

Normal plantar response: integration of flexor and extensor reflex components

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The reflexes elicited by painful stimulation of the plantar surface of the foot have been studied extensively for a long time and the relation between the reflexes obtained in normal and in pathological cases has been the subject of considerable debate. An excellent survey of previous investigations is to be found in the review by Walshe (1956). As in most studies of human reflexes, the technique commonly used has, however, not permitted an exact determination of the latency values of the reflexes, and it has thus not been possible to judge with certainty to what extent the movements studied have been purely spinal and to what extent of cerebral origin.

By means of brief electric stimuli and an electromyographic recording technique these latency values can, however, be exactly determined, and in this way a clear distinction can be made between purely spinal reflexes and movements of a more uncertain origin. Using this technique, the spinal skin reflexes of the trunk (Kugelberg and Hagbarth, 1958; Hagbarth and Kugelberg, 1958), the leg (Hagbarth, 1960; Kugelberg, Eklund, and Grimby, 1960), and the foot (Eklund, Grimby, and Kugelberg, 1959; Kugelberg *et al.*, 1960) have previously been investigated, and these studies have established the existence of an extensive system of spinal skin reflexes representing a highly purposeful defence mechanism for appropriate withdrawal reactions.

In investigations of the spinal pain reflexes normally elicited from the plantar surface of the foot Kugelberg *et al.* (1960) found that stimulation of the ball and hollow of the foot evokes plantar flexion of the toe, whereas, conversely, stimulation of the ball of the great toe produces dorsiflexion of the toe. It was further established that in extreme pathological cases (with pronounced Babinski signs) painful stimulation of the plantar surface of the foot elicits a stereotyped flexor reflex with dorsiflexion of the great toe, independently of the stimulus site, and that the main difference between this pathological reflex and that normally evoked by hallux stimulation lies in the extent of the receptive field. The conclusion was drawn that the two reflexes are essentially identical but that in normal cases, due to

the suprasegmental control of the reflex centres, the receptive field of the reflex is limited to the skin area where it is adequate for protective purposes, *viz.*, the ball of the great toe.

Previous investigations (Eklund *et al.*, 1959; Kugelberg *et al.*, 1960) have shown that the main difference between the electromyographic pattern of a flexor plantar response and that of an extensor plantar response is that the reflex plantar flexion of the great toe is associated with activity in the short hallux flexor and reciprocal inhibition of the voluntary activity in the short hallux extensor, whereas, conversely, reflex dorsiflexion of the great toe is accompanied by activity in the short hallux extensor and reciprocal inhibition of the voluntary activity in the short hallux flexor. Landau and Clare (1959) have, however, put forward the view that the flexor plantar response differs from the extensor plantar response in that the long hallux extensor is engaged in the latter but not in the former reflex type. The controversial results thus obtained in the two investigations will be discussed below.

On the basis of the results reached by Kugelberg *et al.* (1960), on painful stimulation of the plantar surface of the foot, investigations were started on pathological cases showing few pronounced or uncertain Babinski signs. In the course of the experiments it was, however, soon apparent that before being able to judge of the results obtained in abnormal cases a closer study had to be undertaken of the receptive fields and the variability normally existing; the present work gives an account of the results obtained in this investigation of normal cases.

In the present study, the latency values of the recorded bursts of activity have been determined (sect. 1). Only reflexes of shorter latencies than 200 msec. have been included. The interest has been focused on, and all conclusions drawn from, responses recordable within 100 msec. The receptive fields of the various foot and toe reflexes which could be elicited by stimulation of the plantar surface of the foot have been examined in detail under varying experimental conditions (sect. 2). Special attention has been given to the hallux movements evoked, as

well as to the border areas between the skin regions where stimulation produces hallux dorsiflexion, *viz.*, the ball of the toes, and the regions where plantar flexion of the hallux results, *viz.*, the hollow of the foot (sect. 3). The investigations have been limited to a selected material of 25 subjects who were neurologically healthy, to judge from their medical history and physical examination, and who proved to have typical and brisk flexor plantar responses. The primary aim of the work has been to establish the reflex variants that can be observed in a typical normal material under varying experimental conditions, and only secondarily to get an idea of the frequency of the different reflex variants in general in healthy humans.

METHODS

The technique employed in the experiments to be described below is essentially the same as that used by Kugelberg *et al.* (1960), and as a detailed description has been given in their work only the salient data will be given here.

Electric stimuli were applied to the skin on the plantar surface of the foot by means of a pair of needle electrodes insulated except for the tip and inserted a few millimetres apart into the horny layer of the skin. In most experiments the stimulus consisted of a series of shocks delivered over a period of 20 msec. and of a single duration of 1 msec. and a frequency of 500/sec. The maximum strength of the current was approximately 25 mA. The stimuli were experienced as a pinprick and, when they produced a reflex response, were as a rule slightly painful. Most of the experiments could, however, be carried out with stimulus strengths causing only slight discomfort.

The reflex responses obtained were recorded electromyographically. A pair of needle electrodes insulated except for the tip were inserted 1 or 2 cm. apart into each muscle. Most of the muscles studied were easily accessible to examination, but for some of them that were not so easily found the following procedure had to be adopted. In the short hallux flexor the electrodes were placed immediately medial to the tendon of the long hallux flexor, a few centimetres behind the ball, at a depth of about 1 cm. In the long hallux flexor the electrodes were inserted from the lateral side of the leg, about 5 cm. proximal to the malleoli; the muscle could then be found at a depth of about 2 cm. In the long hallux extensor and the extensor digitorum longus the electrodes were placed immediately below the respective tendons, a few centimetres proximal to the malleoli. Confirmation of the placing was obtained by the following checks:—Passive extension of the muscle should cause displacement of the electrode; voluntary contraction of the muscle should give rise to several action potentials; no activity should result on voluntary contraction of nearby muscles. When inserting the electrodes into the different muscles, great care was taken to attain the most favourable recording conditions. In this manner our previous recording technique could be considerably improved. At least as far

as the short hallux extensor and flexor are concerned, it has become possible to record contractions that are too weak to result in discernible movements and to keep the stimulus strength low enough not to make the subject exposed to the procedure averse to further cooperation.

In the following, when referring to the strength of the electromyographic reflex, this expression is used to denote the amount of activity evoked.

In addition to the electromyographic recording of the reflexes, the movements evoked have also been observed by ocular inspection. In one series of experiments they were also recorded photographically by means of a stroboscope giving a series of pictures at intervals of 50 msec. This recording was, however, abandoned as it had no advantage over the electromyographic recording plus inspection beyond giving a picture of the movements.

RESULTS

1 LATENCY VALUES OF REFLEXES STUDIED A strong painful stimulation of the plantar surface of the foot may give rise to a series of discharges in the muscle involved, of latencies varying between 50 and 500 msec. Responses of short latencies were found to be comparatively stable, whereas the later responses are varying and very susceptible to habituation. If, in a subject with brisk reflexes, a strong stimulus is applied to a skin area from which no reflex activity can be evoked in the short hallux flexor, and if the subject is instructed to bend his toes as soon as he experiences the stimulus, the latencies of the voluntary flexor activity thus obtained have been found to be highly variable from one stimulation to the other, the subject being never capable of reacting within 150 msec. and only exceptionally within 200 msec. The present work is mainly concerned with reflex responses obtained within 100 msec. and of constant latency from one stimulation to another. There is thus a broad margin between the latencies of the reflex responses studied here and the purely voluntary responses.

A threshold stimulus often results in reflex responses of comparatively long latency, and when using weak stimuli it is difficult to judge whether the recorded activity is to be considered as a reflex. A progressive increase of the stimulus strength gradually shortens the latency of the reflex up to a certain limit which differs somewhat in different individuals. The shortest latency observed for the reflexes in the short hallux flexor and extensor is 55 msec. With the present technique it is, however, as far as most subjects are concerned, impossible to obtain shorter latencies than 70 to 80 msec. These minimum latencies require strong stimuli and can often not be obtained until a strong stimulus has been repeated once or twice. The shortest latencies were observed in subjects with brisk reflexes, and in

these cases the minimum latency of the subject can often be reached without having to resort to maximum stimulus strength. In subjects with higher reflex thresholds it is generally impossible to obtain such short latencies, but it would seem as though the latency might be further reduced in these cases if stronger stimuli could be set in. As a rule, the minimum latency is slightly shorter when the hollow of the foot is stimulated than on stimulation of other areas. The reason is probably that the stimulus strength available is not sufficient to bring forth the actual minimum latency when less sensitive parts of the foot are stimulated. There is no difference in latency between a short hallux extensor reflex elicited by hallux stimulation and a short hallux flexor reflex evoked by stimulation of a part of the sole with the same reflex threshold.

The short latency values mentioned require very high conduction velocities in the reflex arc and a very short central reflex time. A determination of the afferent conduction velocity is of special interest, as this may give an idea of the types of impulses giving rise to the reflex type studied. It has, however, not been possible to make an exact determination, as no values were available as to the efferent conduction velocity and the central reflex time of the subjects examined. Hodes, Larrabee, and German (1948) have shown, however, that the efferent conduction velocity of the fibres to the short hallux flexor are not likely to exceed 60 m./sec. Kugelberg and Hagbarth (1958) have shown that the central reflex time for the abdominal reflex, which is also polysynaptic, is not likely to be below 3.5 msec. In one subject examined, with an afferent and efferent conduction distance of about 135 cm. each way, the minimum latency for the short hallux flexor reflex was 55 msec., calculating from the stimulus onset. This short latency could, however, not be obtained by a single shock but required two to five shocks at intervals of 2 msec.; the actual latency must thus be at least 2 msec. shorter than 55 and the maximum afferent conduction velocity can then be calculated to be not below 50 m./sec.

2 VARIATIONS OF REFLEXES WITH SITE AND STRENGTH OF STIMULUS The conclusions drawn in this section have mainly been based on the electromyographic recording, as the latencies of the movements evoked have not been measured. The intensity of a reflex in a certain muscle has been compared with that of an antagonist muscle while shifting the site or the strength of the stimulus. All conclusions are based on experiments in which the recording electrodes were not displaced in the course of the experiment. Under these experimental conditions, a change in the relation between the reflex intensities in the two

muscles must be identical with a change or a tendency to a change in the direction of the movement evoked.

Plantar and dorsal flexion of the great toe As has been shown previously (Kugelberg *et al.*, 1960), stimulation of the ball of the great toe always results in dorsiflexion of the toe and electrical activity in the short and the long hallux extensor but not, especially when using weak stimuli, in the short and the long hallux flexor (Fig. 1). A certain activity may, however, sometimes be observed in the short hallux flexor (sect. 3). As the stimulus is successively shifted backwards towards the hollow of the foot, vague hallux movements are evoked within a rather broad area corresponding to the ball of the foot. An electromyographic investigation reveals (see Fig. 3) that the short hallux extensor reflex is gradually reduced in this area and that there appears instead a progressively intensified reflex in the short hallux flexor. In the same way, by shifting the stimulus toward the lateral side of the sole, via the balls of the lesser toes, the short hallux extensor reflex is gradually substituted by a flexor reflex. Stimulation of the hollow of the foot or the lateral side of the sole evokes (Fig. 1) plantar flexion of the great toe and electrical activity in the short hallux flexor but not, especially when using weak stimuli, in the short hallux extensor (Kugelberg *et al.*, 1960). Sometimes, however, a certain activity can be seen in the short hallux extensor (sect. 3).

As appears from Fig. 1, there is no marked change in the activity of the long hallux extensor when the stimulus is shifted from the hallux to the hollow of the foot, *viz.*, the muscle is involved in the reflex movement both on plantar and dorsal flexion of the hallux. This seems to be due to the double function of the muscle as a dorsal flexor both at the hallux joint and the ankle joint (*cf.* Kugelberg *et al.*, 1960). To what extent a contraction of the muscle will result in dorsiflexion of the great toe and to what extent it will result in dorsiflexion of the foot probably depends on what other muscles are simultaneously engaged in the reflex movement.

Electromyographic recording in the long hallux flexor is a rather difficult undertaking, and previous attempts to record reflex activity from this muscle have not been successful. In the material studied in the present investigation it has, however, been possible to record a reflex activity in the long hallux flexor on stimulation of the medial side of the sole in a few cases under especially favourable recording conditions. In these cases the latency values were, however, about 30 to 40 msec. longer than for other reflex responses (Fig. 1). No satisfactory explanation for this has been found, but it can be established that the latency of the activity in the long hallux

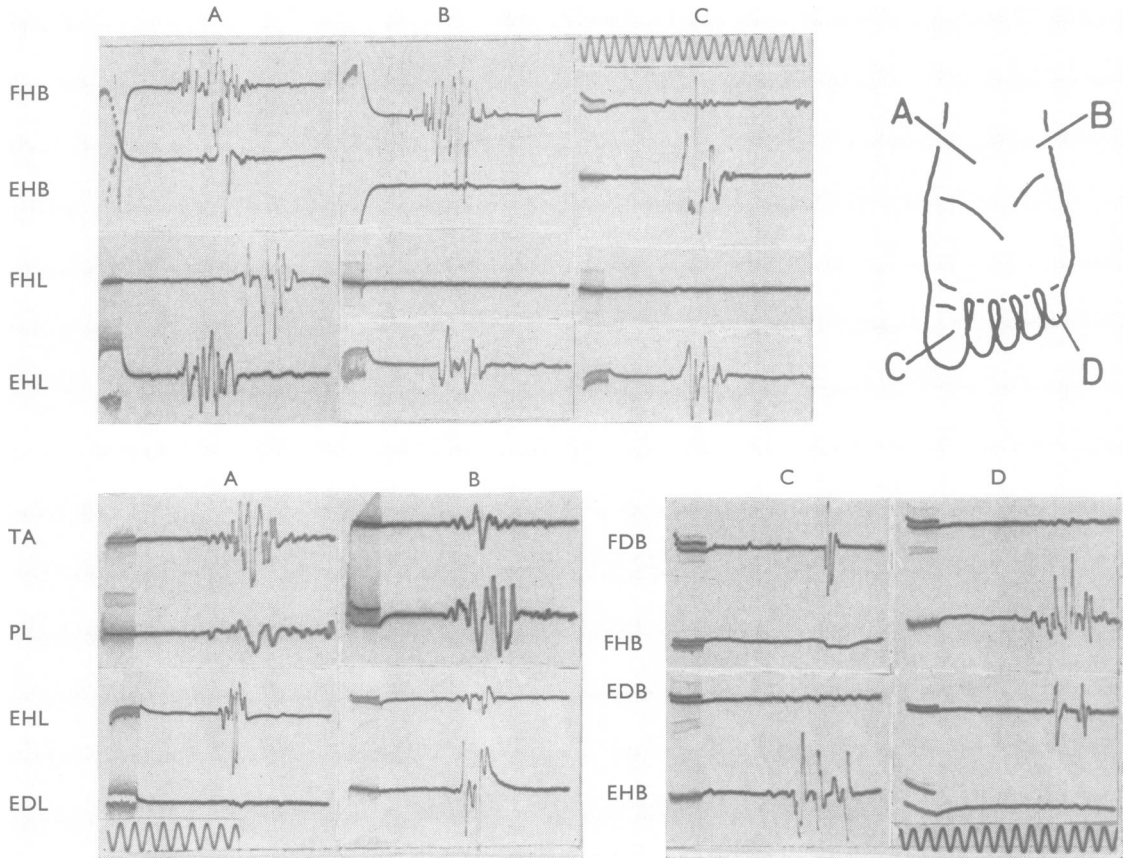


FIG. 1. Reflex obtained in one muscle is substituted by reflex in antagonist after shifting position of stimulus. Stimuli applied to points marked A, B, C, D; recordings from FHB=flexor hallucis brevis, EHB=extensor hallucis brevis, FHL=flexor hallucis longus, EHL=extensor hallucis longus, FDB=flexor digitorum brevis, EDB=extensor digitorum brevis, TA=tibialis anterior, PL=peroneus longus, EDL=extensor digitorum longus. Time 10 msec.

flexor is so short (down to 90 msec.) that it is likely to be of spinal origin. No activity in the long hallux flexor could be recorded by stimulation of the ball of the great toe, nor by stimulation of the lateral side of the foot. This is of a certain interest, as it may perhaps give a hint why the Babinski signs are practically always easier to evoke by stimulation of the lateral than of the medial side of the sole.

As appears from the foregoing, the hallux movement evoked is closely reflected in the relation between the strength of the reflexes in the short hallux flexor and extensor, respectively, as observed by simultaneous recordings in the two antagonists.

In their studies of normal and pathological plantar reflexes Landau and Clare (1959), however, regularly obtained simultaneous responses of fairly equal intensity in the short hallux flexor and extensor both on plantar and dorsal flexion of the great toe. This

may be due to the fact that they used surface electrodes; these have not nearly the same selectivity as needle electrodes but may pick up activity also from the interossei which are engaged in the reflex response independently of the direction of the hallux movement (Kugelberg *et al.*, 1960). Besides, when using surface electrodes a strong activity in the deep short hallux flexor muscle may very well appear to be weaker than a feeble response from the short hallux extensor which is more superficial and thus easier to record from. They have, also, mainly been concerned with reflexes of long latency and, as will be further mentioned below, the tendency to simultaneous activity in the short hallux flexor and extensor is more pronounced for reflexes of long than for those of short latencies.

The hallux movement evoked is of course also influenced by the activity prevailing in the strong

long hallux muscles but these are not so closely correlated to the hallux movement as are the short muscles; most likely this is due to the fact that the long muscles are also involved in the movements of the ankle.

In contrast to the results described here, Landau and Clare, on stimulation of the planta, succeeded in recording long hallux extensor activity only in connexion with the vigorous dorsiflexion of the foot and hallux obtained in pathological cases, and they drew the conclusion that 'the extensor reflex is not a different reaction from the flexor but rather a hyperactive flexor response in which the extensor hallucis longus is included by irradiation'. As, however, concentric needle electrodes were used in their experiments, their recordings emanate from a very small part of the muscle; besides, they have chiefly stimulated the lateral side of the sole, which has a higher threshold for the long hallux extensor response than has the medial side in normal cases.

In view of the great clinical importance of the reflex movement of the great toe, a special study has been performed concerning the variability of the relation between the strength of the short hallux flexor and extensor reflex (sect. 3).

Supination and pronation of the foot When a stimulus is applied to the medial side of the planta, the result is generally a tendency to supination of the foot (cf. Babinski, 1898), whereas stimulation of the lateral side often results in a tendency to pronation. As the stimulus is shifted from the medial to the lateral side of the planta a gradual shift can be observed in the intensity of the reflex responses from muscles partly involved in supination toward muscles partly involved in pronation, the former subsiding in proportion as more vigorous responses appear in the latter (Fig. 1). Reflex activity is also set up in the tibialis posterior on stimulation of the medial (but not of the lateral) side of the planta. The differences thus observed vary greatly from one individual to another. They may be large enough to be observed by mere inspection; in other cases, although not apparent to the eye, they are reflected in the electromyographic recording as a distinct change in reflex pattern as the stimulus is shifted; in still other cases no differences are recorded even in the electromyogram.

In many individuals also the toes are involved in the supination-pronation process when a stimulus is applied to the ball of the foot and especially when applied to the balls of the toes. On stimulation of the great toe, dorsiflexion of this toe and plantar flexion of the lesser toes can be observed in connexion with the general supination. On stimulation of the fifth toe, plantar flexion of the great toe and dorsiflexion of the lesser toes can be seen connected with the

general pronation. The electromyographic recording shows (Fig. 1) that when the stimulus is shifted from the first to the fifth toe the short hallux extensor reflex is substituted by a flexor reflex and the reflex in the flexor digitorum brevis is replaced by one in the extensor digitorum brevis. A distinct plantar flexion of the great toe following stimulation of the fifth toe, and a similar flexion of the lesser toes after hallux stimulation were, however, observed only in part of the material studied and mainly on application of relatively weak stimuli. The stronger the stimulus, the greater is the tendency to simultaneous dorsiflexion of all toes. That in the previous investigations dorsiflexion was a regular finding, irrespectively of which toes were stimulated (Kugelberg *et al.*, 1960), is probably due to the strong stimuli employed.

The differences in reflex responses obtained on medial and lateral stimulation are often very vague when the stimulus is set in without previous warning but distinct when the subject knows in advance when and where the stimulus is going to be applied.

Plantar and dorsal flexion of the foot As has been demonstrated previously (Eklund *et al.*, 1959; Kugelberg *et al.*, 1960; Hagbarth, 1960), stimuli applied to the ball and hollow of the foot produce dorsiflexion at the ankle joint and activity in the tibialis anterior, whereas stimuli to the posterior parts of the planta, and particularly to the plantar surface of the heel, result in plantar flexion at the ankle joint and activity in the gastrocnemius muscle.

A closer electromyographic study of these reflexes shows that the tibialis anterior reflex is most readily evoked by stimulation of the anterior and medial parts of the planta and that there is a gradual rise in reflex threshold as the stimulus is shifted toward the lateral or posterior parts of the foot. In some individuals the tibialis anterior reflex is gradually substituted by a gastrocnemius reflex as the stimulus approaches the plantar surface of the heel. In other individuals stimulation of the heel may produce either a weak gastrocnemius reflex or a weak tibialis anterior reflex, and it would seem as though the tibialis reflex is more common if the heel stimulation is preceded by a strong stimulus to the anterior part of the foot.

Influence of stimulus strength on reflex movement As shown in the previous section, the site of the stimulus determines the direction of the various components constituting the reflex movement, but the stimulus strength also plays a certain role in this connexion. It is a clinically well-known phenomenon (cf. Riddoch, 1917) that very strong and sudden stimuli applied to the planta may, even in apparently healthy individuals, provoke brisk flexor reflexes

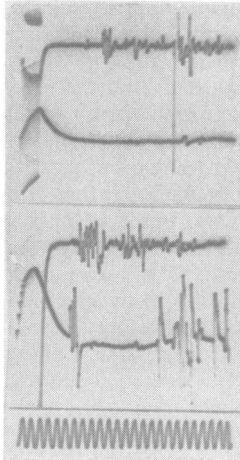


FIG. 2. *Very strong stimuli favour the EHB reflex more than the FHB reflex. Upper record result of weak, lower record of strong stimuli applied to anterior part of planta; recordings from FHB (top) and EHB (lower tracings). Time 10 msec.*

with hallux dorsiflexion, but so far evidence is lacking whether this phenomenon is of a spinal nature or not.

The reflex changes obtained by varying the strength of the electric stimulus are as a rule too small to be apparent to mere inspection but as recorded in the electromyogram they may be significant. When a stimulus is applied to an area where it gives rise to reflexes both in the short hallux flexor and extensor, it is often possible to see quite distinctly how, following a strong increase in stimulus strength, the extensor reflex increases in intensity at a faster rate than the flexor reflex (Fig. 2). Correspondingly, a very strong stimulus favours the extensor digitorum brevis reflex more than the flexor digitorum brevis reflex; it favours the tibialis anterior reflex more than the gastrocnemius reflex. As the stimulus strength is increased, the activities in muscles engaged in the pathological reflex will thus tend to be predominant.

3 VARIABILITY OF REFLEX PATTERN IN SHORT HALLUX FLEXOR AND EXTENSOR In view of their clinical importance, the reflex movements of the hallux elicited by painful stimulation of the plantar surface of the foot deserve a closer investigation. Of special interest is the variability of the reflex movements in different individuals and, also, in different recordings from one and the same individual. This variability ought to be most pronounced in the border area between the toes and the hollow of the foot. The vague movements elicited in these areas cannot be discerned by ocular inspection, but by means of electromyographic recording it is possible to follow, step by step, how the short hallux extensor reflex is gradually being substituted by a short hallux flexor reflex as the stimulus is shifted from the

hallux to the hollow of the foot and as the reflex movement changes from dorsal to plantar flexion (Fig. 3). When a stimulus gives rise to reflex activity both in the short hallux flexor and extensor, the discharges elicited in the two antagonists are hardly ever of exactly identical latency but tend to be alternating. Purely synchronous contractions occur only exceptionally or following excessively strong stimuli. However, simultaneous contractions (of latencies of 200 to 500 msec.), can often be observed after the initial reflex responses, and they may also occur as a result of strong stimuli of the usual clinical type, such as heavily dragging a pin along the planta.

In the following, the expression 'reflex pattern' will be used to denote the combination of alternating discharges obtained in the short hallux flexor and extensor by a given stimulus and by simultaneous recording in the two antagonist muscles; this reflex pattern will be presumed to give a true reflection of the hallux movement evoked.

On application of very strong stimuli there are practically always signs of activity both in the short hallux flexor and extensor; in a border area between the hallux and the hollow of the foot even weak stimulation results in a combination of flexor and extensor activity. This border area will in the following be called the 'transition zone'.

The stimulus strength necessary to obtain an electromyographic response varies with the position of the electrodes. As these experiments are based on a comparison between the thresholds of the short hallux extensor and flexor responses, the recording conditions in the two muscles have to be absolutely identical otherwise no comparison is possible between individual reflex patterns. The technique used in this study has made it possible to attain satisfactory recording conditions in this respect, and repeated experiments on a few subjects have shown that the differences caused by the recording have been very slight and of no consequence for the results.

As a rule, the initial reflex pattern has the same composition as the final pattern, but in several cases a marked difference has been observed in so far as there has been an early part within 100 msec. and a later part after 150 msec., in which later part flexor activity has been more dominant than in the early part of the reflex pattern (see Fig. 3). The following description will deal exclusively with the early part of the reflex pattern, and when this part consists of alternating discharges in the short hallux extensor and flexor it is often accidental or a matter of the recording technique whether the discharge in the extensor or the flexor has the shortest latency.

Variations in reflex pattern from one individual to another The site as well as the width of the tran-

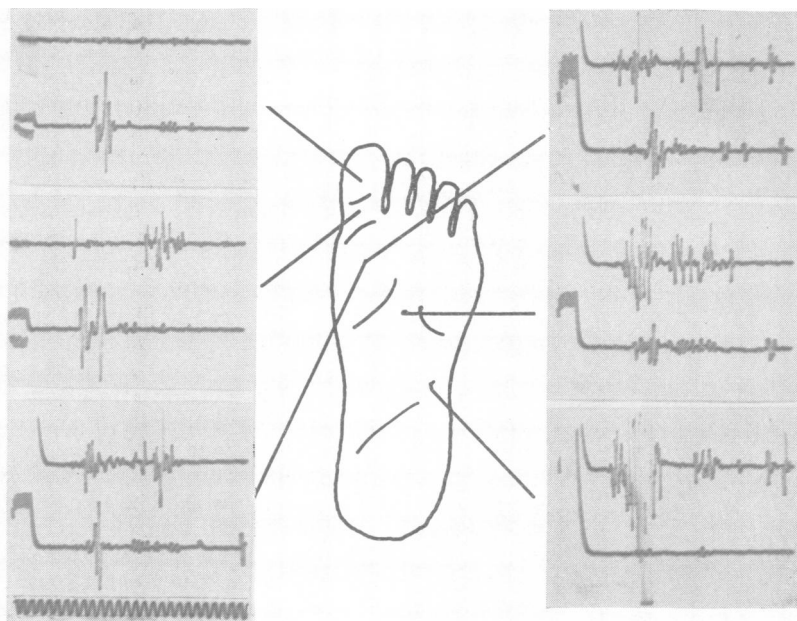


FIG. 3. *Short hallux reflex is gradually substituted by short hallux extensor reflex as stimulus is shifted from middle of planta to hallux ball. Stimuli applied as shown on the schematic drawing; recordings from FHB (top) and EHB (lower tracings). Time 10 msec.*

sition zone may vary considerably from one individual to another (cf. Fig. 4).

In one group of cases, the transition zone has a relatively far distal site, close by or even on, the hallux; in these cases there is a considerably greater tendency toward short hallux flexor activity in the hallux pattern than toward short hallux extensor activity in the pattern of the hollow of the foot. In another group, the transition zone has a relatively proximal site, close by or even behind, the ball of the foot; in these cases the tendency toward short hallux flexor activity in the hallux pattern is much less pronounced than is the tendency to short hallux extensor activity in the pattern of the hollow of the foot. The course of the zone in relation to the transverse axis of the foot may also vary from one individual to another. When the zone is located proximally, short hallux extensor activity is generally more pronounced in the pattern on stimulation of the anterior medial part of the sole than of its anterior lateral part.

In the two groups described above variations may also be observed in the width of the transition zone. Thus, in one type of case the transition zone is relatively narrow, a stimulus shift of only one or two centimetres being sufficient to change the reflex pattern; in these cases the contrast between the pattern elicited by stimulation of the hollow of the foot and that evoked by hallux stimulation is practically maximal. As appears from Fig. 4, stimulation of the hollow of the foot results in a strong, short hallux flexor reflex but none in the

extensor; hallux stimulation results in a strong, short hallux extensor reflex but none in the flexor. In another type of case the transition zone is relatively broad; it may even be necessary to move the stimulus from the hallux to the hollow of the foot before any significant change can be observed in the reflex pattern. In these cases there is also a less pronounced contrast between the reflex pattern resulting from stimulation of the hollow of the foot and that resulting from hallux stimulation. As shown in Fig. 4, the reflex pattern of the hollow of the foot includes, besides the dominant short hallux flexor activity, also signs of extensor activity; the hallux pattern includes, besides the dominant short hallux extensor activity, signs of flexor activity. There is no direct correlation between the strength of the clinical plantar reflex and the width of the transition zone, but it would seem as though remarkably broad transition zones were more common in individuals with high reflex thresholds than in those with brisk reflexes.

On an average, the width of the transition zone in the material studied has been some centimetres, and it has been located between the base of the toes and the ball of the foot. The reflex patterns depicted in Fig. 4 should be regarded as extreme; generally the plantar pattern and the hallux pattern are in the range between those shown in Fig. 4.

Variations in reflex pattern with subject's attention and expectancy The reflex pattern elicited by a given stimulus does not only differ from one individual to another but may also vary in one and the same indi-

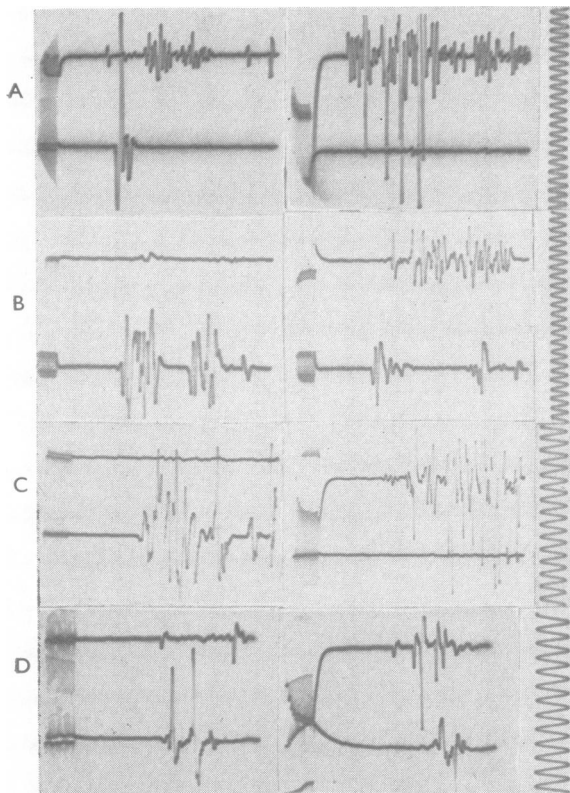


FIG. 4. Individual variations in reflex patterns. Stimuli applied to hallux ball (left-hand column) and to middle of planta (right-hand column); recordings from FHB (top) and EHB (lower tracings). Time 10 msec. Case A, subject with distally located transition zone and relatively dominant short hallux flexor reflex; case B, subject with proximally located transition zone and relatively dominant short hallux extensor reflex; case C, subject with narrow transition zone and good contrast between hallux and planta patterns; case D, subject with broad transition zone and less marked contrast between hallux and planta patterns.

vidual, as has been shown in a series of experiments using stimuli of a given strength and unchanged electrode positions throughout the experiment.

The reflex response obtained on the first, unexpected stimulation is generally strong and long-lasting. On repeated stimulation a very rapid habituation occurs, resulting in a weaker and, particularly, more brief-lasting response; even after one or two stimulations the responses however seem to be stabilized both in regard to intensity and duration, and in a series of about ten stimulations no further habituation effects can, as a rule, be observed.

The initial stimulation in a series may sometimes give rise to a reflex pattern that is atypical of the

stimulus site; as a rule, these atypical features have disappeared on the second stimulation. The tendency to atypical responses to the initial stimulation is, besides, much more pronounced when using weak than when using strong stimuli. In some subjects with very brisk reflexes a weak but pure short hallux extensor reflex may be observed as the result of a weak, scarcely painful stimulation of the hollow of the foot; or a weak but pure flexor reflex may appear on weak, scarcely painful hallux stimulation.

Except for the first stimulations in a series, no significant successive changes can be observed in the reflex patterns elicited. Some fluctuations in the composition of the pattern may, however, occur in the series; these variations are more pronounced when using comparatively weak stimuli and on stimulation in the transition zone. As appears from Fig. 5, a series of stimuli applied to this zone may give rise to reflex patterns in which either the short hallux flexor or the short hallux extensor is dominant. In a series of stimulations of the hollow of the foot or of the great toe, however, such marked differences are exceptional, very likely due to the fact that activity in the short hallux flexor or extensor, respectively, is so strongly dominant at these stimulation points that minor fluctuations in the reflex pattern do not become apparent.

If a strong hallux stimulation is interpolated in a series of stimulations in the transition zone, the subsequent reflex pattern is often characterized by a more dominant short hallux extensor activity than was the reflex pattern preceding the interpolated stimulation. A strong interpolated stimulation of the hollow of the foot results in a corresponding shift toward predominance of short hallux flexor activity. In a few easily suggestible subjects, such shifts to dominant short hallux extensor or dominant flexor activity could be evoked merely by a verbal threat to set in strong stimuli on the planta or the hallux.

It is evident that cerebral factors, such as the subject's attention or expectancy, have a certain influence on the reflex pattern. By adopting the following experimental procedure, these cerebral factors could be varied according to the intentions of the investigator and studied more systematically. The subject was instructed to concentrate his thoughts on making a certain movement with his toes without actually contracting the muscles, which could be checked by the subject himself by listening to a loud-speaker connected to the amplifier. Suddenly a relatively weak, unexpected stimulation was elicited; by exposing the subject to strong stimuli he may become averse to further cooperation in the course of the experiment. Experiments of this kind are rather difficult and have, in fact, only been performed on the author and two other subjects who were

willing and capable of a high degree of cooperation.

On stimulation in the transition zone, the short hallux extensor reflex becomes stronger and the flexor reflex weaker if the subject is intent on dorsiflexion of the great toe; in the same way, the short hallux flexor reflex becomes stronger and the extensor reflex weaker if he is intent on plantar flexion of the toe. A relatively strong short hallux extensor reflex, without any perceptible activity in the flexor, often develops when the subject is intent on dorsiflexion of the hallux, and a relatively strong short hallux flexor reflex, without any perceptible activity in the extensor, often results when the subject is intent on plantar flexion of the hallux.

If the hollow of the foot is stimulated while the subject is intent on dorsiflexion of the hallux, reflex activity develops in the short hallux extensor, either immediately preceding or immediately following upon the flexor reflex which at the same time becomes weaker (Fig. 5). Occasionally, short hallux extensor activity is predominant in the reflex pattern evoked, and in these cases a brief-lasting but distinct dorsiflexion of the hallux may also be observed.

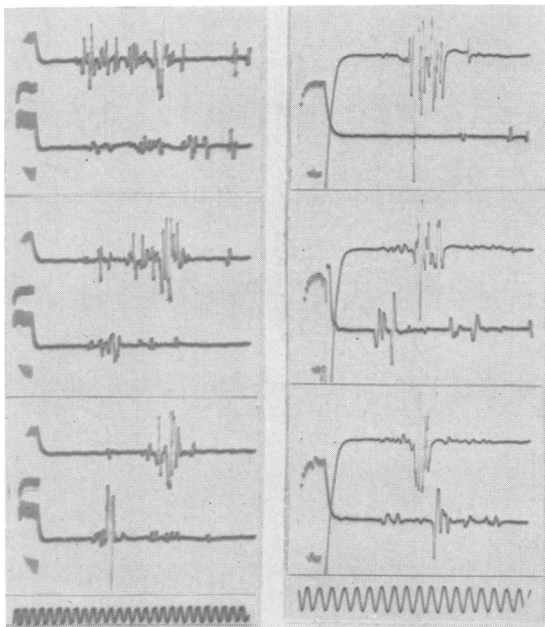


FIG. 5. Reflex pattern variations in a given individual, at given stimulus site and strength. Records from FHB (top) and EHB (lower tracings). Left-hand column shows 'spontaneous' variations in series of 10 stimuli to transition zone. Right-hand column shows normal reflex pattern on stimulation of middle of planta (upper record) and deviations resulting when the subject is intent on hallux dorsiflexion at moment of stimulation (lower records). Time 10 msec.

If the hallux is stimulated while the subject is intent on plantar flexion of this toe, reflex activity develops in the short hallux flexor side by side with the simultaneously reduced extensor reflex. In a few records, short hallux flexor activity has been slightly dominant in the reflex pattern evoked, but no distinct plantar flexion of the hallux has been discernible.

Changes in reflex pattern under voluntary contraction of the short hallux flexor or extensor In their studies of the abdominal reflex, Kugelberg and Hagbarth (1958) demonstrated that reflex responses in a muscle are facilitated by voluntary contraction of the muscle and inhibited by voluntary contraction of its antagonist. They also showed that the facilitatory effect does not increase in parallel with the strength of the voluntary contraction. As a rule, voluntary contraction of the short hallux flexor results in facilitation of the reflexes in that muscle and inhibition of reflexes in the short hallux extensor, and *vice versa*. Occasionally, however, strong contraction of the short hallux extensor does not result in any discernible facilitation of the extensor reflex, nor in inhibition of the flexor reflex. Besides, as shown above, the facilitatory and inhibitory effects may develop if the subject is intent on making a movement without actually contracting the muscles. In some experiments performed on one subject, the following observations were made. If during a maintained weak voluntary plantar flexion of the toes an unexpected hallux stimulation was set in, the short hallux extensor reflex became substantially reduced and the voluntary background activity in the short hallux flexor considerably increased. If, on the other hand, the hallux stimulation was set in during plantar flexion of the toes and while the subject expected the stimulus, the short hallux extensor reflex was practically normal and the voluntary flexor activity inhibited. It is evident that the facilitatory and inhibitory effects do not only depend on the contraction as such, and it seems as though the subject's expectancy might be of decisive importance.

DISCUSSION

When strong stimuli are applied to the sole, the earliest reflex discharges evoked are of such short latencies (down to 55 msec. for the reflexes in the short hallux flexor and extensor) that only purely spinal reflex arcs can be involved. When weaker stimuli are used the latency of the response becomes longer, but the change is gradual and even when the latency is in the vicinity of or slightly above 100 msec. the initial part of the reflex must be presumed to be of spinal origin. This does not of course exclude that the later part of the reflex may be conducted through

a cerebral reflex arc although this is hardly probable for the discharges to be discussed below, *viz.*, those recorded within 100 msec. from the onset of the stimulus. When reflex discharges of very short latencies are elicited both in the agonist and the antagonist, the briefest latency may be recorded alternatively from both muscles, and both reflexes should be considered as being fundamentally equivalent. Part of the volleys may perhaps be some kind of rebound phenomenon, but no attempts have been made to study this problem more closely, as the main subject of the present investigation has been to study the direction of the toe movement evoked, and this direction is influenced by all the discharges recorded. As mentioned above, those parts of the reflex that are of longer latency than about 150 msec. are of a more uncertain origin; of special interest are the reflexes composed of two distinctly separate parts, *viz.*, an early part of a latency between 50 and 100 msec., and a later part of a latency between 150 and 200 msec. The two parts of the reflex may represent two different responses, one of spinal and one of cerebral origin, but it may also be possible that both are spinal, the latter part being transmitted by slower afferent impulses or via more polysynaptic reflex arcs. In a reflex pattern obtained from a 'transition zone', as defined above, and composed of these two parts, short hallux flexor activity is often more dominant in the later than in the early part of the reflex. On stimulation of the anterior part of the planta by the brief electric stimulus used in the present experiments, there is often a tendency toward hallux dorsiflexion, which is only rarely seen in connexion with the long-lasting mechanical stimulation used in clinical routine work. It would seem as though the later parts of the reflex are more conspicuous in the clinical type of stimulation than when using the electric stimuli.

The latencies measured in these experiments are so short that the maximal afferent conduction velocity in the reflex arc can hardly be below 50 m./sec. (see Results). The conduction velocity of the pure pain fibres of the delta group has been calculated to be about 20 m./sec. (Gasser, 1943), and even though no exact figures are available as to the quickest conduction rate in the human pain fibres, the maximal afferent conduction velocity estimated in the present experiments might be taken as an indication that, besides pain impulses, touch impulses are also of importance for the initiation of the reflexes studied. A previous sensitization is necessary before extremely brief latencies can be recorded, and it is possible that touch impulses do not become involved to any greater extent until after sensitization.

The toe movements provoked by painful stimu-

lation of the plantar surface of the foot may be either dorsal or plantar flexion; at the ankle joint the resulting movement may be either dorsal or plantar flexion and either supination or pronation. The character of the reflex movement evoked on each single occasion is determined by the stimulus site; it represents the most appropriate movement for a withdrawal of the stimulated area from the harmful stimulus, and this functional differentiation of the reflex response must be presumed to be dependent on suprasegmental control over the spinal reflex centre (cf. Kugelberg *et al.*, 1960). That the reflex obtained on excessively strong stimulation resembles the pathological stereotyped flexor reflex may be due to the suprasegmental control not being sufficiently prevalent at these very high stimulus intensities. The more subtle integration of the reflexes into highly purposeful movements requires that the subject expects the stimulus and knows where it will be applied. The reflex mechanism is thus to some extent capable of 'learning' and is evidently under a direct influence from higher cerebral levels capable of changing the direction as well as the intensity of the reflex movements at the various joints. Of great interest in this connexion are the recent investigations on decerebrate cats by Holmqvist and Lundberg (1961), demonstrating that the flexor motoneuron activity elicited by skin stimulation of an extremity can be both facilitated and inhibited at a supraspinal level.

If, in a given subject, a given point of the foot is stimulated and the activity thus obtained is recorded simultaneously in the short hallux flexor and extensor, the result is a reflex pattern of a certain basic composition. With changes in the subject's attention and expectancy, significant changes may appear in this basic pattern, either in the form of increased flexor or increased extensor activity, and it is reasonable to presume that a still wider range of variations could be obtained by a more elaborate experimental arrangement than that used in this investigation. The range of variations is larger on weak than on strong stimulation, and it would seem as though cerebral factors played a more important role on weak than on strong stimulation, whereas the stimulus site is, relatively, more important on strong stimulation. Under certain conditions a weak stimulation applied at the middle of the planta may give rise to a reflex pattern in which short hallux extensor activity is dominant; in this connexion there is also sometimes a distinct hallux dorsiflexion, and even if it is very brief it is anyhow typical of the sign of Babinski as described by him (1896), *viz.*, hallux dorsiflexion elicited by painful stimulation of the sole. It is, however, striking how rapidly and completely such an atypical reflex pattern is corrected on

repeated stimulation, and there is nothing to suggest that a reflex pattern of a healthy individual could be permanently changed into the types of pattern seen in pathological cases (Grimby, to be published).

The results obtained from experiments on different subjects differ significantly in several respects. The range of variations of the reflex pattern obtained at a given stimulus site may be rather wide in some individuals and very narrow in other cases, but these differences may be due to psychological factors. In the basic reflex pattern obtained at each stimulus point there are, however, such pronounced individual differences, for instance in regard to the width and location of the transition zone, that it must be inferred that the organization of the reflex mechanism is not quite uniform from one individual to another. These individual variations must be due to differences in the organization of the suprasegmental control (cf. above). In the material studied, variations in the width of the transition zone are independent of its location, and the suprasegmental control must thus be presumed to occur via more than one pathway.

Although it cannot be excluded that there may have been pathological changes in the reflex mechanism of one or two of the subjects studied, such cases cannot explain the individual variations observed; the normal range of variations should rather be presumed to be considerably wider than that actually observed. The average width of the transition zone has been found to be a few centimetres, and its average location has been between the hallux base and the ball of the foot; the more extreme the deviations from these average findings, the more rare have they been in the material studied. This material is limited but the average values mentioned above might be considered as fairly representative also of a larger material chosen in the same manner, although no doubt the range of variations will then be wider. The material studied has further been selected in so far as all the subjects have had clinically typical flexor plantar responses, and healthy individuals with exceptionally proximal transition zones may have been excluded; all the subjects have also had clinically brisk reflexes, and healthy subjects with extremely broad transition zones may have been excluded, this type of transition zone being, as it seems, more common in individuals with high reflex thresholds than in those with brisk reflexes. The deviations from typical normal cases that may be observed in various pathological conditions must thus be judged with the utmost caution. It would be of great interest to fix an extreme limit for the normal variations, but this would imply testing also of individuals who are apparently healthy but have plantar responses widely deviating from the normal,

and there is no safe method to determine whether the reflex mechanisms of these individuals are actually intact.

SUMMARY

In an investigation of the skin reflexes of the foot, experiments were carried out on a group of 25 neurologically healthy subjects with brisk and typical flexor plantar responses. Painful stimuli consisting of a series of repetitive electric shocks delivered over a period of 20 msec. and of a single duration of 1 msec. and a frequency of 500/sec. were applied to various points on the skin of the plantar surface of the foot. The resulting reflex movements were observed and the discharges obtained in various muscles of the foot and lower leg were recorded electromyographically.

1 The study has mainly been limited to reflexes of shorter latency than 100 msec.; these were presumed to be of purely spinal origin. On stimulation of the hollow of the foot, the shortest latency observed for the reflexes recorded in the short hallux flexor and extensor was 55 msec. The maximal afferent conduction velocity in the reflex arc was estimated to be not below 50 m./sec.

2 As the stimulus was shifted from the hollow of the foot to the hallux ball, the hallux movement provoked gradually changed from plantar to dorsal flexion. As the stimulus was shifted from the hollow of the foot to the plantar surface of the heel, the resulting reflex ankle movement gradually changed from dorsal to plantar flexion. As the stimulus was shifted from the medial to the lateral side of the sole, the ankle movement evoked gradually changed from supination to pronation.

3 The coordinated reflex movement resulting in each single case represents a defence mechanism by which each skin area is removed from the noxious stimulus. On sudden, unexpected stimulation only the coarse features of this functional organization appear; the more subtle integration of the reflexes into highly purposeful movements requires that the subject expects the stimulus and knows where it will be applied.

4 On excessively strong stimulation, the differences in reflex responses caused by changes of the stimulus site become less pronounced, and the coordinated reflex movement evoked tends to resemble the pure flexor reflex seen in pathological cases.

The relation between the strength of the short hallux flexor and extensor reflexes, as observed in the 'reflex pattern' obtained by simultaneous electromyographic recording from the two antagonists, has proved to be a sensitive index of the hallux move-

ment elicited by the stimulus. In view of the clinical importance of the hallux movements a special study has been performed on the variability of this reflex pattern.

1 If, in a given individual, a given point of the foot is stimulated, a reflex pattern of a certain basic composition results. Fairly wide deviations from this basic pattern may result from changes in the cerebral influence on the spinal reflex centre. Thus, for instance, a stimulus applied to the hollow of the foot in healthy individuals may give rise to a reflex pattern dominated by short hallux extensor activity and even to a distinct hallux dorsiflexion. On repeated stimulation the normal reflex pattern is, however, always restored, *viz.*, short hallux flexor activity is dominant and the hallux plantar flexed.

2 The variations displayed in the reflex pattern as the locus of stimulation is varied differ significantly in more than one way from one individual to another. Thus, the boundaries between the skin areas where short hallux flexor and where short hallux extensor activity is dominant may be more or less distinct and, further, the receptive field of the short hallux extensor reflex may be relatively small

or relatively large as compared with that of the short hallux flexor reflex. It has been concluded that the organization of the suprasegmental control over the reflex centre in different individuals is not uniform and that this suprasegmental control is exerted via more than one pathway.

3 The variability of the reflex pattern in typical normal subjects has been explored, and the results obtained are intended to provide a basis for further investigations to be performed on pathological cases.

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