MECHANICAL CONSIDERATIONS OF THE HUMAN FOOT,

WITH SPECIAL REFERENCE TO FLAT-FOOT.*

BY

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SOME time ago a man came to me with what he called a problem in mechanics. He was troubled, he said, with flat-foot, and had found great relief on making the heels of his boots higher by means of ordinary rubber heel pads. I asked him if the value of the rubber heels might not be due to the shock-absorbing qualities of rubber, and suggested experiments with leather heels of equal height. But he declined the experiments, and said he was quite certain that the elevation of the heel was the important factor, because one or two hours on his feet in low-heeled slippers brought back to him the pains of flat-foot. He asked me to investigate the mechanical conditions of the foot in order to see if raising the heel might give some mechanical advantage to those parts which maintain the arch of the foot. What I have been able to do will be seen below.

From the mechanical point of view the human foot is a structure of great complexity, so complex, in fact, as to be, in its complete form at any rate, quite beyond the power of exact mathematical treatment; mathematicians would call it a statically indeterminate structure.

By making one or two legitimate assumptions, results at least qualitative may be simply deduced. The foot may be considered replaced by a simple structure like an unsymmetrical roof truss (see Fig. 1): *AB* and *AC* represent the anterior and posterior limbs of the pedal arch, and *BC* is the tie of the truss which may be regarded as the resultant of the various ligaments and muscles which have a similar function in the foot. The points *B* and *C* represent, of course, the centres of pressure under the toes and heel respectively. Thus we replace the foot, with its numerous bones, muscles, and ligaments, by a virtual arch or truss supported against collapse by a virtual tie. It is now a matter of simple statics to calculate the variation of tension in *BC* as the heel of the truss is raised or lowered. The downward force at *A* is, of course, regarded as a constant and proportional to the weight of the man.

Fig. 1.

In the first place there are two limiting positions of the foot to be considered—the one, entirely supposititious, when the toes are raised until the posterior limb *AC* of the arch becomes vertical, the other, a case exemplified by many professional dancers, when the heel is raised so that the anterior limb *AB* becomes vertical. In both of these extreme positions there is no tension in the virtual tie of the arch. For any intermediate position there is a tension in *BC*, and the variation of this is shown graphically in Fig. 2. The abscissae of points on the curve in Fig. 2 represent in degrees the inclination of the sole of the foot to the horizontal; the angle of inclination being positive when the heel is higher than the toe and negative when lower. The ordinates of the curve represent the tensions in the virtual tie at the various angles of inclination. The scale of the ordinates is clearly quite immaterial, since the absolute tension is proportional to the weight of the man.

The important point to be observed from Fig. 2 is that the tension (what would be popularly and erroneously termed the strain) is greatest when the sole of the foot is inclined

Fig. 2.

at 23 degrees to the horizontal. (In this position the tension is about 58 per cent. of the vertical load on the foot.) When the heel is raised or lowered from this position the tension is decreased. Thus, if the normal inclination of the foot were 23 degrees, then raising the heel would lessen the tension; but so also would lowering the heel, and this is distinctly inconsistent with the opening sentences of this paper.

It is to be remembered that the curve of Fig. 2 is deduced from a simple structure very different in detail from the foot which it is assumed to represent, and it might be supposed that the inclination of 23 degrees is not the exact angle of maximum tension in the actual foot. I have considered the chief elements which render the foot mechanically different from our simple roof truss model, such as a slight shifting of the astragalus and the finite curvature of the ends of the metatarsals and of the inferior surface of the os calcis. But these factors do not produce any material alteration in the results shown by Fig. 2. Thus the angle, at which maximum tension occurs in the foot must be about 23 degrees. In Fig. 3 a boot is drawn in which the foot sole is at 23 degrees to the ground, and it will be seen to have a much higher heel than any ordinary man's boot. Thus raising the heel of the ordinary man's boot would have the effect of increasing instead of decreasing the tension in the supporting tissues. It is fitting to remark here that the boot shown in Fig. 3 is quite an average woman's boot, and we are led to wonder if women ordinarily wear boots which impose the maximum tension in the supporting tissues.

Fig. 3.

From the two preceding paragraphs it would appear that raising the boot heel could not in general have a beneficial influence in cases of incipient flat-foot. This conclusion is, however, only partly justifiable because our investigation has been purely statical and cannot take account of the foot in motion. On the other hand, flat-foot mostly occurs in people who do a great deal of standing, so that it might seem rational to suppose that the causes producing the trouble are statical. These results are in nowise affected by considerations of muscular tone except in the sense of corroboration. For if the muscles become flaccid the effect would be to increase the stress in the large ligamentous fascia at the sole of the foot and in fact to approach more nearly the statical conditions of the roof truss model.

So much, then, for statics. When we consider the foot in motion there are reasons why raising the heel might be advantageous. In the first place raising the heel must bring a greater proportion of the load on the anterior limb of the arch (see Fig. 4, where the maximum force in the anterior limb occurs when the inclination is 66° and is then equal to the vertical load—the ballet dancer condition). Now since the anterior portion of the foot is much more resilient than the other, there is every reason to believe that the dynamical stresses in the other parts of the foot would be reduced; speaking generally the momentum of the descending masses is destroyed in a longer time and thus the impulsive force is less. There

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is also another consideration: anyone who observes pedestrians in a city thoroughfare will see at once a difference in the gait of those wearing high heels and

Fig. 4.

those wearing low; the high-heeled person seems to the eye to step more lightly, and this is confirmed by the ear of one who sits at a window in a quiet street and listens to the steps of the passers-by. This lightness of step artificially induced by the high heel involves a greater proportional stress on the anterior parts of the foot, which are, of course, supported by some of the calf muscles (tibialis posticus, etc.), and this would probably tend to maintain a degree of tone in these muscles, and almost certainly lessen the stress in the ligamentous fascia. Yet further, in the action of walking, the heel is raised largely by the action of the gastrocnemius. This muscle pulls on the os calcis, which in turn pulls on the ligamentous fascia. If the lifting action begins from a high heel, it is obvious that the stress in the ligamentous fascia due to this part of the motion must be less, for the weight of the body has then less moment about the toes, or, in less technical language, a smaller leverage.

Why the modern boot has been evolved with a heel thicker than the sole is a matter for speculation. The vanity of increased stature cannot be alone responsible, nor the advantages in raising the wearer out of the wet. The obvious advantage of a high heel in ascending a hill is more than neutralized in descending. Probably the reduction of jar on the heel and spine is an important factor; a high heel is capable of storing more strain energy than a low one. Thus it should not only lessen the shocks on the human frame, but, other things being the same, it will not be so highly stressed, and should thus last longer. This will be clearly grasped by those who understand why a wax candle may be projected through the panel of a door. The jarring action on the heel is easily perceived: by walking on hard pavement in thinly-soled gymnasium shoes, taking long strides, so as to bring the heel down first.

An interesting paper by Mr. Dennis Cotterill on the treatment of flat-foot appeared in the *Edinburgh Medical Journal* of 1912.* In this paper the method described and recommended is that due to Mr. Robert Jones, of Liverpool, who, following Mr. Thomas, modifies the boots of the patient, making the soles and heels inclined transversely and in opposite directions. By this means and general exhortation the patient is induced to walk with his feet parallel, or nearly so. The argument for this method is practically entirely statical—namely, that by wedging over the boot a greater proportion of the load is thrown on to the shorter and stronger arches at the outside of the foot, and by inclining the toes inwards the resultant or virtual anterior limb of the pedal arch is shorter. These notions are, as far as they go, quite correct, but it would be irrational to suppose that the great majority of civilized people walk with out-turned feet for no good reason. By splaying the feet to a reasonable extent the base of support is widened, lateral stability is increased, and the control is much better; that is why a Swedish gymnastics instructor always recommends his pupils to land from a high jump with the feet inclined at 90 degrees so as to lessen the liability to spraining the ankle.

It is extremely difficult to see how purely statical effects could produce any appreciable benefit with the

system recommended by Mr. Cotterill. The changes of stress consequent on such small changes of form would be very small indeed. Thus, as in the method of raising the heel, one is compelled to reject a statical explanation as insufficient. In the method of the high heel there are plausible dynamical considerations which might account for appreciable benefit to the patient, but the method of wedging the foot over is hard to justify dynamically. The only factor to account for the admitted efficacy of the method seems to be that of induced muscular tension, and this, if tenable, supports the employment of high heels too. Wedging the foot over and turning the toes in would induce a contraction of the tibialis posticus, and this would support the astragalus and the arch of the foot. Similarly, since by raising the heel the angles between the foot sole and the toes and between the foot sole and the tibia are both increased, the flexors of the foot would be brought into more active employment, and liability to flat-foot lessened.

It must not be thought that this article recommends the use of high heels universally. For long distance walking or rough country walking high heels would be absurd, because of the short strides which must be taken if the balance is to be convenient and sure. There is also the undoubted difficulty of avoiding undue pressure and constraint on the anterior part of the foot, but that is the bootmaker's problem. Our main conclusion is this, that for the ordinary inactive life of the drawing-room, office, and shop, high-heeled boots and shoes may be advantageous in giving to the feet a pleasant, braced-up feeling, quite different from that enjoyed or suffered by those who slither about in heel-less slippers.

Migrations from one to another branch of science are usually very difficult unless one has the advantage of expert help in those departments not one's own. In connexion with this inquiry I have been especially fortunate. To Mr. A. H. Miller, M.A., M.D., I am indebted for the suggestion of the problem, and to Mr. R. Cattley, M.B., B.Sc., for many instructive and interesting conversations. Mr. J. Kay Jamieson, M.B., C.M., Professor of Anatomy in the University of Leeds, took great trouble in making clear to me the essential structure of the foot, and Mr. J. C. Brash, M.A., M.B., B.Sc., Demonstrator of Anatomy in the University of Leeds, not only discussed the matter on every occasion most willingly, but dissected a foot for my especial benefit and instruction. These gentlemen I heartily thank.

DISCUSSION.

Mr. ROBERT JONES stated that the problem of flat-foot could not be solved merely by attention to the height of the heels. Undoubtedly certain cases of painful feet were alleviated by wearing high-heeled boots, and, furthermore, the use of sandals had been a factor in the production of flat-feet in children. High heels, however, tended to flatten the transverse arch, and to produce metatarsalgia, and failed in supplying the development of the muscles of the sole. The pain complained of by people changing suddenly from wearing high heels to wearing low ones was real, but it was equally true that pain was as marked when the low heels were suddenly substituted by high ones. Mr. Jones doubted the improvement in walk spoken of by Mr. Rowell as brought about by high heels. Nor did he agree that the abducted foot gait should be encouraged. Valgus could be artificially produced by training children to walk with their toes out-turned, and for this error the dancing mistress was largely responsible. The eversion of the foot was a complication which could only be met by so altering the footgear that body weight became transferred from the inner to the outer side of the tarsus. This relieved the ligaments and muscles of the sole from strain, and relaxed the internal lateral ligament of the ankle. In a condition such as flat-foot it was impossible to work out a code of treatment by dynamics without studying the variants that played a part in the problem. For the cure of the condition it was fundamental that the feet should be parallel when walking, that the walk should be heel and toe; that body weight should be deflected from the inner side, and that exercises should be practised, designed to strengthen the invertors of the foot.

* Tilting the Soles of the Boots and its Use as a Means of Treatment in various Common Conditions. *Edinburgh Medical Journal*, N.S., viii, 1912, p. 111, et seq. My best thanks are due to Mr. J. C. Brash for having brought this paper to my notice.