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EVOLUTION AS AN AETIOLOGICAL FACTOR IN FOOT DISORDERS*

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The most significant feature in man's recent evolutionary history has probably been the adoption of the upright posture, for there can be little doubt that as a direct and immediate consequence of the emancipation of the fore limb thus attained there arose an ability to explore with an unaccustomed precision, and later to utilize, whatever came within its range. This accurate examination of the surrounding world must have had a profoundly educative influence upon a brain already ripe for expansion, to which it responded in such degree that within a comparatively short geological period the skull capacity has had to increase fourfold in order to accommodate it. The rapidity (geologically speaking) with which the many adaptations of bodily structure and function necessary for permanent orthograde progression have appeared is a matter which deserves further consideration, for where change has been rapid it may be expected that stabilization will be more or less deficient and so variations of both structure and function will be frequent. The thesis of this lecture is that such variations may be mistaken for acquired pathological conditions, and may, indeed, in certain circumstances lead, as a result of failure of normal adjustment, to actual pathology. If we take the body as a whole the changes consequent upon the adoption of the upright attitude are considerable and widespread. They have possibly received too little attention; for the skeleton, the musculature, the pelvis, the thorax, the alimentary canal, the cardiovascular system—all are involved, both anatomically and physiologically, in greater or less degree. Many years ago Arbuthnot Lane applied these principles to the study of certain abdominal conditions and introduced some novel and intriguing ideas concerning the ways in which the effects of the change of gravitational axis on the support of the viscera are countered. Such conceptions are less popular than they were, but there is little doubt that his perception of the problem as primarily an evolutionary one is correct.

Demands of the Upright Mode of Progression

However this may be, the veriest novice would suspect that if any part of the body underwent more change than another in the adaptation of an originally pronograde animal for an orthograde existence it would be the foot, upon which all the demands of the new form of progression will fall. We can therefore study the human foot from this point of view with some degree of expectancy. If we possessed such complete details of the last million years of man's history as we have of some other animals—e.g., the horse—we could present a continuous picture, and our

task would be an easy one. As it is, our knowledge must be obtained in devious ways, none of which is by any means exact, so that our deductions cannot be beyond criticism, and in many ways may be little more than a creed or working hypothesis. Our three chief sources of information are: from the sparse fossil remains of man's pre-human ancestors; from a study of the variations to be noted in the feet of the existing anthropoid apes to adapt them to terrestrial progression (we may reasonably assume them to be parallel to the changes in the pre-human foot); and from a study of the changes undergone by the individual human foot during its development, although it is recognized that great reserve must be exercised in comparing ontogenetic and phylogenetic changes. Here acknowledgment must be made to Keith, Le Gros Clark, Schultz, Gregory, Dudley Morton, Wood Jones, and others whose painstaking work has enabled us to piece together the somewhat scrappy story.

Adaptive Changes in the Foot

Since evolution is a continuous process there is no particular era at which man's evolution may be stated to have started, but for our purpose it will suffice to go back to the middle of the Cenozoic Era (possibly ten to twenty million years ago), when our ancestor was a comparatively small tree-dwelling monkey which by its habit of suspending itself by its arms from overhead branches (brachiation) was already initiating itself to the vertical posture, although its feet were not as yet used for weight-bearing in this attitude.

At this stage the foot was still a prehensile structure in which the outer four toes opposed the innermost to produce the grasp; it was therefore comparable to the foot of the average pronograde monkey of to-day. Perhaps it was the abundance of available food which led to a considerable increase in bulk; but, whatever the cause, by the middle of the Miocene Period there had evolved a number of large tree apes (*Dryopithecus*), of which there are many, unfortunately incomplete, fossil remains. For animals of such bulk the habit of brachiation becomes an impossible mode of progression, and so, with the retention of the upright attitude the feet were now forced to carry a large proportion of the body weight. When the final and permanent descent to the ground occurred it is difficult to say with accuracy; possibly it was earlier than is usually accepted, but the continued increase in the weight of the animal was surely the determining factor. The early shuffling gait of pre-man, like that of the present-day anthropoids, was certainly assisted by the use of the hands; but as time went on orthograde progression became more

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perfect, the hand was completely liberated, and the feet had to sustain all the stresses and strains connected with the carriage of the whole body weight (Fig. 1).

To enter into a full description of the anatomical and physiological changes which have accompanied this evolution would require much more space than is available, but if we limit our observations to a few of the outstanding

the cost of a great loss of general utility. And so from the point of view of complexity and delicacy of structure and function the human foot must be regarded as undergoing retrogression, except in so far as any part subserves orthograde progression. As the upright posture is more and more nearly achieved the centre of gravity falls progressively further back and the main stresses and strains

FIG. 1.—Phases in the adoption of the upright posture. Note how the centre of gravity falls progressively further back.

points we shall nevertheless discover much of real practical significance. To begin with, the comparative size of the bones forming the various sections of the foot may be noted. Fig. 2 shows in outline the skeletal basis of the bones of the foot as we pass from the brachiating monkey

are thrown on the posterior half of the foot, hence the increasing size of the tarsal bones. Complementary to this the anterior half becomes less important and undergoes relative diminution; but as the weight is at the same time transferred more to the inner side, the first toe does not share in the general process of absorption, and so in man comes to rival in its forward extension the second and third toes. In the stage of evolution reached at the present time there is, as might be expected, considerable variation in the relative lengths of these digits (Fig. 3), and, insignificant as these differences might seem to be on purely morphological grounds, in practice they assume importance because of the interaction of two other factors which have simultaneously occurred.

FIG. 2.—Skeletal basis, in outline, of the anthropoid series. The second human outline has been enlarged to equal in length that of the gorilla for easier comparison of the relative proportions of the bones.

to the completely orthograde human. It reveals the following changes: (1) the progressive reduction of the anterior section, made up of metatarsals and phalanges, and the corresponding increase in the posterior section—i.e., the tarsus; (2) the change in the relative lengths of the digits, especially the reduction of the dominant third digit of the pronograde type and the increase in the size of the first (great) toe in the human foot; (3) the gradual decrease in the abduction of the first digit and its final entire incorporation in the main structure of the foot; (4) the downward and backward extension of the os calcis to form a true heel, and, as an important corollary of this, the appearance of a longitudinal arch to the foot, for it is clear that without this disposition of the os calcis there would be no arch. In addition there is a notable increase in the general rigidity of the foot to fit it for its new purpose; this may be taken as a pointer to the type of extremity which the human foot is destined to become in the future.

Reasons for the Changes

Before inquiring into the practical import of these changes it will help if we attempt to discover the reasons for their appearance. They may be regarded, one and all, as adaptations towards the perfecting of upright terrestrial progression, specializations for one particular purpose at

FIG. 3.—As the foot rises to the take-off position the weight is distributed to the metatarsal heads. Their conformation varies considerably in the human foot: a few examples of the "line of metatarsal heads" taken from radiographs of apparently normal feet are shown, to indicate the extent of the variation.

One of these factors is the incorporation of the first metatarsal and its digit into the general mass of the foot, a change consequent upon the loss of any need for prehension and opposition of the great toe as the foot became debased to a purely locomotor function. This means that the great toe, with its metatarsal, falls parallel to the others, and so differences in their relative lengths determine where the stresses will be thrown in a way that they do not when the first toe is independent of the rest of the foot.

The second factor becomes obvious when we consider the movements of the human foot under conditions of civilized life, for it is then recognized that these movements

are particularly stereotyped and quite unlike the variable movements of the feet of the anthropoid apes. That this is true is demonstrated very clearly by the observation that with an artificial foot having but two simple joints, one at the ankle and the other across the instep, the subject of an amputation can walk so well that it is often difficult to detect that there is anything unusual.

A further factor which is closely linked with the last and which tends to enhance the stereotyping of foot movements is the levelling of all surfaces with which the sole comes into contact, not only by the provision of roads, pavements, and paths, but even more so by the adoption of footwear, the rigid sole of which constitutes in effect an artificial level surface for the foot, which we carry with us much as a caterpillar tractor carries its own track to enable it to progress over rough ground. At the risk of unduly labouring this point it must be emphasized that these two factors are of aetiological importance in relation to certain foot disorders. Consider for a moment the unshod foot walking over an unprepared ground surface: at one step the ground contour is such that the weight is sustained by one part of the foot, at the next step by another. No two steps are alike, and so stresses are widely distributed among the bones and ligaments, etc. Under these conditions anatomical variations such as a long first or second metatarsal are unlikely to cause much trouble, but where each step is a precise repetition of that which went before, the stresses all fall repeatedly in the same places, so that small anatomical variations may have distressing consequences. This conception can be summarized thus: for the stereotyped movements upon prepared surfaces which upright progression in civilized life demands, the greatest efficiency will be exhibited by a foot which is also stereotyped—i.e., conforms to certain standard proportions. Such a type of foot is in the process of evolution in the modern human being, but has not yet attained its ultimate perfect adaptation for this purpose; its present form is therefore not stabilized, but is subject to anatomical (and functional) variations, some of which—e.g., short first metatarsal—render it unsuited for this mode of progression. Of course, a foot which is badly proportioned for stereotyped progression might nevertheless be efficient if employed quite naturally—i.e., unshod upon unprepared ground, conditions which practically never arise in a civilized community. This observation may dispel the doubts of those who find it difficult to credit that Nature's adjustments ever fall short of perfection; for the two artificial factors we have introduced (prepared ground surfaces and soled footwear) have been operative over much too short a time, say 4,000 years or so, for structural adaptation to have occurred, quite apart from the knowledge that civilization has completely disturbed the ordinary working of every form of natural selection.

Adaptation of the Foot to Civilized Life

Within the range of normal variations we can now examine what sort of foot is best adapted to the demands of civilized life; here we shall be guided not merely by the evolutionary indications already outlined but also by observations of the types of foot which most often fail to stand up to these demands. It seems that the great toe should take most of the strains of the "take-off" during walking; its bones and joints are relatively sturdy, and it appears on evolutionary evidence to be becoming the dominant toe of the foot. In a foot in which it is equal to or longer than the second and third it is able to perform this function perfectly, provided its incorporation into the rest of the foot has been sufficiently stabilized to prevent undue movement of the first metatarsal on the tarsus. But if, owing to the forward projection of the second and third meta-

tarsals or to a defect in the stability of the first, the strains fall upon these weaker bones, painful callosities form under their heads and other secondary effects arise, including clawing of the toes and splaying of the foot as a whole. It will be recalled that the first metatarsal is provided with a sesamoid mechanism which enables the bone to rise to the take-off position while carrying the main portion of the body weight without undue friction, and particularly without any rolling movement which would displace the head forwards. When the weight falls upon the second or third, however, there is no such mechanism, and so the heads are rolled forwards, pushing in front of them the fibro-fatty pads on which the callosities develop, together forming a conspicuous feature of this type of foot.

FIG. 4.—The gradual incorporation of the great toe into the rest of the foot. The accompanying longitudinal rotation is indicated by the position of the nails. (1) Macaque; (2) gibbon; (3) chimpanzee; (4) gorilla (lowland); (5) gorilla (highland); (6) human.

FIG. 5.

FIG. 6.

FIG. 5.—Radiograph of newly born infant's foot, showing abduction of the great toe and the wide space between that toe and the rest.

FIG. 6.—Footprint of an African native, aged 50, who had never worn footwear of any description. Note the well-marked hallux valgus, splay-foot, and obvious clawing of the toes.

At the same time, the proximal phalanx is forced into a position of dorsiflexion by the forward displacement of both the head of the bone and the fibro-fatty pads, the first stage in the development of clawed toes and hammer-toes. In these feet the radiograph shows a compensatory hypertrophy of the second metatarsal which confirms the above views.

Here, then, we have an example of a foot which on account of evolutionary maladjustment is a common cause of disability, far troubles other than those instances can be traced back to the same origin; but we pass to the effects of the second evolutionary variation—namely, the degree of incorporation of the previously abducted great toe into the foot as a whole (Fig. 4). From this point of view the most satisfactory foot for stereotyped usage seems

to be one in which the incorporation has been as thorough as possible, making the first metatarsal rigid with the rest of the foot. When, through an evolutionary shortcoming, this fails of complete achievement we have a first metatarsal which is either somewhat abducted and unstable from birth (see Fig. 5) or readily becomes so when subjected to strain. Abduction of the first metatarsal may thus be regarded as something in the nature of an atavism, a point that tends to support this view being the accompanying rotation of the bone which places it in the same position as the opposable great toe of the anthropoids or the human thumb. For two reasons the phalanges are unable to follow their metatarsal into the abducted position: first, the structures attached to the base of the proximal phalanx on its lateral aspect—i.e., ligaments and adductor muscles—have undergone evolutionary retrogressive changes which leave them too short; secondly, no form of footwear, however rational, would allow an abducted position of the toe itself. And so the stage is set for the development of the common deformity of hallux valgus. That an evolutionary aetiology of this deformity deserves consideration is perhaps made clear by certain indisputable observations: (1) The condition occurs in those who have never worn other than perfectly rational footwear and in both sexes; (2) it is much commoner in women than in men, since high heels throw the stresses on to the anterior metatarsal region, so that any evolutionary tendency here will rapidly reveal itself; (3) it is often associated with hammer-toe, which we have already suggested is due to a similar evolutionary weakness (obviously with an abducted first metatarsal the strain of the "take-off" can be no more sustained by the head of that bone than it can when the bone is not properly stabilized, as described above); (4) the toe, with its nail, is often rotated in its longitudinal axis as in the anthropoids; (5) the deformity is met with in those who have never worn footwear (Fig. 6); (6) it is almost invariably associated with a splay-foot—i.e., a greatly increased width of the foot at the metatarsal heads.

The evolutionary theory of the aetiology of hallux valgus seems to be the only one which offers a complete explanation of all these facts, and incidentally of others that are not included here.

Development of the Heel

The third evolutionary feature to which attention must be directed is the development of a true heel and the general increase in the mass of the tarsal bones, with a simultaneous shrinkage of the skeletal basis of the anterior portion of the foot. These changes are inextricably bound up with the appearance of an "arch" to the foot. The question whether the arch (or, better, triangle) is to be thought of as a functional or an architectural feature of the foot is still hotly debated. It is impossible here to enter into this discussion, but my point of view is that the arch is a permanent architectural character resulting from the backward and downward extension of the os calcis which was determined by the adoption of the upright posture. However this may be, a comparison of the proportionate sizes of the tarsal elements as we pass from pronograde to orthograde types (Fig. 7) reveals without any possibility of misinterpretation the progressive increase in the mass of the heel bones. This is necessitated by the backward displacement of the centre of gravity, as is obvious from a glance at Fig. 1. The implication would seem to be that the human foot is designed to take the main stresses and strains, both static and dynamic, on the posterior half, and so any use of the foot which deliberately throws these strains forwards is acting in direct opposition to the indications of evolution. This is the real reason why high heels lead not only to considerable disability but also to

many secondary deformities. A poor stance in which the centre of gravity falls through the anterior metatarsal region is equally likely to produce the same results.

From this it may be deduced that if one is compelled to stand upright and inactive (a circumstance to be avoided as

FIG. 7.—Diagram illustrating percentages of foot-length formed by tarsal, metatarsal, and phalangeal elements respectively. The range extends from completely pronograde (macaque) to completely orthograde (human) types.

much as possible, since it is entirely unnatural) the body should be so braced that the weight all falls on the heels, the fore part of the foot being used merely to keep the balance. This is a point to which those in charge of gymnastics, drills, etc., should pay attention. After prolonged and debilitating illnesses, operations, etc., the posture when the patient first gets up again is apt to be one in which the weight falls on the front of the foot, which, additionally weakened by the illness itself, is unfitted to sustain it and so splaying with all its consequences may result. Much the same state of affairs arises if the body weight increases rapidly, especially if the addition is abdominal, since, unless compensated for by lordosis, this also causes the centre of gravity to move forwards. It is of course true that there is normally a phase in walking when the heel is off the ground and the anterior section carries all the weight, and that this occurs equally in normal and abnormal feet, shod or unshod. This, however, does not nullify the above indictment, because in the unshod foot this action is intermittent, lasting for but a short period of the stride, whereas with a high heel the effect is maintained for a much longer period of each step. It is obvious that when we stand still a high heel or poor posture makes the effect a continuous one without respite, and this the foot is particularly incapable of sustaining.

Conclusion

We have considered but three of the evolutionary factors which play their part in the aetiology of foot disorders; there are many others which those interested might care to study, using as a guide their knowledge of the more recent events in the evolution of the human foot. My object has been to show by reference to the more outstanding examples that there is a definite influence of evolution on aetiology which may call for some revision of our accepted tenets. One sees in every branch of medicine—and foot conditions are no exception—the operation of a psychological trait which attributes every disturbance of bodily function to external factors and refuses to admit that there might be any inherent fault in the body itself.

The layman's ideas of aetiology certainly are practically always of this kind, the classical example being the mentally defective child whose parents attribute its defect to a fall out of a pram. No doubt from the point of view of human self-respect such an attitude is very admirable, but when searching for the truth we must recognize it for what it is—namely, a form of self-conceit. In the case of the feet it has become customary to place the blame for almost all disabilities and deformities (other than those patently congenital) upon footwear. That the form of the foot can be profoundly altered by restricting forces is not denied—the Chinese ladies' feet of a previous generation are sufficient evidence—nor is it proposed to exonerate the shoemaker entirely; but I feel that only when due consideration is given to such evolutionary factors as have here been instanced shall we get a true picture of the origin of many foot troubles or be able to explain their distribution among the population—well shod, badly shod, or even completely unshod. A well-developed foot, judged by evolutionary criteria, may stand up to considerable abuse, failing only when the maltreatment becomes excessive; but a badly adjusted foot may fail under the normal stresses of ordinary locomotion without any misuse whatsoever.

17-KETOSTEROID EXCRETION IN ADRENAL VIRILISM

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In an earlier publication (Broster *et al.*, 1938) we reported the results of a biochemical study in adrenal virilism and intersexuality. This was mainly concerned with the urinary excretion of androgens, and the qualitative and quantitative findings were based upon the capon method of assay of androgens. Since the completion of that work the introduction of a purely chemical procedure for the estimation of urinary ketosteroids has provided an alternative investigation method of great value in this field, with notable advantages over the biological method for the study of clinical cases, especially in regard to the ease of application and reproducibility. The enhanced facility thus afforded has rendered possible the rapid extension of our knowledge of a subject hitherto studied only with great difficulty. Such knowledge has already established some of the salient

features of adrenal virilism as they appear against a background of normal standards.

In the interest of the general reader it should be explained that the androgens—i.e., substances having male hormone activity—are derivatives of the parent hydrocarbon androstane, which has the skeleton ring structure indicated above. The term "17-ketosteroid" denotes steroid com-

pounds like the two chief androgens of urine, androsterone and transdehydroandrosterone, which have a ketonic group in position 17. Now, it has been found that these two androgens, and certain related compounds of the steroid class all possessing the keto group in position 17, give an intense red colour with meta-dinitrobenzene and potassium hydroxide, such reaction making possible the rapid estimation of the urinary 17-ketosteroids. Because in addition to androgens certain other substances are included in this reaction which are not physiologically active, the colorimetric technique is not capable of giving an exact measure of the male hormone activity of the urine. Nevertheless the assay of the collective 17-ketosteroid has potentially as much interest as has the assay of that fraction which possesses biological activity.

Agreement is reasonably good among those investigators who have attempted to define the normal limits of androgen and ketosteroid output with which to compare findings in pathological cases. Thus Callow *et al.* (1939) give 1.7 to 12.6 mg. as the daily ketosteroid output for normal women, with a mean value of 6.75, and for men 3.5 to 15 mg., with a mean of 9.05. For androgens their values are 2 to 50 I.U. for women and 6.5 to 110 I.U. for men. These same authors review the findings of other investigators, which on the whole do not differ substantially from their own. Friedgood and Whidden (1939) quote 4 to 15 mg. as the daily excretion for normal women, while Chou and Wang (1939) report results in terms of body weight, obtaining values of 1 to 3 I.U. per kg., corresponding to an absolute range of 4.3 to 21 mg. daily. In sharp contrast to these scales, Callow and his fellow workers found outputs varying from 40 to 288 mg. of ketosteroid daily in adrenal tumour cases, while Friedgood and Whidden record figures from 45 to 325 mg., and various isolated tumour cases of which clinical and biochemical details have been published have shown similarly enhanced figures. In general these are of an order which appears to place adrenal tumour cases in a category entirely separate from all other pathological cases. A group of cases classified as "hirsutism, adrenal hyperplasia" investigated by Callow (1938) showed a range of 1 to 33 mg. ketosteroid daily, while in a somewhat similar group which was composed of cases of benign hirsutism and adrenal virilism, studied by Friedgood and Whidden, the range was from 1 to 29 mg.

While these investigations have provided the broad framework for an understanding of the significance of ketosteroid determinations in respect of adrenal cases, there remains much detail to be fitted into it. In particular the relation of ketosteroid excretion to the various types of adrenogenital virilism which have now been classified clinically calls for a closer study than has hitherto been attempted, and we therefore have endeavoured, with the aid of a considerable mass of clinical material placed at our disposal, to contribute further detail to existing knowledge.

Methods

For considerations of space only the briefest indication of the technical procedure will be given, as this paper deals essentially with results on clinical cases.

All ketosteroid determinations were made upon twenty-four-hour specimens preserved with either toluene or chloroform, 25 ml. aliquots being taken for an analysis. Hydrolysis was accomplished by boiling with 3% sulphuric acid for thirty minutes; and ether, or a mixture of equal volumes of ether and petroleum ether, was used for extraction. Purification of the ethereal extracts followed the usual lines, and the final product was taken up in 0.5 ml. of alcohol. For the purpose of colorimetric estimation 0.2 ml. of the alcoholic extract was treated