previously determined, is the area giving contractions of both flexor and extensor groups, but now a point in this area was found which on faradic stimulation yielded pure contractions of the extensor group, unaccompanied by contractions of the flexor group, and so strongly as to cause vigorous extension of the paw.

(b) *Left Side of the Brain.*—Outside of the area for the hind limb there is a wide area on which stimulation produces at any point the same result, namely, contractions of both flexor and extensor groups of muscles in the right forearm. No point could be found in which these contractions could be separated. Farther out in the portion of the gyrus near the outer extremity of the crucial sulcus, stimulations fail to produce any contractions, and in the corresponding part on the right side stimulations produce combined flexion and extension contractions, and at one point pure extension. This area on the left side is inexcitable.

2nd. Stimulation of the peripheral nerves of right limb—

The brain was covered up, and the following stimulations carried out:—

(a) *Peripheral ulnar segment.*—This produced strong contractions in the flexor group of the forearm, and flexion of the paw.

(b) *Peripheral median segment.*—The result here was strong contraction of the flexor group and strong flexion of the paw.

(c) *Peripheral musculo-spiral segment.*—Here the response was strong contraction of the extensors and strong extension of the paw.

(d) *Central musculo-cutaneous, median, and ulnar segments together and separately.*—Stimulation of these gave the same result, namely, contraction of both flexor and extensor groups of muscles, and flexion of the paw.

(e) *Central musculo-spiral segment.*—This produced no vestige of a contraction of any muscle in the forearm.

3rd. Re-examination of the cortical areas—

The cortical areas were again exposed and the various stimulations repeated with results which confirmed the observations already made. The animal was killed at 2 P.M., the examination having taken $2\frac{1}{4}$ hours.

Post-mortem Examination.—The junction of the nerves was dissected out, and no connection could be traced between the point of union and the central end of the musculo-spiral nerve, but from the central end of that nerve the branches of supply to the muscles above the elbow were seen coming off. The peripheral segment of the musculo-spiral was seen coming off from the point of junction. The muscles of the forearm on complete exposure were ascertained to be well developed, both in the case of the extensors and in that of the flexors, there being but little difference from those of the opposite leg.

(2) Experiment II.—*Anastomosis of Musculo-cutaneous, Median, and Ulnar with the Musculo-spiral, the Central Segment of the Musculo-spiral being Prevented from Reuniting.*

On October 19, 1909, at 10 A.M., a young fox-terrier dog was anæsthetised with 0·1 grm. morphia sulphate, followed by chloroform-ether. The skin of the right fore-leg having been prepared as in the previous experiment, the nerves were similarly exposed on the inner aspect of the limb through an incision extending from the axilla to the olecranon. The musculo-spiral was exposed, stimulated, and divided at the outer side of the anconeus internus, midway between the upper and lower limits of the origin of that muscle, and the peripheral end drawn to the inner side. The musculo-cutaneous, median and ulnar were then divided at a suitable level, and the central ends of these three reunited by one suture of chromicised catgut to the three corresponding peripheral ends and, in addition, to the peripheral end of the musculo-spiral, the central end of the musculo-spiral being left in the normal situation, and, therefore, separated from the anastomotic junction by the entire breadth of the anconeus internus muscle. This experiment was, therefore, a repetition exactly of the first experiment. The wound having been closed and dressed, the limb was put up in a plaster bandage and wire, extending up the leg and round the body, the leg being maintained straight.

At 5.30 P.M. the dog was still under the influence of the morphia, and the plaster was partially dry.

November 11 (23 days): The plaster was removed and the wound found united by first intention. The stitches were removed. The animal was found to walk on the wrist joint.

November 15 (27 days): The skin has been knocked off the wrist from walking on it.

November 16: The limb was put in a short plaster splint from the toes up to the elbow to keep the leg straight.

December 28 (70 days): Plaster was removed, and the dog allowed to run about, and it was found that he occasionally placed the sole of the foot on the ground correctly, but, as a rule, landed on the end of his radius. Joints flaccid. Leg was supported by a flannel bandage.

January 20, 1910 (93 days): There is now a distinct flexion contracture, and there is also distinct power to flex and extend the paw.

January 22 (95 days): To-day the contracture was forced straight, and the straight limb fixed in plaster.

February 1 (105 days): The dog has been using the plastered leg for walking, running, and standing.

February 19 (123 days): The plaster was removed to-day, and on liberating the animal it ran round the room, making normal use of its leg and never making a false step. On examination it was found to be able to make flexion and extension movements of the paw. It was observed pawing the ground with both fore-limbs in a normal fashion. A supporting flannel bandage was applied to the leg. The animal was photographed using his leg in standing.

February 20 (124 days): Animal again photographed (Plate 4, fig. 5).

March 6 (138 days): The dog has since the last note been using the leg constantly in walking, running, etc., quite normally, but a slight flexion contracture is present which evidently causes an extension effort on the part of the animal to use the paw properly. Despite this he walks very well, and is only now commencing occasionally to hold the paw up. Therefore to-day a plaster bandage was applied to attempt to overcome the slight flexion contracture, the animal having had an injection of 0·15 grm. morphia sulphate.

March 11: Photographed to-day (Plate 4, fig. 4).

March 12 (144 days): The plaster was removed to-day and the flexion contracture appeared to have been overcome. The dog uses the leg quite normally, and gives the paw, on request, quite naturally, and makes flexion and extension movements at the wrist and in the digits through an almost normal range.

March 20 (152 days): The slight flexion contracture has again become evident. Plaster was re-applied.

April 9: The plaster was removed, but the flexion contracture does not appear to have been quite overcome.

April 13 (176 days): An attempt was made to overcome the contracture by a short wire splint, bandaged so as to maintain the wrist joint in hyper-extension, and it appeared to be successful, the animal making satisfactory use of the limb in walking, running, etc., even after the splint had been removed; but as the animal appeared to be in an unsatisfactory state of health, it was deemed desirable to proceed with a physiological examination.

April 24 (187 days): The animal was anæsthetised with 0·2 grm. morphia sulphate and chloroform-ether. Death unfortunately took place before the nerves had been exposed. However, they were rapidly exposed, and the faradic irritability tested with the following results:—

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A. *Stimulation of Peripheral Nerves.*

1st. With the forearm muscles unexposed, faradic stimulation—

(*a*) Of the peripheral segments of the musculo-cutaneous, median, and ulnar, gave flexion of the paw.

(*b*) Of the central segment of the musculo-spiral, gave no movements below the elbow.

2nd. With the forearm muscles exposed, faradic stimulation—

(*a*) Of the central segments of the musculo-cutaneous, median, and ulnar, gave contractions of the muscles of both flexor and extensor groups in the arm.

(*b*) Of the distal segment of the musculo-spiral, gave contractions of the extensor group in the forearm only.

(*c*) Of the central segment of the musculo-spiral, gave no contractions in the forearm muscles.

B. *Stimulation of the Exposed Cerebral Cortex.*

By the time that this stage of the examination was reached it was found that the irritability of the cortex had been lost, as no motor responses could be produced on stimulating any part of the right or left crucial gyrus.

Post-mortem Examination.—The muscles of the forearm having been exposed by removal of the integuments, all the muscles were seen to be healthy and of normal appearance, the extensors comparing quite favourably with the flexors. The left forearm was similarly exposed, and the muscles showed somewhat greater bulk. Measurements of the differences were made in the following way:—Two points were marked on the forearm, one $2\frac{1}{2}$ and one 5 cm. below the external condyle of the humerus on the two forearms. Circumferential measurements at the upper level gave 8 cm. for the right and 8·1 cm. for the left, and at the lower level 6 cm. for the right and 6·5 cm. for the left.

The seat of suture was dissected out and showed the central segment of the musculo-spiral terminating after giving off branches to the muscles above the elbow. The peripheral segment was seen passing outwards from the seat of suture to the three flexor nerves to reach the outer side of the limb, where it followed its normal distribution. The distance between the two ends of the musculo-spiral was about $2\frac{1}{2}$ cm., and one was on the inside and one on the outside of the humerus. No connecting strands were found between them. The central termination of the musculo-spiral was bulbous.

(3) Experiment III.—*Anastomosis of Musculo-cutaneous, Median, and Ulnar with the Musculo-spiral, the Central Segments of the Musculo-cutaneous, Median, and Ulnar being Prevented from Reuniting.*

On October 31, 1909, at 12 noon a young fox-terrier dog having been anæsthetised with 0·1 grm. morphia sulphate followed by chloroform-ether, the musculo-cutaneous, median and ulnar and musculo-spiral nerves were laid bare at the inner side of the fore-limb in the same situation as in the preceding experiments. A weak faradic current was applied to the nerves with the following results: When stimulated, the musculo-cutaneous caused flexion of the wrist, mainly by the muscle on the radial side of the forearm; the ulnar gave flexion of the wrist mainly by the muscle at the ulnar aspect of the forearm, while the median similarly stimulated gave mainly flexion of the digits. When the musculo-spiral was stimulated below the level of the origin of the anconeus internus, extension of the paw and wrist and flexion of the elbow resulted. Next the three nerves supplying the flexor group in the forearm were divided about the level of the upper limit of the origin of the anconeus internus, and the three peripheral ends transfixed near the cut surface with a horse-hair suture. The musculo-spiral was then drawn inwards below the level of the origin of the anconeus internus, and was transfixed with the same horse hair above and below a point on the nerve trunk corresponding when in its normal position to the mid-point between upper and lower limits of the origin of the anconeus internus. The musculo-spiral was then divided between the two points of transfixion, and the suture tied. This caused the three peripheral ends of the musculo-cutaneous, median, and ulnar to be drawn outwards and upwards into the depths of the wound, so that the junction lay on the outer aspect of the anconeus internus. The central ends of the musculo-cutaneous, median and ulnar were then widely resected. The wound was closed and dressed, and the limb fixed in plaster, as in the previous experiments.

November 13 (13 days): The plaster was removed and the wound found healed by first intention. No use was made of the leg on removal of the splint, although the dog had been running about on it before the plaster was removed. The limb was supported by a flannel bandage.

December 5 (35 days): The animal has not been making any use of the leg, but holds it up while walking or standing. To-day, the forearm muscles were electrically examined. The positive pole was applied at the opposite foot, and the negative over the affected forearm muscles, and the galvanic current passed. The result was contraction of muscles, causing always flexion of the paw. The same result was got when the negative pole was placed over the seat of suture. No contractions whatever were evoked when the faradic current was passed. There was no sign of sensation.

December 8 (38 days): The dog still holds up the leg. On running, it occasionally places the paw on the ground correctly, possibly by accident.

January 20, 1910 (81 days): There is evidence of movements being regained, and a flexion contracture is developing. He is not walking on the leg yet.

January 23 (84 days): The leg was put up in plaster.

February 1: The dog has been running about, but holding up the leg, although plastered.

February 19 (111 days): The plaster was removed, and it was found that it had caused a pressure sore at the wrist. This prevented a proper examination of the leg.

February 25: As it was ascertained that the sore had extended into the joint, it was decided to kill the animal.

February 26 (118 days): The animal having been anæsthetised with chloroform-ether, the examination was made as follows:—

A. *Exposure of the Nerves at the Seat of Suture.*

1st. A bulbous enlargement was found connecting all three central ends of the nerves which normally innervate the flexor muscles. When these were stimulated by the faradic and galvanic currents no contractions were produced in any of the forearm muscles which had been laid bare for examination, but there were contractions of the flexor group above the elbow.

2nd. The peripheral segments of the median, ulnar, and musculo-cutaneous, found joined to the central segment of the musculo-spiral, gave on stimulation contractions of the flexor group of muscles in the forearm, and no contractions in the extensor group

3rd. Stimulation of the musculo-spiral proximal to the suture gave distinct contractions in the extensor and flexor groups in the forearm, visible in the exposed muscles. An attempt was made by stimulating with a minimal current to find if the position of the two groups of nerve fibres could be separately localised in the nerve trunk, and it was found that stimulation of the trunk laterally produced contractions of the flexor group, while stimulation mesially evoked contractions entirely in the extensor group. The extensor group of muscles appeared to be more atrophied than the flexor group, perhaps from greater pressure of the splint.

B. *Exposure of the Brain and Cortical Stimulation.*

The roof of the skull was removed, and also the forearm muscles of the left side were exposed. The crucial sulcus was exposed on both sides and stimulated on the sigmoid gyri. On the normal side the arrangement was of a typical kind, showing the extension centre pure, situated at the extremity of the crucial sulcus, and the flexion centre internal to that. On the left side, on the other hand, the result of the experimental alterations on the cortex was marked in the clearest possible manner, as, in the area corresponding to the flexion centre, the cortex was inexcitable, while in the part corresponding to the extension centre stimulation with the faradic electrode produced contractions of both flexor and extensor muscles. The dog was then killed.

Post-mortem Examination.—The dissection showed the stumps of the three flexor nerves at the junction of the upper and middle thirds of the humerus imbedded in scar tissue. From this no connecting bands could be traced. The musculo-spiral was found disappearing lateral to the anconeus internus, and its junction with the four peripheral ends was marked by the horse-hair suture found still in place. The junction was found to be one embracing all five ends. The dissection of the fore-limb showed atrophy of the muscles as compared with those of the opposite side.

The circumferential measurement at the highest point of the forearm, when the elbow was flexed to right angles, was $2\frac{7}{8}$ inches in the right leg and $3\frac{1}{8}$ inches in the left. The atrophy was found to involve flexor and extensor groups equally.

(4) Experiment IV.—*Anastomosis of Musculo-cutaneous, Median, and Ulnar with the Musculo-spiral, the Central Segments of the Musculo-cutaneous, Median, and Ulnar being Prevented from Reuniting.*

On May 15, 1910, at 11.30 A.M., a 6-month old Irish terrier dog was narcotised with 0·2 grm. morphia sulphate followed by chloroform-ether inhalation, and the same exposure of nerves was made as in the previous experiment and also the same anastomosis, the central ends of the nerves distributed normally to the flexors in the forearm being cut off short. The suture was of catgut, and the leg was fixed in a plaster splint as in the preceding experiments.

May 25 (10 days): The plaster was removed and the wound found healed, and the leg was fixed with a flannel bandage and wire splint.

June 12 (28 days): The bandage was removed and the dog ran about, putting the leg down. It was seen, however, that he had no control of the limb, and often laid it down on the wrist joint, the paw having doubled in.

July 13 (59 days): The animal can now run about using the paw correctly, but full control has not been regained yet, as he still knocks the skin from the dorsum of the wrist and digits from making false steps.

August 2 (79 days): The animal has now considerably improved, and may be regarded as having recovered quite satisfactorily. He gives the paw on request in a quite natural manner, and shows at the radio-carpal joint no over-extension while standing. There are no abrasions to be found in the paw, and the animal can run about in a natural way without making any false steps. He was taken out for exercise in the streets, having no apparent defects.

August 17 (94 days): Dog photographed to-day (Plate 4, fig. 6).

August 28 (105 days): The animal within the last day or two has abraded the paw and is not using the leg.

September 9 (117 days): The abrasion not having healed, and the dog still continuing to hold up the leg in flexion, it was decided not to attempt to bring it back into use again, seeing that so good a restoration had already been attained. It was therefore thought better to proceed with the physiological examination.

Physiological Examination.—The animal being under the influence of chloroform-ether the following examination was made :—

A. *Stimulation of the Nerves at the Seat of Suture.*

1st. The central segments of the musculo-cutaneous, median, and ulnar being stimulated with the faradic current produced flexion at the elbow and no movement below the elbow.

2nd. The central segment of the musculo-spiral on stimulation with the faradic high up in the limb gave extension of the elbow and extension of the paw. On careful stimulation round the surface of the trunk with a minimal current, at certain points slight flexion movements of the paw were evoked.

3rd. The peripheral segments of the nerves attached to the central musculo-spiral segment were then stimulated with the faradic current with the following results :—

(*a*) The musculo-cutaneous gives flexion of the paw.

(*b*) The median gives very strong flexion of digits and wrist.

(*c*) The ulnar produces flexion of the paw, *i.e.* digits and wrist.

(*d*) The musculo-spiral gives extension of the paw and wrist.

B. *Stimulation of the Exposed Cerebral Cortex, without Disturbing the Skin of the Forearm.*

1st. *Left Side of Cortex.*—A weak faradic current showed a normal hind-limb centre, but the fore-limb centre was placed near the extremity of the sulcus, and on stimulation gave distinct flexion of the paw.

2nd. *Right Side of Cortex.*—There was in general a normal arrangement, but the flexion centre was not so clearly defined as is frequently the case.

C. *Stimulation of the Cortex, the Muscles of the Forearm being Exposed by Removal of the Skin.*

1st. *Left Side.*—Distinct contractions of both extensor and flexor muscles on stimulating at the extremity of the crucial sulcus. The portion of brain internal to this on the sigmoid gyrus gave no indication of excitability till the hind-limb centre was reached.

2nd. *Right Side.*—On stimulation at the point of the sigmoid gyrus external to the extremity of the crucial sulcus there was a distinct and pure extension centre found, as evidenced by the contractions of the forearm extensor muscles, and no contractions in the flexor group in the forearm. Flexor contractions were evoked by stimulating more internally.

D. *Stimulation of the Nerves, with the Exposed Forearm Muscles.*

The examination of these with the exposed muscles served to confirm the observations made before uncovering the muscles. The central segment of the musculo-spiral showed very distinctly the different effects of stimulating round the surface of the nerve at different points, as the contractions of flexor or extensor groups were found to predominate at different points of stimulation.

Post-mortem Examination.—The circumferential measurement of the right fore-limb at a point $2\frac{1}{2}$ cm. below the external epicondyle was 7 cm., and of the left fore-limb at a corresponding level $8\frac{1}{2}$ cm. At a point 5 cm. below the epicondyle the measurement was $5\frac{1}{2}$ cm. for the right and 7 cm. for the left fore-limb. The seat of suture of the nerves showed the three central ends passing down into a confluent mass of cicatricial tissue about the middle of the humerus, but on attempting to trace them farther they broke away and terminated. No junction could be found between the central ends of the three flexor nerves and any of the distal segments of the flexor nerves. The peripheral ends were clearly seen passing across the elbow, and, traced upwards, they passed external to the anconeus internus, and were found to lead to the musculo-spiral, and a confluent junction was found from which issued also the distal segment of the musculo-spiral to its normal distribution. These nerve trunks were normal in appearance. The forearm muscles, compared with those of the left fore-limb showed some wasting; but the wasting was not more marked in the flexor than in the extensor group.

(5) Experiment V.—*Anastomosis of Musculo-cutaneous, Median, and Ulnar with the Musculo-spiral, the Central Segments of the Musculo-cutaneous, Median, and Ulnar being Prevented from Reuniting.*

On February 27, 1910, at 11 A.M., a young Irish terrier dog was anæsthetised by 0·15 grm. morphia sulphate followed by chloroform-ether. The same anastomosis was made as in the two preceding experiments, the central segment of the divided musculo-spiral being left to supply the entire forearm musculature, and the union being made with a single stitch of catgut. The leg, after the operation, was similarly fixed in a plaster splint passing round the body (Plate 3, fig. 3).

March 13, 1910 (14 days): The plaster was removed and the wound found healed.

April 12: The splint, which had been left off, was re-applied to-day.

April 27 (59 days): The dog has been losing flesh and was apparently dying, so it was decided to make an examination of the progress forthwith.

Physiological Examination.

A. *Examination of the Brain.*—1st. Right Side: The faradic current applied to the sigmoid gyrus showed a normal hind-limb area, producing drawing up of the left hind-leg and rotation out. Farther out on the same gyrus the flexion area of the fore-limb was clearly indicated, the paw being flexed and the leg drawn up, and there was some extension at some points. Still farther out there was a pure extension centre, causing on stimulation extension movements of the paw.

2nd. Left Side: On the sigmoid gyrus the hind-limb area was normal, and in the position of the flexion and extension areas no movements of the forearm muscles could be got on stimulation, the only movement obtainable being a drawing up of the right leg, due to contractions of the muscles above the level of the elbow.

The muscles of the leg were then exposed by removing the entire skin, and the cerebral stimulation repeated with confirmatory results.

B. *Stimulation of the Nerves.*—No contractions could be caused in the muscles of the forearm by stimulation of any of the nerves, either the peripheral or the central segments, either by the faradic or by the galvanic currents. The muscles of the forearm when directly stimulated with the galvanic current gave contractions both in the case of the flexors and in that of the extensors, but when the faradic current was applied to them there was no response, until a very strong current was allowed to pass through. The animal was then killed.

Post-mortem Examination.—At the junction of the nerves the musculo-spiral was seen after it had reached the limb descending and forming a thickening, from the distal aspect of which issued four trunks, one the distal musculo-spiral and the other three the musculo-cutaneous, median, and ulnar respectively. The junction appeared to be well formed, and the nerves of normal aspect. The central segments of the three flexor nerves were found above, ending in bulbs, from which no definite strands could be traced, but merely connective tissue soon breaking away on attempting to follow it downwards. The distance between the central ends and the junction was 2 cm., but the anconeus internus was interposed. The forearm muscles were next exposed and found to be atrophied, but presented muscular substance of healthy appearance. Both flexion and extension groups were affected about equally as regards the atrophy. The corresponding groups in the left leg were exposed, and circumferential measurements taken at $2\frac{1}{2}$ and 5 cm. respectively below the external epicondyle of the humerus. In the right at the former point it was $7\frac{1}{2}$ cm., and in the left 9 cm., and at the latter level the respective measurements were $6\frac{1}{2}$ cm. in the right limb and $7\frac{1}{2}$ cm. in the left.

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3. TABULAR STATEMENT OF RESULTS.—Experiments on Elimination of the Nerve Supply of the Flexor or Extensor Muscles of a Limb and Restoration by Means of Anastomosis.

No. of experiment.	Central segments eliminated.	Central segments remaining.	Peripheral ends united in the junction.	Time allowed to live.	Date when returning power first observed.	Date when recovery satisfactory.	Physiological examination. Nerves.	Physiological examination. Brain.	Course of wound.
1	Musculo-spiral	Musculo-cutaneous, median, and ulnar	Musculo-cutaneous, median, ulnar, and musculo-spiral	225 days	96 days = contracture. 126 days = walking very well	126 days. Recovery so good that able to be taken out in streets for exercise	No connection found between central musculo-spiral and any of the peripheral segments. Stimulation of central musculo-cutaneous, median or ulnar = contractions of both flexors and extensors of forearm	*Right Side.*—Flexion and extension centres normal. *Left Side.*—Over the centre normally a flexion one, there is both flexion and extension evoked on stimulation. Over centre normally an extension one, there is no excitability	*Per Primam.*
2	Do.	Do.	Do.	187 days	93 days = slight flexion and extension. Not walking. 123 days = walking	123 days, but continued improvement hindered by slight flexor contracture	No reunion of musculo-spiral. Stimulation of central segments of three flexor nerves = contraction of both flexors and extensors of forearm	Excitability of cortex lost due to death under anæsthetic	Do.
3	Musculo-cutaneous, median, and ulnar	Musculo-spiral	Do.	118 days	81 days = flexion and extension. Not walking	Pressure sore from plaster interfered with further progress	No reunion of central musculo-spiral, median, and ulnar to the peripheral ends. Stimulation of musculo-spiral on mesial aspect = extensor contractions; and on the lateral aspect = flexor contractions	*Right Side.*—Normal. *Left Side.*—No contraction on flexion centre. Both flexion and extension in extension centre	Do.
4	Do.	Do.	Do.	117 days	59 days = able to run about, but makes false steps, and falls on wrist occasionally	79 days = runs about normally and able to be taken out in the street. Voluntary flexion and extension observed. No over-extension	Musculo-cutaneous, median, and ulnar central ends formed no connection to their peripheral ends. Musculo-spiral central gives strong extension and at certain points of its circumference flexion on faradic stimulation	*Right Side.*—In general, normal arrangement except that flexion centre deficient. Pure extension centre. *Left Side.* — Absence of flexion centre. In the position of the normal pure extension centre there is now both flexion and extension	Do.
5	Do.	Do.	Do.	59 days	None	—	No contraction of forearm muscles on stimulation of any of the nerves. Junction good; no reunion of central musculo-spiral	Stimulation of the arm centres produced no contractions of the forearm muscles	Do.

4. Comparison of Experiments.

(1) *The Two Forms of Experiments.*

The experiments were all of the same nature, in so far that the nerve supply of one of two antagonistic groups of muscles was eliminated, and the group whose supply had been eliminated made to receive its supply from the nerve supply of its antagonistic group of muscles, which nerve supply thus was induced to supply both of the two antagonistic groups. While, however, of the same nature, an important difference was made in that, in two of the experiments, it was the nerve supply of the extensors, while in the other three it was the nerve supply of the flexors which was abolished. Thus, in two of the experiments, the musculo-spiral was cut out, and the entire musculature (flexors and extensors) below the elbow supplied by the musculo-cutaneous, median, and ulnar. In the remaining experiments the reverse obtained, both groups, flexors and extensors, being supplied through the single nerve trunk, the musculo-spiral. It is of importance, therefore, to contrast the results in these two forms of experiment.

(2) *The Earliest Sign of Recovery.*

(a) *In Experiments* I *and* II.—In these two experiments, in which the identical conditions obtained, namely, the elimination of the musculo-spiral, the extensors deriving their new nerve supply in common with the flexor muscles from the normal supply of the flexors, the first indication of recovery took place in the one in 96 days and in the other in 93 days. In both cases the evidence of recovery consisted of an indication of commencing flexor contracture. In both cases previous examination showed that not only was there no power to lay the paw on the ground correctly and to support the weight of the body on the paw, but it was also ascertained that the joints of the affected leg were flaccid, showing that no recovery in the muscles had occurred. The evidence of recovery obtained on the 96th and 93rd day respectively was not of a nature to show return of co-ordinated movements, for it took the form of a flexor contracture, showing that the flexor muscles had recovered, but, so far, there was no evidence of recovery of power in the extensors nor of development of co-ordinated movements. The capacity to walk on the affected leg was first shown in the one experiment at 126 days, and in the other at 123 days, the two experiments thus approximating very closely in their development. In both cases the amount of recovery was very similar, and admitted of no doubt. In both cases the limb had been fixed in plaster of Paris since the date of the previous examination, namely, 30 and 28 days respectively before the observation was made, and in both cases, on removing the plaster, although the weight of the body could not be borne on the leg previously to the splint being applied, the animal was able to use the leg freely in walking and running, and the movements of extension and flexion were seen being made. Both animals were photographed about this time, showing the capacity of each to make use of the limb for standing (Plate 3, fig. 2, and Plate 4, fig. 5). The further development of these two experiments differed materially. In the first there never was any falling-off in the recovery, but, on the contrary, still further improvement was seen. It was impossible, indeed, at 145 days, to tell at a glance which leg had been operated on, and the leg was used in all the ordinary movements and actions in the usual way. Thus the paw was given on request, being held out for that purpose in extension. Even the bulk of the muscles of the leg became restored, and by 196 days the limbs were practically indistinguishable, except for the cutaneous scar. There was no falling-off up to the time of the examination, namely, 225 days after the initial operation of the experiment. Soon after the recovery the dog walked so well that he was taken out in the streets for exercise, without fear of attracting the notice of anyone.

In the second experiment of this type the course of events did not run so satisfactory a course, as, although a very good recovery of co-ordinated movements appeared at 123 days, about a fortnight later a slight preponderance of action of the flexor group led to a disturbance of the balance of muscular action, with the result that a slight flexor contracture developed. The measures taken to overcome this were successful in restoring the co-ordinated movements by 144 days, but by 8 days subsequently the same defect again exhibited itself. This was again overcome by appropriate treatment, but, although it was evident that the animal had regained co-ordinated movements, it was being hindered by the recurrence of this flexor contracture. As it had not been able to be taken out for exercise because of this difficulty, it began to show declining health, and had therefore to be submitted to a physiological examination earlier than in the other experiment. Thus the two experiments agreed in so far as the first appearance of the recovery was concerned, and in the nature of it, although further comparison was interfered with by the trouble with the contracture in the second experiment.

(b) *In Experiments* III, IV, *and* V.—Of the three experiments in which the musculo-spiral was the only source of supply for the various muscles below the elbow, all the other nerves having been eliminated, only one presented a satisfactory result. In Experiment III there was evidence of commencing recovery at 81 days, as a flexor contracture had developed, showing the recovery of the flexor muscles at least. In order to maintain the leg in position till recovery of co-ordinated movements occurred, it was put up, as in the case of the other experiments, in plaster of Paris, but, unfortunately, this caused a pressure sore, which extended into the joint and prevented further development of the experiment. In Experiment IV a more successful result followed (Plate 4, fig. 6). Thus at 79 days the dog was able to walk, using the affected limb normally, and showed at this date distinct recovery of co-ordinated movements, as evidenced not only by his capacity to walk, making use of the limb to support the body, but also by giving on request the paw, holding it out in extension. The recovery at this date was so satisfactory that he was taken out in the streets for exercise. From the 79th to the 105th day this very satisfactory recovery lasted, but at the latter date the animal ceased using the limb, the result, apparently, of an abrasion on the paw. This state continued up to the 117th day, when the physiological examination was made. In Experiment V no recovery had been recorded by 59 days when the examination had to be made on account of the defective health of the animal.

(c) *Experiments* I *and* II *compared with Experiments* III *and* IV.—In the first two experiments the recovery commenced in 96 and 93 days respectively, and this compares with 81 days in Experiment III, where the same flexor contracture became evident about this time, showing at least the recovery of one of the groups of muscles. In Experiment IV the flexor contracture stage was not observed, but at 59 days the animal appeared to be at times laying down the paw correctly, but no certainty as to real recovery existed at this date, and certainly no stage of flexor contracture existed. It was only at 79 days that the very satisfactory recovery was shown. As far as ultimate results went the first experiment was very much the most satisfactory, as the recovery was maintained until the physiological examination was made, *i.e.* over a period of 99 days; whereas in Experiment IV the apparently equally satisfactory recovery lasted only about 26 days. The cause, however, of the interference was a trivial one and a pure accident, *i.e.* it was not due to a preponderance of action of one group of muscles. It is thus seen that in Experiment IV the date of the recorded recovery compares not with the 96 and 93 days of Experiments I and II, but with 126 and 123 days of these experiments, as it was at these days that the recovery had reached the same stage as in the case of Experiment IV at 79 days.

(3) *The Physiological Examination.*

This consisted of two parts, namely, examination of the peripheral nerves where they had been anastomosed, and examination of the cerebral cortex associated with the nerves which had been interfered with. In the first part of the examination it was ascertained in all the experiments in which recovery had taken place that the union of the nerves had resulted at the seat of suture in the way which had been aimed at, and that there were no paths developed between the seat of suture and the proximal nerve trunk or nerve trunks which had been intended to be eliminated. In the case of Experiments III and IV, where the musculo-spiral was the nerve which had the double function to perform, it was found that the two functions were represented by clearly separated paths in the musculo-spiral trunk. Thus in Experiment III stimulation with the electrode on the mesial aspect produced contraction only in the extensor muscles, while stimulation on the lateral aspect produced only flexion (p. 48), and in Experiment IV a separation of the two paths was also demonstrated by the faradic current (p. 50).

In the second part of the physiological examination the cortex was investigated, and the results were in agreement as far as the observations went, merely differing in so far as explained by the difference in type of experiment.

(a) *In Experiments* I *and* II.—In the first experiment the observations showed that on the unaffected side there was in the sigmoid gyrus distinct separation of the cortical centres associated respectively with flexion and extension of the paw, but that on the opposite side the arrangements were altered by the experiment. Thus the centre normally associated with flexion gave now on stimulation contractions of both flexor and extensor groups, and no point could be found where only one group could be caused to contract. On the other hand, stimulation over the position of the normal extension centre failed to elicit any movements. It had lost its excitability. In the second experiment the death of the animal at the commencement of the physiological examination had the result that, although the brain was exposed as quickly as possible, the entire cortex was found to have lost its excitability.

(b) *In Experiments* III *and* IV.—In both of these experiments excitability of the cortex was found, and in both the same alteration had taken place on the portion of the cortex concerned. In Experiment III the right side of the cortex showed a clearly defined flexion and extension centre on the sigmoid gyrus, and on the left side the position of the flexion centre was found to be occupied by a non-excitable area, and in the position of the normal extension centre there was found an area which gave on stimulation contractions of both flexor and extensor muscles. The same result was got in Experiment IV, the only difference being that there the normal flexion centre was somewhat deficient although present, but on the affected side of the cortex the flexion centre was quite absent, while that which on the normal side was a pure extension centre was represented on the affected side by a corresponding area as far as position went, but which gave, no stimulation, contraction of both sets of muscles.

(c) *Comparison of Experiment* I *with Experiments* III *and* IV.—The findings on the cerebral cortex in these two types of experiment corresponded exactly. Thus the centre on the cortex which normally is associated with the movements of those muscles whose ordinary nerve supply had been eliminated was found to have lost its excitability completely. In both cases also the centre which normally is associated with the contraction of the muscle groups antagonistic in action to those whose nerve supply had been eliminated was found to cause on stimulation not only contraction of its normal group of muscles but also of the antagonistic group. The experiments agreed in showing that the centres in which the muscle representation had been combined were of such a nature that no point could be found on the centre where the two movements could be separated, *i.e.* both movements were produced on stimulating at any point.

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5. General Considerations.

(1) *Methods employed in the Experiments.*

(a) *The Operative Technique.*—No preliminary treatment was employed, except to give the animal a bath on the day preceding the operation. Immediately before the operation, a dose of morphia sulphate suitable to the size and breed of the animal was given hypodermically. This varied between 0·1 and 0·2 grm., but much larger doses would be used in other breeds of dogs, *e.g.* in collies. The animals used in the research were of the smaller breeds. The importance of using morphia is not only to facilitate the inhalation anæsthesia, but also to keep the animal quiet for some time after, so as to allow the plaster splint to set and dry. The animal having come under the influence of the morphia, the inhalation anæsthesia was commenced, and as soon as the dog was quiet the part to be incised was shaved and disinfected. For this purpose in these experiments a solution of iodine was used.

The material used for suture of the nerves was usually catgut chromicised to disappear in about three weeks. It is specially important to employ catgut for this purpose only if the sterility of the thread can be thoroughly relied on, as any infection in these wounds would destroy the reliability of the experiment. Should a trustworthy catgut not be obtainable, a horse-hair makes a very satisfactory suture for nerves, and can with certainty be sterilised by boiling in water.* The wounds were closed by silkworm gut stitches.

(b) *Prevention of Confluent Reunion.*—The tendency of nerves to reunite after division is well known, and this takes place even although the ends are not in contact, but are separated by some distance. Although the reunion under such circumstances might not be perfect, there might be partial reunion enough to vitiate the conclusions from an experiment. This has actually been found to have taken place in the experiments published by Rawa (2) and by Stefani (3), causing the rejection of experiments so vitiated, and it has therefore been recognised by previous workers at this subject that it is necessary to take precautions to prevent it. The method employed in this series to avoid confluent reunion, and therefore the joining up of the central end or ends intended to be left ununited, was the same as was adopted in a previously published series in which

* The process by which the gut was prepared for these experiments was as follows:—1st. The raw catgut was wound on to reels, made of glass rods bent into rectangles. On these reels it was soaked for 24 hours in ether, in order to rid it of fat, and then dried in air. 2nd. It was then soaked in 0·1-per-cent. aqueous solution of chromic acid for three to five days, according to the degree of absorbability required, and then washed in running water for four hours. 3rd. It was then boiled in alcohol in an open tube for one hour, so as to dislodge all the air-bubbles from the gut, and allowed to cool in the alcohol. It is these air-bubbles which make catgut so difficult to sterilise, as they prevent the antiseptic liquid used for sterilisation of the gut from getting access to the organisms present in the gut. 4th. It was then soaked in 20-per-cent. carbolic glycerine for a few days and preserved in the same fluid till required for use. Before use the antiseptic is removed by rinsing the gut in alcohol.

the nerves were "crossed," where this was secured by making the two junctions with a bulky muscle intervening, namely the anconeus internus. The normal arrangement of the parts renders this an easy matter. Thus the three nerves which supply the flexors pass down on the inner side of this muscle, while the musculo-spiral descending in company with them crosses to the outer side of the arm over the upper end of this muscle, and therefore this muscle, in the normal arrangement of the parts, intervenes between that nerve and the others. The anastomotic junction therefore was made on the outside of this muscle, if the musculo-spiral was to be used as the source of supply, and the other three central ends left unconnected on the inner side of the muscle or widely excised. If, however, the latter nerves were to be used as the source of supply, then the junction between the three central and four peripheral ends was made to lie on the inner side, while the central end of the musculo-spiral was left lying unconnected on the outer side of the muscle. Thus there was always the bulky muscle intervening between the end or ends not to be united and the anastomotic junction, a barrier which, as the physiological examination proved, was invariably efficient to prevent any reunion between the nerves thus separated.

(c) *Preservation of the Limb from Damage until Restoration of Function occurs.*—In addition to the precautions taken at the operation to ensure the success of the procedure, it is necessary to take steps to guard the wound and limb from damage, not only until the healing of the wound occurs, but until function is restored by regeneration of the nerves and muscles. In this series this object was attained by using a plaster of Paris casing, which at once retained the dressing in place and kept the leg in the desired position. With all the nerves which supply the muscles below the elbow cut, it is necessary, until the muscles regain function, to keep the leg supported. Otherwise the animal would keep the leg held up and the joints would be flexed, and when recovery took place the flexion would develop into a contracture which it would be impossible wholly to overcome. To prevent this the leg is fixed in a plaster of Paris bandage extending from the toes up the limb and round the body, and additional rigidity is given to this splint by a stout iron wire enclosed between the folds of the bandage (Plate 3, fig. 3). This plaster bandage was retained from 10 to 25 days, and on taking it off the stitches were removed from the wound. It was then necessary further to support the leg, as the function had not yet returned so as to enable the animal to walk. This was done by means of a short plaster splint extending from the toes up to the elbow (Plate 4, fig. 4) so as to maintain the radio-carpal joint rigid. This was removed and re-applied from time to time until on removal the function was found to be sufficiently restored to enable the unsupported leg to be used in walking.

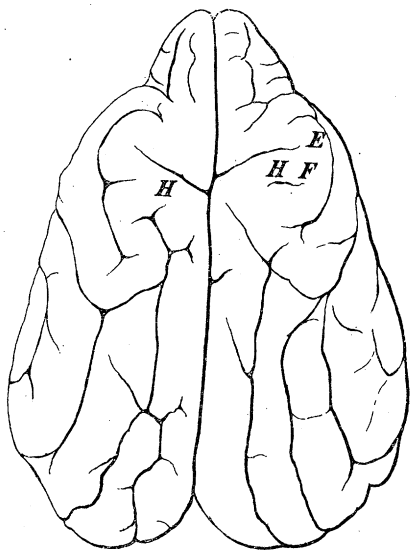
(d) *The Physiological Examination.*—After it was decided from observation of the functional recovery that the object of the experiment had been attained as far as probable, the animal was submitted to a physiological examination. This consisted of three parts as follows :—

1st. Exposure of the seat of union of the nerves—

This was carried out with care not to disturb the parts any more than absolutely necessary so as to observe the results of stimulation of the nerves, with the object of finding out the effect of stimulation of the proximal trunk or trunks leading to the junction, and also to decide if stimulation of the proximal trunk or trunks intended to be eliminated had remained without forming connections to the junction.

2nd. Exposure of the brain—

This was done by completely removing the roof of the skull so as to expose the entire surface of the brain, and enable an exact localisation to be made of the position of the centres, which on stimulation give contraction of the hind- and of the fore-limb. The normal arrangement is exhibited on the diagram, which represents the cerebral hemispheres of the dog. The sigmoid gyrus on the right side shows the normal arrangement, where H represents the centre for movements of the hind-limb, F that for flexion of the fore-paw, and E, at the extremity of the crucial sulcus, the centre for extension of the fore-paw. On the left side the centres were found either both at the extremity of the crucial sulcus in the position of the normal extension centre, or both in the position of the normal flexion centre. One normal area had become inexcitable, which of the two areas depending on the nature of the experiment.



Cerebral Hemispheres of Dog.

3rd. Examination with exposed muscles—

The last part of the examination consisted in removing the integuments from the fore-limb and repeating the examination of the nerves and also that of the brain so as to confirm the previous part of the examination, and to ascertain the exact muscles which contracted or remained passive at each stimulation.

(2) *Comparison of Dates and Extent of Recovery with those in Previously Published Experiments.*

(a) *Comparison with the Author's Previously Published Experiments.*—The experiments in crossing of the nerves of the limb published by me (7) in 1901, resembled the present experiments in that they involved the same nerves, that is the entire nerve supply to muscles below the elbow in the fore-limb of the dog. They differed, however, in the important respect that in the previous experiments no nerve was cut out, but on the other hand a crossing was effected between the nerves normally supplying flexors with those normally supplying extensors, contrasting therefore with the present series, in which the one nerve supply was made to perform the double function. It is important, therefore, to compare the results of these two series of experiments, in order to find what differences, if any, the two forms of experiment produced. The result of this comparison is to show that, as far as the experiments go, considerably more time is required for the commencement of recovery after the initial operation of the experiment and for the development of the recovery in the present series than in that formerly published. This difference is considerable. The first point to be compared, naturally, is the date on which some evidence was forthcoming of commencing restoration of function. This, in the earlier published experiments, was about the 30th day, while in the present series the earliest recovery varied from the 59th to the 96th day. In the former again the recovery became well developed, allowing the animals to use the limbs in walking, in one case at 45 and in the other at 90 days, while in the latter no such progress was made so early, but a similar progress was not shown till later, namely, from about 79 days to 126 days. Thus it is apparent that the effect of cutting out the central representation of one group of muscles is to increase the length of time required for a recovery to a very marked degree. As far as can be ascertained the two sets of experiments corresponded in all other details, so that the conclusion is inevitable that it is the fact of causing the one central representation to do the work of two, instead of causing the two central representations merely to exchange functions that causes the delay in restoration of function of the muscle groups affected. This increase of time necessary for recovery is due apparently to the reduction of volume of the nerve supply, and possibly also to the fact that the central representation must needs take on a double function, which may involve a more complex change than a mere alteration of function of the entire centre.

(b) *Comparison with the Experiments on Nerve Crossing published by Others.*—Rawa (2), Stefani (3), and Cunningham (5) have published experiments on nerve crossing. With those of Rawa and Cunningham no proper comparison can be instituted, because in the former the crossings were made in the hind-limb, and in order to prevent confluent reünion, involving a restoration of the normal paths for the impulses, Rawa had excised widely the central segment of the one nerve and the peripheral of the other, securing thus a certain pure union between the two other non-corresponding segments. This, however, prevented all recovery of normal function of the limb, and a comparison cannot therefore be made with such experiments. In those of Cunningham again, although the experiments were conducted on the fore-limb of dogs, and were somewhat similar although not so complete crossings (*i.e.* not involving all the nerves of the limb) as those in my previously published experiments, yet they are useless for comparison, as no recovery was found to take place in them, and the author of them concluded that recovery could not take place under such conditions. The only crossing experiments which are capable of being contrasted are those published by Stefani, in which, however, the crossings were not complete, but followed the same principle as that followed in the present series. The experiments were made in the fore-limb of the dog and consisted of crossing the median only with the musculo-spiral. In two of his experiments, in one of which, however, there was some confluent reunion, the restoration of function followed a course very similar to that followed in my former experiments, the restoration of function commencing on the 30th day, and being greatly improved by the 45th to the 47th day. This result, then, of STEFANI coincides with those experiments in nerve crossing which were published by me, and thus confirms the earlier recovery after a crossing experiment than after the kind of experiment here under consideration.

(c) *Comparison with Experiments of the Same Type published by Others.*—There have been, as far as I am aware, no experiments published exactly corresponding to the present series, *i.e.*, involving the nerves of the fore-limb. The only series of the same type available for comparison are those published by KILVINGTON (8). This, as already described in another part of this paper, was a set of experiments on the hind-limb of the dog involving the internal and external popliteal nerves, eliminating the one central end and making the other central end attach to both peripheral ends. The dates of the recoveries which he gives correspond in some respects to those of the present series, although it is difficult to satisfy oneself that the evidence of the recovery is quite certain. He gives 139 days as a date on which one of his dogs did not walk on the dorsal surface of the paw, and a similar date in the other experiment. This contrasts with the dates of the present series, 79 to 126 days, at which satisfactory progress was made. He records 38 days as the commencement of recovery in this animal, from which it appears that recovery commenced earlier than in my series, where 59 days was the earliest recorded. Another of his animals, in which the distal end of the external popliteal nerve (Experiment III) was grafted into a notch made in the internal popliteal, made an even more rapid recovery. At 106 days the recovery was almost perfect, and the first record of recovery is at 16 days. KILVINGTON regards his experiments published in Part I of his research, *i.e.* those just referred to, as being vitiated in their development and results by the presence of "axon splitting." Thus the fibre which descends in the proximal segment attached to the two distal segments may send some of its offsets down one and some down the other of the two distal trunks and cause confusion in the result, when recovery of function takes place. In one of the experiments where conditions were devised to prevent this taking place, he records the recovery as commencing at 49 days, and as being "practically perfect" at 141 days. Thus this method of eliminating the effects of axis splitting did not result in an earlier recovery, and the improvement appears rather to have been in the perfection of recovery.

Comparison may also be made with experiments (6) in which the sciatic nerves in dogs were divided high up in the thigh, and suture made after axial rotation of the distal segment through a semicircle. As a result of this section the musculature below the knee became paralysed. The date on which recovery was apparent is recorded very early, namely, from 14 to 21 days, and the ground on which the recovery was judged was the fact that the animal was placing the paw on the ground plantar surface down. The recovery here then was judged on the same ground as in the animals experimented on by KILVINGTON, but appeared to have commenced at an earlier date.

(3) *Superiority of the Fore-limb over the Hind-limb for Deciding the Questions at Issue.*

In dogs in which the hind-limb has been paralysed below the knee, the limb is still able to be used as a support in walking despite the paralysis of the muscles, the knee joint being supported by ligaments and tendons so as to give a rigid support. Thus the only apparent defect is the turning over of the paw so that the animal treads on the dorsal surface of the foot and scrapes this along until the surface is abraded and an ulcer results. Sometimes in putting down the foot it is passively impelled forwards, and on being laid down lands mechanically on the plantar surface. This apparently becomes more frequently performed as time goes on, so as to give the false impression that recovery is taking place. Thus the hind-limb is difficult to interpret as far as recovery is concerned. This difficulty of interpretation disappears entirely in the case of the fore-limb. Thus, where all the nerves are divided in the fore-limb the test is a severe one, as no power is present to use the limb in walking until an actual recovery of power has taken place in the muscles. The muscles affected by trans-section of the nerves midway between the shoulder and the elbow joints are those controlling the movements of the digits and of the wrist, and the wrist under such circumstances tends to assume a position of slight flexion. If attempts are made by the dog to use the limb, the result is that the limb flexes at the wrist and the animal falls on the end of the radius, thus abrading the skin here and setting up mischief, which will soon open into the joint. It is clear, therefore, that when the animal is able to use the unsupported limb in walking, proof is obtained that recovery of power in the muscles has been attained.

As regards the date of onset of the recovery much importance is necessarily dependent on whether the fore- or hind-limb has been experimented upon. In the case of the former the commencing recovery will tend to be estimated too late, owing to the amount of power over the muscles which must necessarily be regained by the animal before walking can be done. On the other hand, where the hind-limb has been the part operated upon, the recovery will tend to be recorded too early, as chance placing of the paw on the plantar surface is apt to be taken as evidence of commencing restoration of power, and thus cause a recovery to be recorded when really such has not yet occurred. This may be the explanation of the later dates recorded for commencing recoveries in my experiments as compared with those of KILVINGTON. Thus, in the former, the 59th to the 96th day were the earliest recorded dates on which the animal could use the fore-limb in walking, while, in KILVINGTON'S series, improvements are recorded much earlier, although the more perfect recoveries do not so materially differ in date from similar stages of recoveries in the fore-limb in my experiments. Thus the hind-limb is open to the possibility of fallacy in estimating recovery, but the fore-limb is an absolute test, and is a severe one.

(4) *Defective Recoveries Attributed to Axon Branching.*

KILVINGTON attaches much importance to axon branching as a means of complicating results of anastomosis. This is irrespective of what view may be held regarding regeneration of divided nerves. Whether due to outgrowth from the central end of the cut nerve fibres, or whether formed in the peripheral segment and joined subsequently to the cut central end, is a matter of indifference in this question. In either case it is stated that it is possible that a single nerve fibre is apt thus to become connected with each of the two antagonistic groups by the two or more distal trunks connected to one central trunk. As already mentioned, KILVINGTON devised a method of attempting to prevent this, and considered that the result of the experiment was thereby greatly improved. In my experiments, however, no precaution whatever was taken to prevent axon branching, and this must be remembered in reference to the dates and progress of the recoveries, as these do not appear to have been affected.

(5) *The Necessity for Precaution to Prevent Formation of Communications with the Central End or Ends Intended to be Eliminated.*

It is well known that there is a great tendency for a nerve after division to make functional reunion. This occurs even although the ends are not kept in apposition, and, indeed, although portions of the nerve are excised, as in the case where in the treatment of a neuralgia a neurectomy is performed. It is evident in an experiment to determine the capacity of a single nerve centre to supply a set of two antagonistic muscles or muscle groups, normally supplied by two centres, that should a reunion be effected between the central end of the nerve to be eliminated and the seat of anastomosis the experiment will be entirely vitiated and become useless. Therefore in all such experiments, because of the tendency of severed nerves to unite, efficient precautions against this possibility are imperative. Not only this, but after the object for which the experiment has been done has been attained it is necessary to ascertain by an examination that the experiment has not been vitiated in this manner, despite the precautions taken to prevent it. Now the examination which is made may be one of two kinds, namely, either an anatomical or a physiological one. The anatomical one may succeed in showing the presence of connecting strands, which, however, may be only connective tissue strands without nerve fibres, or they may contain nerve substance but non-functional, for the reason that too much cicatricial tissue may be present, which will prevent by its contraction the passage of the impulses, or on the other hand it may be a functional strand of nerve which vitiates the experiment. Thus it is impossible to be certain by the most careful anatomical examination whether or not a pure experiment has been effected. The test which is capable of settling the matter is the physiological one where the electrical current has been applied to the central segment of the nerve which has been eliminated. If on stimulation of this by a current of sufficient strength no response is got in muscles which are capable of responding, then it proves that no undesirable union has been made. In the series of experiments here published this method was applied, and the result was to show that no such reünion had taken place in any experiment. It is necessary to point out that this physiological method of ascertaining the presence of such reunion was not recorded by KILVINGTON as having been carried out in his cases, and therefore, if this was not done, the results of his experiments, in my opinion, are vitiated.

(6) *Factors Determining the Date of Recovery.*

In the experiments the first indication of commencing recovery took the form of evidence of contraction of the muscles. This did not necessarily enable the animal to walk; on the other hand the animal was with one exception quite unable to walk, but the muscles of the limb were contracting, causing in one instance a distinct contracture. With the further development the capacity to walk was regained in three of the animals.

In two of the experiments in which the central segments were the musculo-cutaneous, median, and ulnar, the preliminary contractions of the muscles were noted at 96 and 93 days respectively, so that a marked correspondence in these two experiments was manifested. Also the further course of events showed correspondence, as at 126 and 123 days respectively these animals were able to use the leg in walking. In the other experiments, in which the musculo-spiral was the central segment left to supply the entire limb, an earlier appearance of recovery took place, namely, at 81 and 59 days respectively.

From comparison of experiments on nerve crossing with the present series it has been shown that there is a difference in the dates of recovery in favour of the former. This is what might be expected in consideration of the fact that it is only necessary in the case of the former experiments for substitution of one cerebral centre to be made for another, while in the latter one central segment is removed altogether, and both sets of muscles supplied through the single central trunk. There is thus not only a new connection with the centres to be established, but there is also a reduction of the total volume of the nerves supplying the entire musculature of the limb. In the nerve crossing series the total volume of nerve supply remained the same in the experimental conditions as in the normal conditions, only the arrangement being interfered with. It may therefore be supposed that this is an important factor in influencing the time required for functional restoration.

In the present series, however, there is an apparent contradiction of this view, in so far that the evidence of functional restoration was shown sooner in those cases in which the central segment was smaller. Thus in Experiments I and II the earliest sign of recovery, namely, contraction of muscles, appeared at 96 and 93 days respectively, while the same thing was shown in Experiments III and IV at 81 and 59 days respectively. In the former the musculo-cutaneous, median, and ulnar were the central segments left to carry on the double function, while in the latter the musculo-spiral was left, the other three central segments being eliminated. In view of the greater volume of the central segments in the first two experiments as compared with that in the latter two experiments it might have been expected that earlier recovery would have taken place. One of the latter dogs also developed capacity to walk very soon, being able to be taken out in the streets for exercise, so little did its defect show, as early as 79 days, a date thus much earlier than that at which any evidence of recovery had taken place in the first two experiments.

This apparent contradiction is probably explained by the mechanical conditions involved in the fore-limb of the dog. Thus, if there is the least tendency to contraction of the flexors of the paw, walking is very difficult or even impossible, as the foot doubles under the animal, and a fall on the end of the radius occurs. An explanation of the apparent contradiction is got if it is supposed that, when the two distal segments or sets of segments are joined to a central segment or set of segments which corresponds to one of the distal segments or set of segments, that functional union occurs more readily between the corresponding ends than with the non-corresponding ones. This need not mean that anatomical union of the corresponding and of the non-corresponding ends will follow any different course. Probably the centres in the brain are more readily brought into functional union with the peripheral organs to which normally they have stood in relationship.

If this view is correct, then an explanation is obtained of the earlier recovery in the experiments in which the musculo-spiral acted as the central segment, for through this the first muscles to recover would be the extensors. This would enable or even of necessity cause the limb to be held in the extended position, and in this position the limb would easily be used for support, even although as yet no recovery of voluntary control had occurred in the flexor group. On the other hand, when the nerves normally supplying the flexor group were retained as the sole nerve supply, then the flexors would take precedence of the extensors in recovery. This, however, would not help the animal in walking, but rather the reverse, for, owing to the non-recovery of the extensor group, flexion would be the position of the limb, and in this position the limb would be useless for support of the body, and would remain so until recovery of the extensor group enabled the limb to be held in extension. Thus in Experiments I and II there was some difficulty in getting recovery of power to walk, for while commencing recovery in the muscles was seen at 96 and 93 days respectively, it was 126 and 123 days before the limb could be held in extension sufficiently to enable the limb to be used for walking and running.

This view of the matter is supported by the evidence of the examination by stimulation of the peripheral nerves after recovery of function, where flexion was the predominant movement produced on stimulating proximal to the junction, when nerves originally supplying the flexors were used, and where extension was the predominant movement when the nerve representing the central segment was the musculo-spiral. The latter condition was clearly evident in Experiment IV (p. 50).

(7) *Theories as to Restoration of Co-ordinated Movements.*

When restoration of co-ordinated movements has occurred after nerve crossing or after the form of experiment under consideration in this paper, where one cortical area comes to represent two normal areas, this may be explained as due to re-education of the centre to perform functions not originally proper to it. It is necessary to assume for a process of re-education that the brain will have a source of information by which the process of re-education is carried out, and this must of necessity be ingoing impulses along afferent nerves. It was supposed by SCHIFF that the afferent nerves fulfilling this function were those which ascended from the skin of the forearm and from the joints, *i.e.* nerves not necessarily involved in the crossing. SCHIFF does not take into consideration the muscular sense and the nerves which are involved in this, which have been crossed or otherwise affected by the experimental conditions, in the same way as the efferent fibres. It is now known how important these fibres are in relation to co-ordinated movements.

The process of re-education would necessarily be preceded by many ineffectual attempts at volitional co-ordinated movements, and would only become perfected after many ineffectual and defective attempts. Thus in the form of experiment where the fore-limb is employed and, say, the flexor nerves made to supply not only flexors but also extensors, the following process may be supposed to take place. On regeneration and recovery of the muscles, early attempts at movements may be supposed to result differently, according to the view taken as to the way in which the nerve trunks have united. If it is supposed that axons have branches sending one branch to the flexor group and one to the extensor group, then impulses descending the trunk would, on reaching the bifurcation, send an impulse to the extensor and one to the flexor group. The result would be contraction of both groups, and a mere spastic condition of the limb produced, with uncontrolled movements in the direction of the stronger muscles, and therefore flexion.

In the event, on the other hand, of axon branching not taking place, or not taking place in such quantity as to appreciably affect the result of the operation, then the result would be that some of the fibres of the proximal segment would become connected with the fibres of one distal segment and some with those of the other. In this case the experiment would resolve itself into a case of some of the nerve cells in the central nervous system remaining in connection with their normal muscles, and other nerve cells being connected with new muscles, namely the opponents of their former distribution. Under such circumstances the preliminary discharges would produce a contraction of all the muscles in the limb, thus producing again a movement in the direction controlled by the stronger muscles, namely the flexors. Then on laying down the paw in an attempt to walk, the foot would be flexed and the animal would land on the dorsal surface, and finding in this position no support, a fall would take place, the radio-carpal joint bending and the animal striking the joint on the ground, which if repeated often would cause an abrasion. But, informed by the afferent impulses that something is wrong, the animal gradually would learn that some other movement must be made. In the case of the experiments on nerve crossing where the entire flexor and the entire extensor nerve supply are still, in the new conditions, retained, although they are crossed and made to supply the groups opposing their normal muscle distribution, the consideration of the education process is quite different. There it is much simpler, for the animal might be supposed to learn that it had to make the movement of extension when flexion was required, and *vice versâ*.

Even in the simpler case of nerve crossing it is difficult to see how an animal would be sufficiently responsive to the impressions received by afferent paths to make a change so radical in nature. When, however, it involves not the interchange of function of two centres but the splitting of the function of one, the possibility of this being effected in the way suggested is even more doubtful.

One consideration of importance in judging of this matter is the question of time. Education is a process which takes time, and therefore after nerve crossing the time necessary for restoration of co-ordinated movements may, on the re-education view, be regarded as being necessarily much longer than in the case in which the same nerves have been divided similarly, but united each to each with as much accuracy as possible. A "control" of this nature was published with my nerve-crossing experiments, and the result was to indicate that additional time was not required for the restoration of co-ordinated movements after nerve crossing. In the present series the time required for the reappearance of co-ordinated movements is distinctly greater, and this might be explained as time required for the re-education process, or on the other hand as being due to the reduction of the total nerve supply. Thus there is eliminated in the one type of experiment the central segment of the musculo-spiral, and in the other there are eliminated those of the musculo-cutaneous, median, and ulnar. At first it was difficult to explain why the ability to walk appeared earlier when the central segment of the musculo-spiral was left than in the case where it was the one eliminated, as the combined sectional area of the three flexor nerves was greater than that of the musculo-spiral, and thus it would have been expected that on this ground an earlier recovery would have been seen in those experiments in which the three flexor nerves had been left. Further consideration, however, suggested the explanation already given. Thus when the central segment of the musculo-spiral was retained as the source of supply, this was the normal innervation of the extensor muscles, but when the three flexor nerves were retained and the musculo-spiral eliminated, this was not the normal supply of the extensor group. Apparently under these circumstances an advantage in the recovery lay with the extensor group, and this materially affected the date on which the recovery of the extensor muscles, as a means of keeping the leg extended so as to permit walking, took place. When the opposite condition obtained, then the time required for the efficient contraction of the extensor group was apparently longer. This would tend to show that the normal arrangement preponderates in the recovery, and this may be open to the interpretation that a certain amount of education is necessary, in the case where non-corresponding ends have been united, before function can be carried out.

It was noticed that although when the musculo-spiral served as source of supply, the ability to walk was earlier regained, still the leg did not gain in bulk and in strength so quickly as in the case where the source of supply was the musculo-cutaneous, median and ulnar combination. This again is what might be expected in view of the greater bulk of the nerves forming the source of supply in the latter case. The facts then would be explained by assuming that where one centre is made to supply not only its own muscles, but also a group antagonistic in action to its own muscles, a quicker recovery takes place in the case of the normal distribution than in the case of the new distribution which the experimental arrangement seeks to establish.

Recoveries of co-ordinated movements after experimental alteration of the innervation are simplified when considered in the light of present-day views as to the nature of correlated action of antagonistic muscles. This has within recent years been worked out by SHERRINGTON (13–29) in his long series of papers on reciprocal innervation of antagonistic muscles. Thus in every movement, say of flexion, there is produced not only a contraction of the flexor group, but there are also at the same time impulses which act on the extensor group and cause an appropriately measured inhibition so as to permit of relaxation of the muscle tonus to permit of the extensors relaxing to the necessary length for the movement of flexion to occur. The reverse takes place in the case of an extensor movement being performed. SHERRINGTON has called attention to the very remarkable passage in the work on Anatomy and Physiology, published by J. and C. BELL (1), which shows that this view was first put forward by C. BELL in 1826, with reference to the action of antagonistic muscles. He makes reference to the function of a nerve to cause not contraction but relaxation of a muscle, and in discussing the function of the fourth nerve, he says, "if we suppose that the influence of the fourth nerve is, on certain occasions, to cause a relaxation of the muscle to which it goes, the eyeball must be then rolled upwards."

In a footnote Bell then proceeds to enlarge on this aspect of the function of nerves, and makes reference to the action of antagonistic groups of muscles, and records an experiment in the following words: "I appended a weight to a tendon of an extensor muscle, which gently stretched it and drew out the muscle; and I found that the contraction of the opponent flexor was attended with a descent of the weight, which indicated the relaxation of the extensor." He considers that "there must be particular and appropriate nerves to form this double bond, to cause them to conspire in relaxation as well as to combine in contraction. If such a relationship be established, through the distribution of nerves, between the muscles of the eyelids and the superior oblique muscle of the eyeball, the one will relax while the other contracts." This early experiment on the double action in each movement involving antagonistic muscles has been fully investigated by Sherrington. He has shown that in the reciprocal innervation of antagonistic muscles the co-ordination is independent of the higher centres as the co-ordinated acts are carried out, although the whole brain has been removed, and, therefore, with it all the parts which are considered to be the seat of consciousness and psychical activity. The indication, therefore, is that in these co-ordinated movements we have to deal with reflexes (13, p. 1019). He has shown that when the afferent fibres of one set of muscles are stimulated, a contraction is induced in the antagonists (14, p. 563). Also along with Hering (19) he has shown that cortical stimulation brings out this double action, namely, in the monkey and cat, contraction of the biceps and relaxation of the triceps in the production of the movement of flexion of the forearm. Also in the same paper is published an observation of stimulation of the internal capsule, where relaxation is seen as the result of stimulation, and the important observation is recorded in the following words:—"The area of the capsular cross-section at which the inhibition of the activity of, *e.g.*, the triceps, muscle can be evoked is separate from (that is to say not the same as) that area whence excitation evokes contraction of the triceps (or of that part of the triceps, inhibition of which is now referred to). On the other hand, the area of the section of the internal capsule, whence inhibition of the muscle is elicited, corresponds with the area whence contraction of its antagonistic muscles can be evoked" (19, p. 186).

In the case of the muscles involved in opening and shutting of the eye Sherrington publishes a note in which he points out (20) the effect of relaxation of the levator palpebræ in partially closing the eye after the orbicularis palpebrarum has been paralysed by section of the facial nerve. He describes the synchronous blinking of the eye, although in one eye these paralytic conditions obtain. I have also noted this in the human subject when the facial nerve has been divided, and where spino-facial anastomosis has been done, but before any recovery could have been attributed to that operation, and also in experimentally produced paralysis, and have explained the phenomenon as due to the relaxation of the levator palpebræ and to movements of the eyeball communicated to the flaccid eyelid (Part I, p. 126).

From the point of view of the present consideration an important fact has been proved by SHERRINGTON (23), who shows that although in the cat primary extension of the knee as a motor reaction is only exceptionally obtained by cortical stimulation, yet under the influence of certain doses of strychnine or of tetanus toxin a point is found in the cortex which gives such a contraction. "After exhibition of strychnine extension of knee becomes elicitable regularly from the cortex, and from the very points of it that yielded flexion previously" (23, p. 292). He shows that previously to the exhibition of the strychnine these points were in relationship with the extensors, but cortical stimulation caused not contraction but inhibition so as to permit the movement of flexion. This is altered under strychnine, where the inhibition is changed into contraction. It is important to note that it is necessary to view the inhibition of the antagonistic muscles not as a passive but as an active process, just as is the contraction of the protagonist muscles.

Further it has been shown (25) that two groups of afferent fibres proceed from a muscle of the limb. "Both of these evoke reciprocal innervation in antagonistic pairs of muscles; but one group evokes a reflex which excites that muscle from which the afferent nerve itself proceeds and concurrently inhibits the antagonistic muscles, while the other group evokes a reflex which relaxes the muscle from which the afferent nerve proceeds and concurrently excites the antagonistic muscles" (25, p. 340).

In accordance with these facts so thoroughly demonstrated by SHERRINGTON the phenomena seen after nerve crossing or nerve grafting become intelligible. Each group of nerve cells constituting a centre would thus appear to be associated normally with not only one group of muscles but also with its corresponding antagonists, in the one case evoking on stimuli being applied a contraction, and in the other an inhibition resulting in a relaxation. That this result of the stimulus is capable of variation under altered circumstances is shown by the altered behaviour under the influence of strychnine or tetanus toxin. Likewise it is important to bear in mind how these results are called forth by the afferent impulses. In these experiments then the return of co-ordinated movements after the rearrangement of the nerves results from the muscles being brought into connection with a centre to which normally they were related in connection with the reciprocal innervation. It would thus require only the alteration of the capacity of some of these cells to produce under stimulation contraction instead of the normal inhibition or *vice versâ*. This is the same change which, according to SHERRINGTON, is shown under strychnine, under which condition on stimulating the brain a centre for extension is found where no such result was normally obtainable, but which was in the position of a centre normally giving inhibition of the extensors. The same change may possibly be brought about by the alteration in the nature of the afferent impulses which is caused by the experimental rearrangement of the nerves by the anastomosis, and if this is so an explanation of the adaptation to the altered circumstances is suggested, which may explain the restoration of co-ordinated movements in experiments of this kind.

6. General Conclusions.

(1) In the limb of the dog, when the nerve supply of one group of muscles is eliminated, the nerve supply of its antagonistic group may be used to supply both groups, and under these conditions co-ordinated movements may be restored.

(2) When two antagonistic groups of muscles in the limb of the dog have their nerve supplies cut, and both groups then made to derive their supply from that of the one group, the group whose nerve supply is utilised probably will be the first to recover.

(3) Recovery of function of antagonistic muscles is slower to occur when one nerve supply is eliminated than in the case of nerve crossing experiments where no nerve is eliminated, but where the supply of the two groups is crossed; and this delay is caused by reduction in the former case of the total volume of the nerves supplying the limb, and possibly by greater difficulties of adaptation in the brain to the new conditions.

(4) Where in the dog one nerve has been made to supply not only its own but also the antagonist of its own muscle, the nerve fibres passing to the two muscles in the nerve trunk proximal to the junction may be so completely separated that it may be possible to stimulate each group without affecting the other, producing thus at will contraction either of the one or of the other muscle, both being now supplied by a single central trunk.

(5) When two groups of antagonistic muscles in the limb of the dog are represented by separate cortical areas, and when the nerve supply of one of the groups is eliminated, both groups being caused to be innervated by the remaining nerve supply, the cortical area corresponding to the eliminated nerve supply becomes inexcitable, while the other cortical area on stimulation causes contraction in both groups of muscles.

(6) Where one group of muscles is paralysed, and a portion of an antagonist muscle is detached from its insertion and attached to the tendons of the paralysed group, this substitute for the paralysed group may enable the function of that group to be performed to a certain extent, and the function recovered by means of this procedure is probably controlled by the same adaptation in the central nervous system as occurs in the case of nerve anastomosis.

(7) The adaptation in the central nervous system which allows restoration of function to take place after nerve anastomosis is not due to a simple re-education process, as there is no evidence of this during recovery, but is probably due to an alteration in the centres under the influence of altered afferent impulses from the muscles, the brain thus having the capacity quickly to adapt itself to such alteration.

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8. EXPLANATION OF PLATES.

Plate 3.

Fig. 1.—Case of paralysis of the extensor muscles in the leg in which no movements at the ankle joint were possible, and the foot was drawn into the equinus position by the gastrocnemius. One-third of the gastrocnemius was employed as a substitute for the function of the extensors as a remedial procedure after lengthening of the Achillis tendon. Photographed to show range of movements 103 days after the operation. The photograph was prepared from two photographs, one to show the extreme flexion and the other the extreme extension. These two photographs were superimposed, the legs coinciding, and the range of movement at the ankle is thus shown. It is seen that the new extensor action is accompanied by some eversion of the foot, which is due to the line of action of the new muscle, which comes from the posterior and outer aspect of the leg above, passing downwards and to the front. It may be stated that the actual range of movement was greater than indicated in the photograph, as it was found impossible to induce the child to maintain the extreme extent of movement long enough to obtain a photograph of it. (P. 35.)

Fig. 2 (Experiment I).—Anastomosis of musculo-cutaneous, median, and ulnar with the musculo-spiral, the central segment of the musculo-spiral being prevented from reuniting. The entire musculature below the elbow is thus supplied by the three nerves normally supplying the flexor muscles only. The operation was performed on the right fore-limb. The photograph was taken 127 days after the operation. It shows the leg being used in standing in a normal position. It is also seen that there is no appearance of abnormal hyperextension at the wrist joint. This recovery was only observed on the day preceding the taking of the photograph, but was continuously maintained till the physiological examination at 225 days. (P. 41.)

Fig. 3 (Experiment V).—The operation was done on the right fore-limb, the musculo spiral being used as the sole source of supply to muscles below the elbow. The photograph shows the method employed for fixing the leg after these operations, by a plaster splint extending from the toes up the leg and round the body. This retains the dressings in place, and protects them from interference by the animal, and maintains the leg in the position normal for standing, and prevents the formation of any contractures, which otherwise would be apt to occur by the preponderance of one group of muscles during the recovery of power, thus destroying the experiment by preventing use of the limb. The photograph was taken 12 days after operation. (P. 51.)

PLATE 4.

Fig. 4 (Experiment II).—Same as Experiment I. This shows the other splint which is employed in these experiments, namely the short plaster splint. It enables the dog to run freely about, using the leg, although the muscles have not sufficiently recovered to allow this to be done otherwise. It extends from the toes up to the elbow, and thus immobilises the wrist joint. It is removed from time to time, and re-applied till recovery is sufficient. Without its use the limb would be held up and might develop contractures. Dog was photographed at 143 days after the operation. Function had been recovered, but a slight flexor contracture had been threatening, and it was to overcome this that the short splint was applied. (P. 45.)

Fig. 5 (Experiment II).—This shows the animal 124 days after the operation, and the day after a plaster splint had been removed. It ran round the room, using the leg, when the splint was taken off. The splint had subsequently to be re-applied as shown in fig. 4. This shows the right fore-limb used in standing, and no abnormal hyperextension at the wrist. (P. 45.)

Fig. 6 (Experiment IV).—Anastomosis of the musculo-cutaneous, median, and ulnar with the musculo-spiral, the central segments of the musculo-cutaneous, median, and ulnar being prevented from reuniting. This was done on the right fore-limb. Photographed 94 days after the operation. The dog by this time had been making free use of the leg, since the 59th day, and quite satisfactorily since the 79th day. It may be seen that the letter P on the dish appears visible through the affected leg. This shows how actively the dog could move the leg, as this appearance was caused by the animal lifting and replacing the leg while the photograph was being taken by the magnesium flash. It is seen that there is no abnormal hyperextension at the wrist joint. (P. 49.)

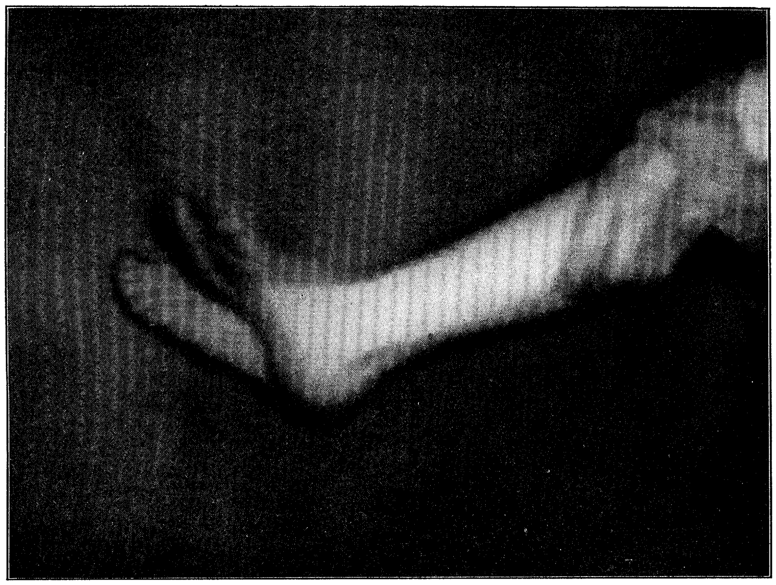


Fig. 1.

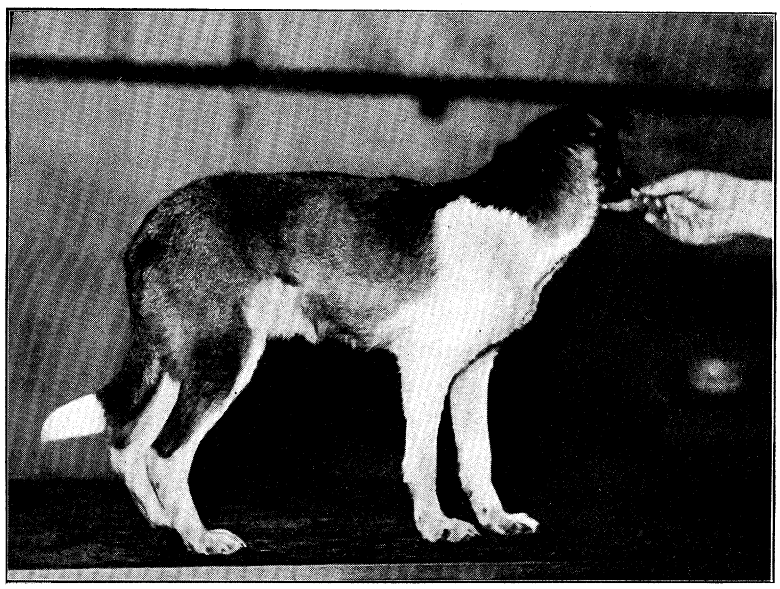


Fig. 2.

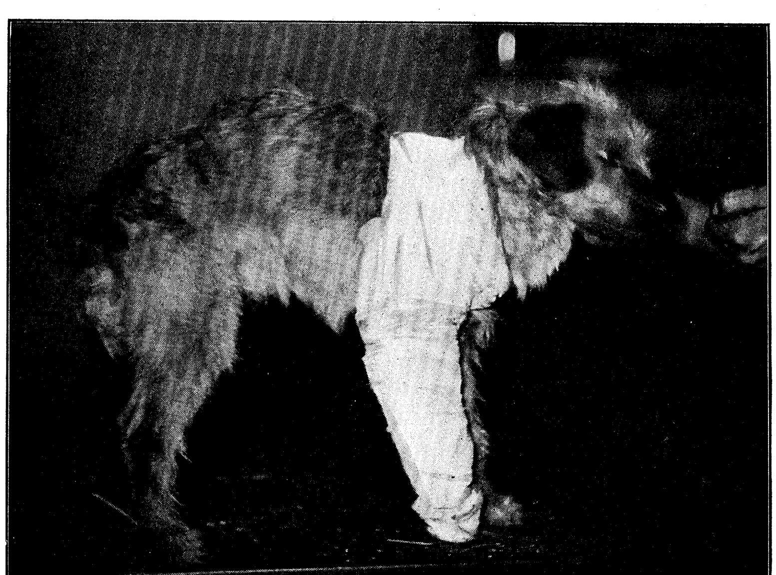


Fig. 3.

R. Kennedy photo.

Fig. 4.

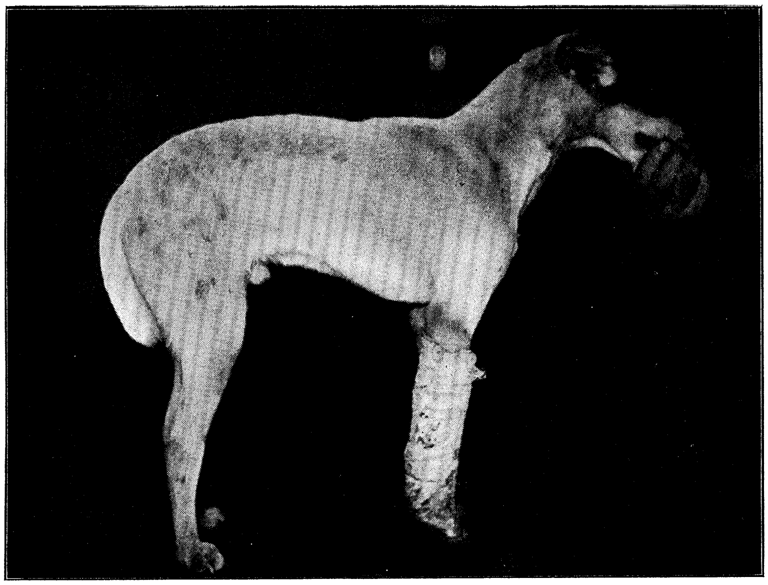


Fig. 5.

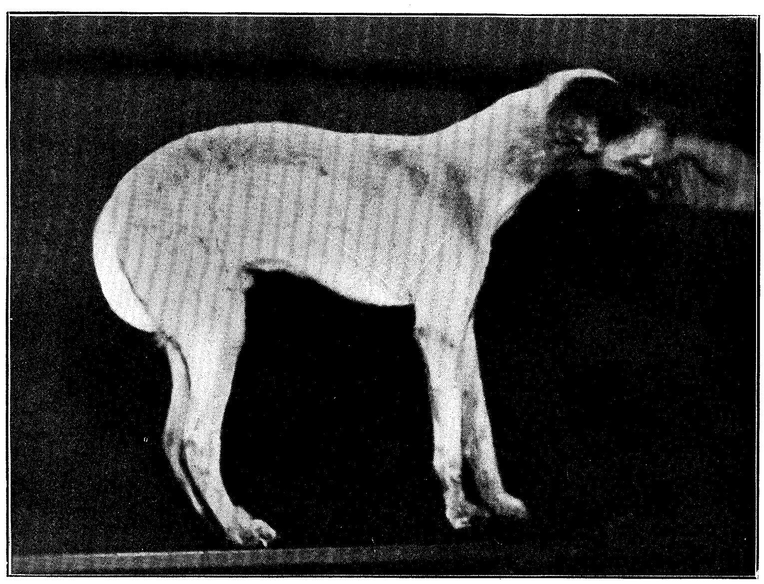
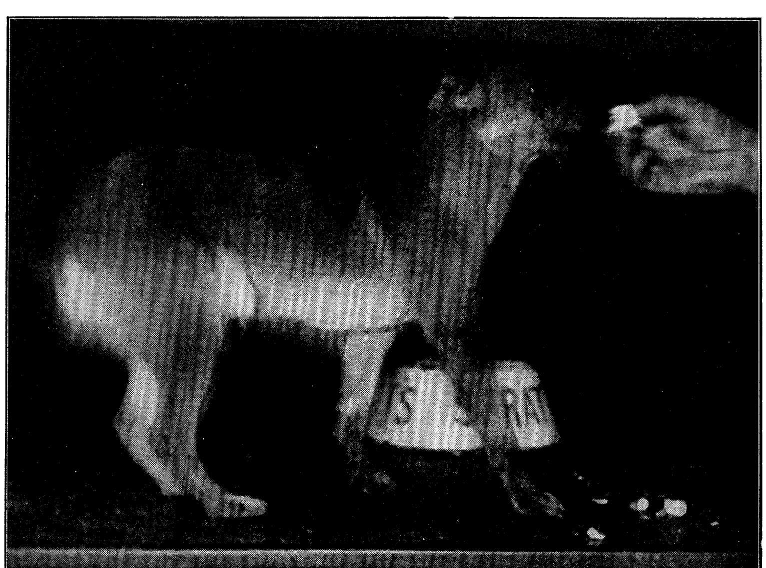


Fig. 6.



R. Kennedy photo.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Fig. 1.

Fig. 2.

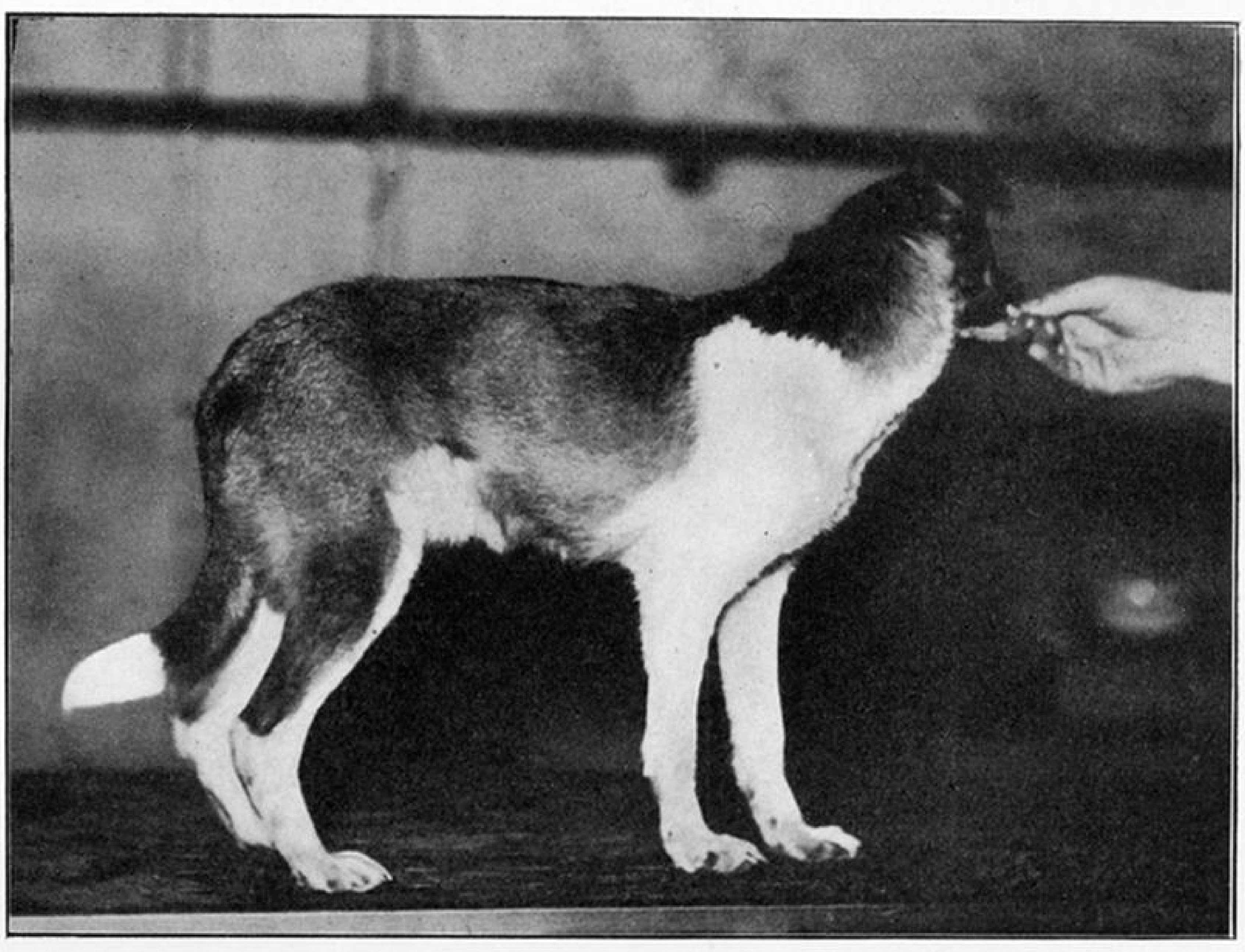


Fig. 3.

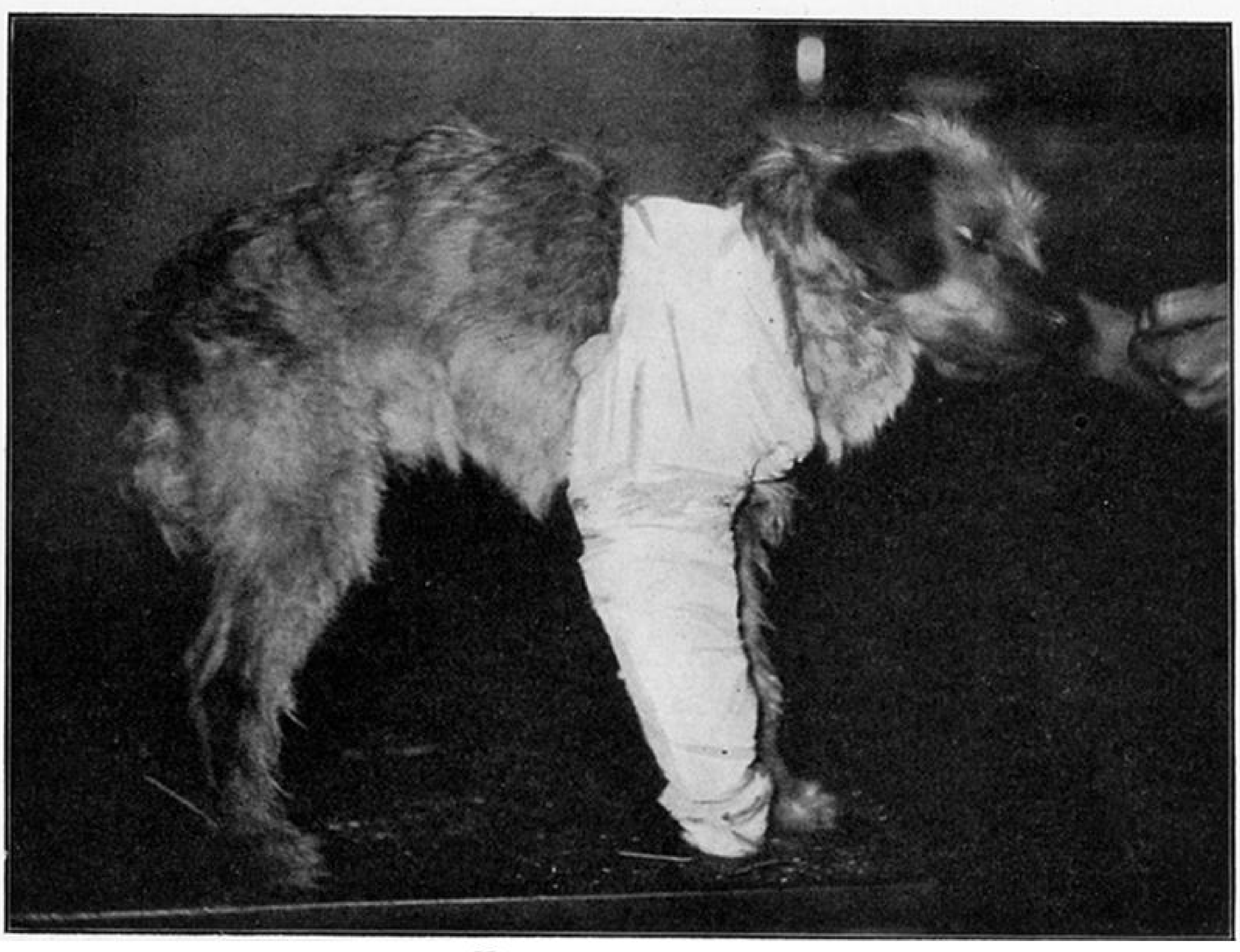


Plate 3.

Fig. 1.—Case of paralysis of the extensor muscles in the leg in which no movements at the ankle joint were possible, and the foot was drawn into the equinus position by the gastrocnemius. One-third of the gastrocnemius was employed as a substitute for the function of the extensors as a remedial procedure after lengthening of the Achillis tendon. Photographed to show range of movements 103 days after the operation. The photograph was prepared from two photographs, one to show the extreme flexion and the other the extreme extension. These two photographs were superimposed, the legs coinciding, and the range of movement at the ankle is thus shown. It is seen that the new extensor action is accompanied by some eversion of the foot, which is due to the line of action of the new muscle, which comes from the posterior and outer aspect of the leg above, passing downwards and to the front. It may be stated that the actual range of movement was greater. than indicated in the photograph, as it was found impossible to induce the child to maintain the extreme extent of movement long enough to obtain a photograph of it. (P. 35.)

Fig. 2 (Experiment I).—Anastomosis of musculo-cutaneous, median, and ulnar with the musculo-spiral, the central segment of the musculo-spiral being prevented from reuniting. The entire musculature below the elbow is thus supplied by the three nerves normally supplying the flexor muscles only. The operation was performed on the right fore-limb. The photograph was taken 127 days after the operation. It shows the leg being used in standing in a normal position. It is also seen that there is no appearance of abnormal hyperextension at the wrist joint. This recovery was only observed on the day preceding the taking of the photograph, but was continuously maintained till the physiological examination at 225 days. (P. 41.)

Fig. 3 (Experiment V).—The operation was done on the right fore-limb, the musculo spiral being used as the sole source of supply to muscles below the elbow. The photograph shows the method employed for fixing the leg after these operations, by a plaster splint extending from the toes up the leg and round the body. This retains the dressings in place, and protects them from interference by the animal, and maintains the leg in the position normal for standing, and prevents the formation of any contractures, which otherwise would be apt to occur by the preponderance of one group of muscles during the recovery of power, thus destroying the experiment by preventing use of the limb. The photograph was taken 12 days after operation. (P. 51.)

Fig. 4.

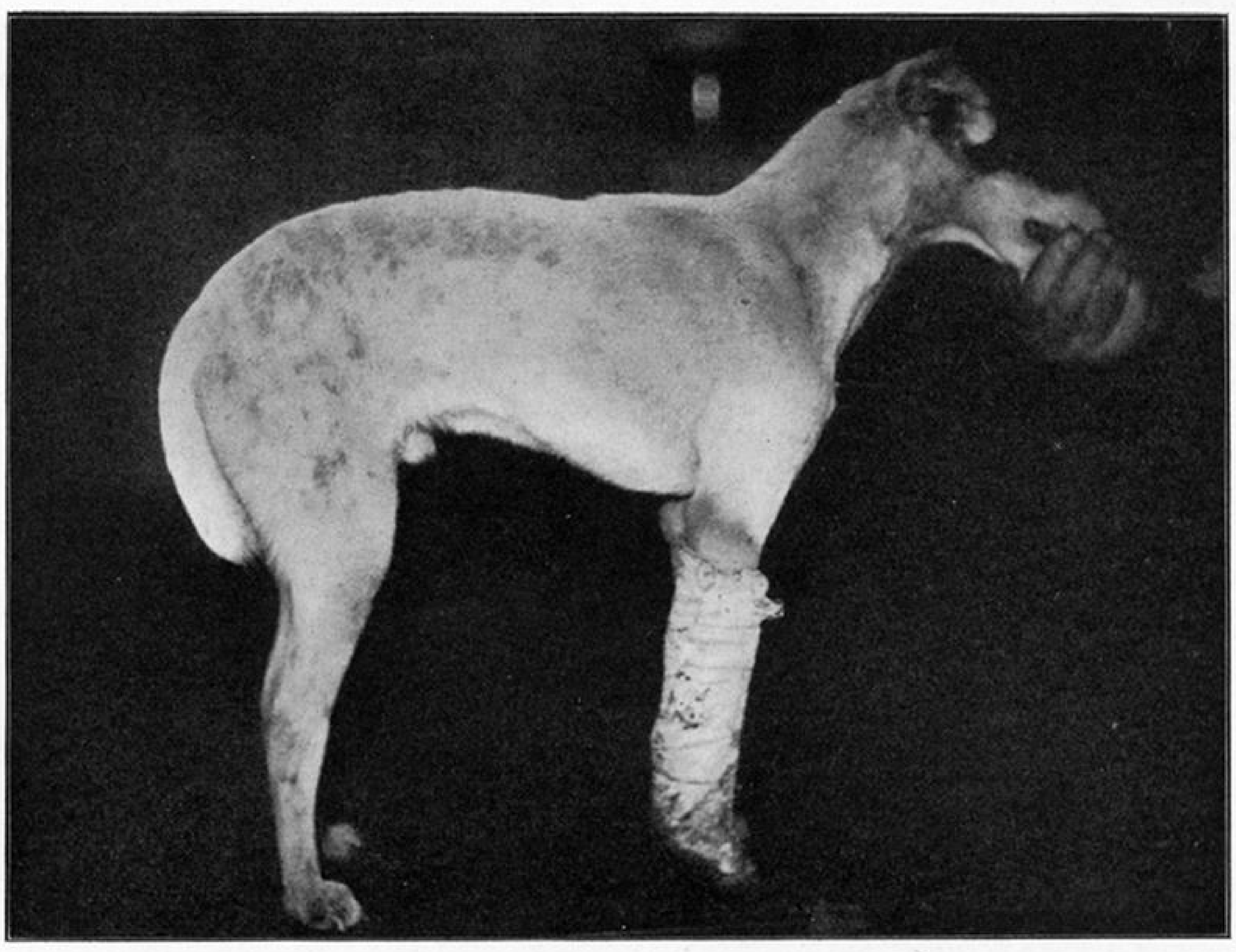


Fig. 5.

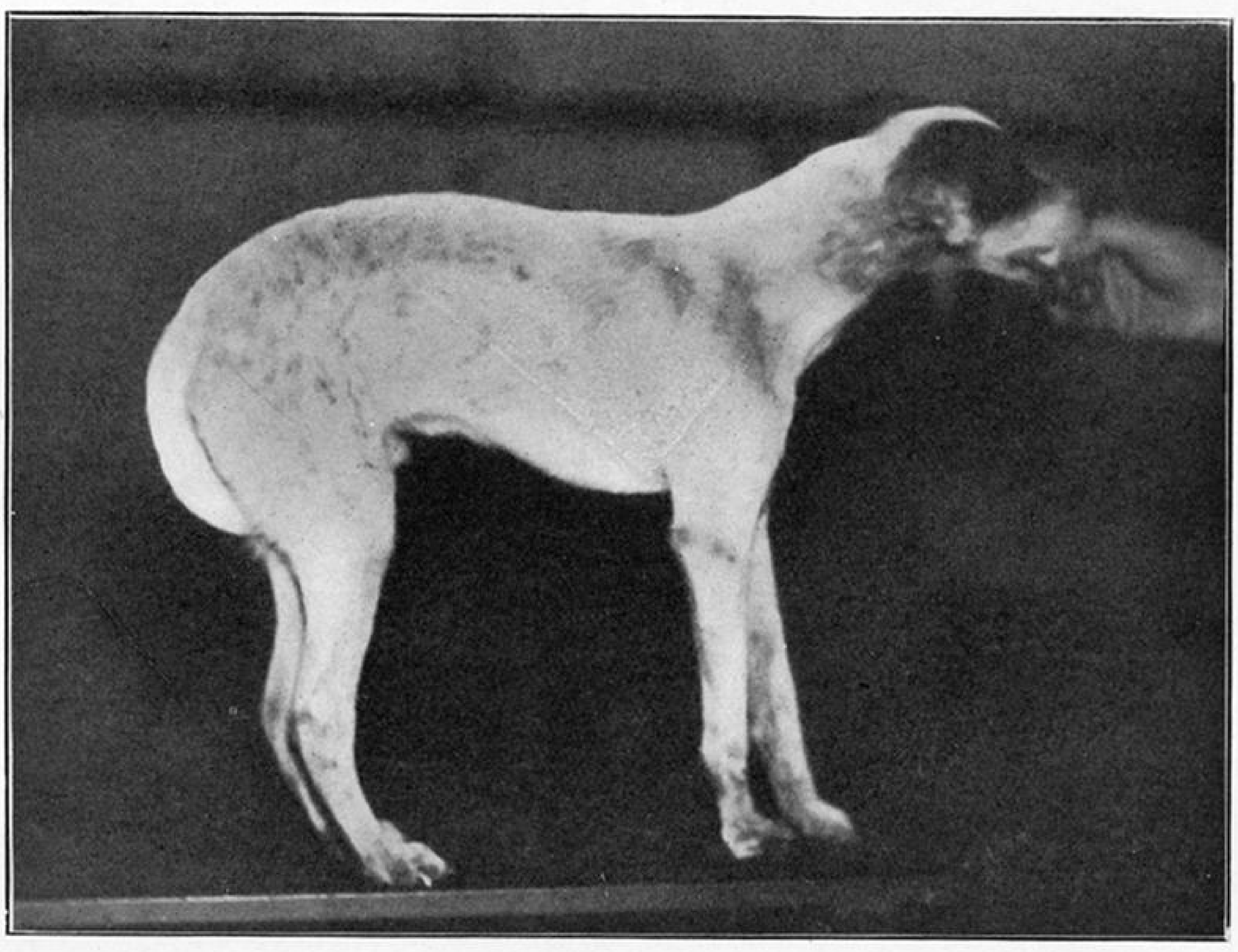


Fig. 6.

PLATE 4.

Fig. 4 (Experiment II).—Same as Experiment I. This shows the other splint which is employed in these experiments, namely the short plaster splint. It enables the dog to run freely about, using the leg, although the muscles have not sufficiently recovered to allow this to be done otherwise. It extends from the toes up to the elbow, and thus immobilises the wrist joint. It is removed from time to time, and re-applied till recovery is sufficient. Without its use the limb would be held up and might develop contractures. Dog was photographed at 143 days after the operation. Function had been recovered, but a slight flexor contracture had been threatening, and it was to overcome this that the short splint was applied. (P. 45.)

Fig. 5 (Experiment II).—This shows the animal 124 days after the operation, and the day after a plaster splint had been removed. It ran round the room, using the leg, when the splint was taken off. The splint had subsequently to be re-applied as shown in fig. 4. This shows the right fore-limb used in standing, and no abnormal hyperextension at the wrist. (P. 45.)

Fig. 6 (Experiment IV).—Anastomosis of the musculo-cutaneous, median, and ulnar with the musculo-spiral, the central segments of the musculo-cutaneous, median, and ulnar being prevented from reuniting. This was done on the right fore-limb. Photographed 94 days after the operation. The dog by this time had been making free use of the leg, since the 59th day, and quite satisfactorily since the 79th day. It may be seen that the letter P on the dish appears visible through the affected leg. This shows how actively the dog could move the leg, as this appearance was caused by the animal lifting and replacing the leg while the photograph was being taken by the magnesium flash. It is seen that there is no abnormal hyperextension at the wrist joint. (P. 49.)