The Shape of the Equine Hoof

by
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The hoof[2] of the horse has evolved over millions of years (about 50 million years, in fact), giving a selective advantage to equids in the environment in which they lived. It is apparent that the hooves of all modern Equids conform to a basic pattern, and we can assume that pattern is optimum, or nearly so. There are variations of that basic pattern, however, and it is the basic premise of this analysis that those variations in different horses in different environments can be understood as a function of the forces exerted on the hoof and the surfaces upon which the animals are habitually moving and standing.

The analysis concerns the fore and hind hooves of barefooted equids: horse, zebra, and onager. There is no consideration of shoeing here: another essay on this site addresses that situation. Also, there is no discussion of the several shoeing and nonshoeing methods widely discussed and employed in the present day.

While one can gain an overall understanding of the shaping of the bare hoof without mathematical mechanics, a clearer grasp can be had by consideration of the bare minimum mechanics given in the Appendix.

The shape of the hoof has been considered by several authors and references are provided in the Bibliography.

Surfaces

The feral horse of the American West, the feral horses (brumbies) of Australia, and the zebra experience a variety of surfaces: hard and inelastic with a variably loose, gritty surface, sandy desert, and packed sod. The hard, inelastic surface is not unlike, in many respects, a harness racetrack.

Barefooted domestic horses can experience a variety of surfaces as well, including sod of varying degrees of compaction and elasticity. The feral horses (so-called ponies) of the barrier islands of the East coast of the United States generally experience soft, marshy footing, but those conditions change during droughts as discussed later.

In order to study the interaction of the hoof and the surface I have broadly categorized the different types of soil and surface conditions. The basic material is soil which is disintegrated rock. The physical character of the soil and surface is a complex function of **soil, organic matter** (largely plant roots), **water**, and **grass cover**. This physical interaction - elasticity/roughness **(ER)** - is sketched in **Figure 1**.

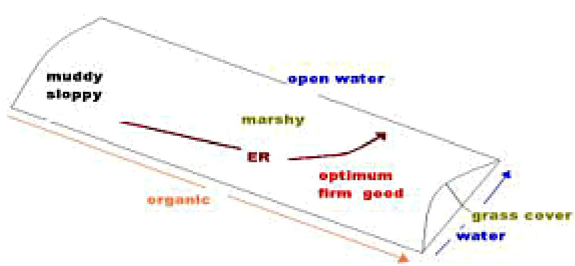

Figure 1

At the front left of the figure are arid conditions: little or no water, organic matter in the soil, or grass cover. Grass cover means the area covered by grass and not the length of the grass. One can follow the ER trajectory as it moves to the right and upward; that is, gaining organic matter, water, and grass cover. Many of the conditions experienced by horses can be deduced from this illustration. If, for example, one goes straight "uphill" from the lower left "aridity," increasing the amount of water because of heavy rainfall, for example, the surface becomes muddy and sloppy. The grass cover increases as well in the figure but in the real world that would come later after the heavy rainfall. I leave it to the reader to construct other scenarios, remembering that this is a model, and real world conditions must be kept in mind (as I did with mud before grass growth in the example).

Consider further: if a period of adequate rainfall is followed by drought, the initially elastic sod gradually changes to inelastic sod and then to inelastic and gritty as the grass cover disappears. In effect the hoof follows the ER trajectory in the opposite direction, from right to left. One can accomplish this, as well, by moving a horse from a sod pasture to a dry paddock. The important point is that the hoof shape will change because of the change of soil conditions. We next look at how that change occurs.

Hoof Wear

The wearing of the ***bearing edge of the hoof wall*** *occurs because of friction between that bearing edge and the ground surface.*

First we consider friction, per se. There are three kinds of friction: **static, sliding, and rolling.** The equation for static and sliding friction is:

$$\mathbf{H = \mu F}$$

H is friction. **F** is the vertical ground reaction force which is the weight of the horse being borne by a given foot whether static or dynamic. The coefficient of friction is μ which is a measure of the roughness or stickiness of the ground surface. Sliding friction is somewhat less than static friction. Rolling friction is the least of all with a slightly different equation incorporating the radius of the rolling.

Wear is a function of friction and friction **(H)** is a function of the weight of the horse **(F)** on the foot and the roughness of the surface **(μ)**. Obviously frictional wearing will be increased as either the weight of the horse (and rider or draft) increases or the roughness, abrasiveness of the surface increases.

At the slow walk, the hoof usually contacts the surface over the whole bearing edge of the hoof wall; that is, the foot impacts flat-footed. The entire bearing edge experiences primarily static friction with a variable amount of sliding depending upon the surface. That is, the hard, dry, gritty surface will allow some sliding while a moist, elastic surface would not. In any case the amount of sliding friction is small compared to the static friction.

As the walk is speeded up or the horse shifts to a faster gait, sliding friction becomes more important. As the animal moves faster the heel of the hoof usually impacts first and is subjected to a brief period of rolling friction as the quarters and finally the toe portions of the bearing edge come successively, serially unto the surface, **Figure 2**.

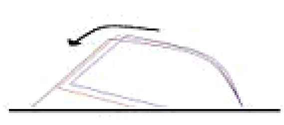

Figure 2

The initial impact on the heels is the blue, then the red and finally the black as the toe reaches the surface. The frictional wearing, sliding and static, increases as each succeeding segment of the hoof reaches the surface because **F** increases from the instant of impact until midsupport and decreases again until lift-off, **Figure A4**. The frictional wearing increases, then, until midsupport, and the hoof is fully on the ground before that. The frictional wearing is sliding with perhaps some rolling as the segment of the bearing edge contacts the surface and becomes static immediately after as the next segment toward the toe reaches the ground.

It is important to recognize that as the vertical loading of the hoof increases during the first half of support, the hoof wall itself will be compressed by the load, contributing to this caterpillar-like tread contact of the bearing edge of the wall with the surface.

The result is well-known and shown in **Figures 3** and **4**, next:

Figure 3

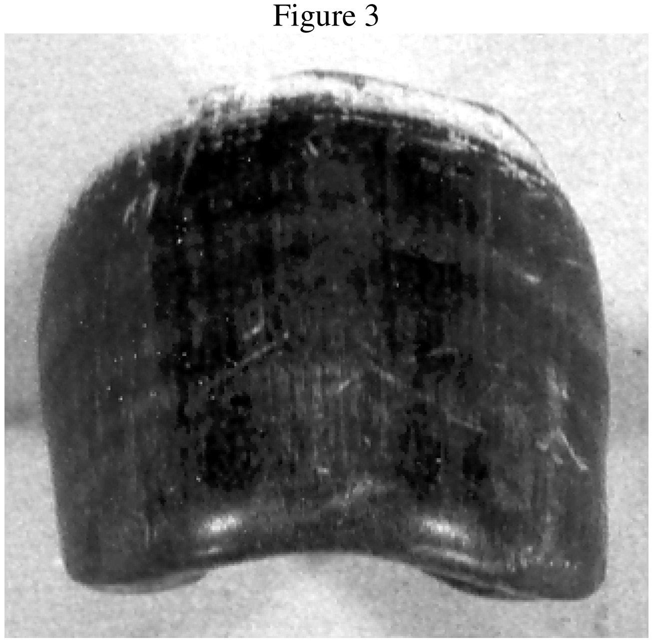

Figure 4

These are lateral and dorsal views of the hoof of a zebra foal, showing the wearing of the quarters and the toe. It is important to note, at this point, that the concavity seen in the lateral view is only to be seen when the foot is not bearing dynamic weight (that is, the weight on the foot when moving which is about

1.8 times greater than the static, standing still weight). When the foot is on the ground and experiencing dynamic weight, the entire bearing edge of the hoof wall is in contact with the surface[3]. If this were not true, the wall would not wear the way it does. The same is generally true for the concavity at the toe, but the rounding off there may still be evident even when the foot is loaded.

Examine **Figure 5**, the imprint of a bare foot on a firm surface with a loose, sandy surface layer (harness horse training track). The heels have cut down into the loose surface material while that material is compacted beneath the bearing edge of the quarters. The rolling over at the toe during lift-off has scooped out the loose sandy dirt and, so, obliterated the compaction of the surface which had continued from the quarters around to the toe before lift-off occurred.

Figure 5

It is clear that there is greater wearing of the quarters and the toe than of the heels. The wearing of the toe is easily explained by the rolling on the surface at lift-off. As the hoof rolls over the toe during lift-off, the bearing edge comes off the surface last in the center of the toe, so that the central part of the toe is rolling and sliding longer than the more abaxial part of the toe, **Figure 6**. Also, as the toe rolls it pushes loose material backward into a mound and experiences greater friction as it rolls through this mound of gritty material, **Figure 7**.

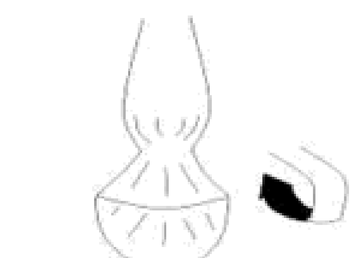

Figure 6

Figure 7

The greater wearing of the quarters, giving the concave profile of the unloaded foot, occurs because of the increasing **F** (the force acting on the foot as the bearing edge of the hoof wall is coming into contact with the surface). Once the bearing edge is fully in contact with the surface, there is only static friction (very slight sliding may occur under some circumstances) and no further differential wearing until the rolling lift-off. The increase and decrease of **F** during the step is shown schematically in **Figure A4**.

The inner and outer edges of the hoof wall are rounded off, **Figure 3**, because of the gritty surface material through which the wall moves as it impacts and slides into the surface.

The wearing of the toe automatically allows the toe to "drop down" as shown in **Figure 8**, the black representing the hoof material worn away, giving the larger hoof angle characteristic of the feral hoof on rough, abrasive surfaces. Ovnicek and Jackson both found the hoof angles, fore and hind, to be about 50^{o} to 60^{o} for feral horses and my measurements of bare foot domestic horses, zebras, and one onager were the same.

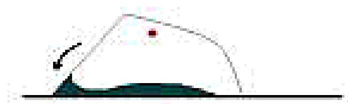

Figure 8

These wearing effects on an inelastic, gritty surface are qualitatively the same but quantitatively greater on a predominantly sandy or loose sandy loam (such as the cushion of a dirt racetrack).

Barefooted horses on less abrasive surface conditions, such as pastures in the eastern part of the United states, will have the concavity of the quarters though to a lesser extent than with the gritty, abrasive surface while there may be little or no wearing of the toe There are several reasons: 1. on a hard, dry pasture the grass cover provides less frictional wearing; 2. there is less tendency to mound up gritty material behind the rolling toe; 3. on near optimal surfaces the toe can rotate into the softer moist surface.

Hood *et al* (1997) observed that the highest pressure contact (force) was at both heels and either side of the toe when barefooted horse were first taken from pasture to stand on a rubber-covered, pressure-sensitive mat[4]. That is not inconsistent with what has been said here since the horses were standing still, not moving and experiencing dynamic loading of the foot (as already noted the dynamic load is about 1.8 times the static load).

Hood *et al* also noted that the concavity of the quarters disappeared if barefooted horses were moved to a concrete surface for seven days and that there was more contact of the sole with the surface after those seven days. This is similar to the foot (fig.2(c) of Ovnicek *et al* (1995) which had adapted to shale and granite surfaces. Ovnicek's figure shows the concavity of the quarters to be expected with the loose surface material on natural shale and granite as opposed to smooth concrete. As well the horses on concrete were no doubt standing or walking and would, therefore, not been experiencing the heel first contact necessary for the quarter and toe wearing being discussed here. These horses did, however, wear the toe as would expected with even walking speed rolling of the toe on concrete. The increased area of sole contact with the surface is readily explained by the rapid wearing away of the hoof wall, bringing the sole down to the concrete surface.

With the generally marshy, boggy surfaces experienced by barrier island ponies and other horses during prolonged wet periods, the hoof is softer, more flexible, and tends to flatten out. The bearing edge of the hoof wall does not wear at an appreciable rate and breaks up irregularly once it has extended sufficiently beyond the level of the sole. As such an animal moves onto a harder surface, or the surface becomes harder, the wall becomes drier and toughens, and the heel/toe wearing appears to the degree appropriate for the roughness of the surface. This has been observed in Assateague Island ponies over a number of years, the broken up feet of wet years being replaced by quarter/toe wearing in drier years.

Figure 9 attempts to summarize the shape of the hoof with different surface conditions with the understanding that there are many intermediate stages among those shown. **The shape of the hooves of any given horse is largely a function of μ, the coefficient of friction of the habitual surface.**

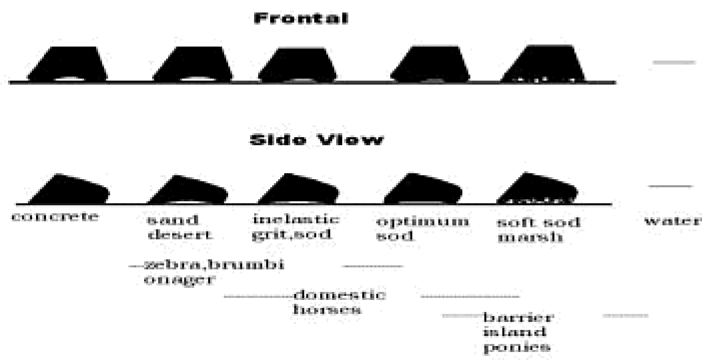

Figure 9

Sole Pressure and Weight Bearing

It is generally recognized, and my observation, that the initial impact of the bare foot with the surface and the major weight-bearing is on the bearing edge of the hoof wall, including the bars. The imprint of frog and sole on the surface (given that there is sufficient loose material on the surface to permit such an imprint) occurs after impact as the vertical force on the foot approaches maximum at midsupport, **Figure 10**.

Figure 10: On this sandy surface the imprint of sole and frog is clearly apparent

No doubt the frog and sole can share the weight-bearing once the bearing edge of the hoof wall is fully loaded, particularly in marshy, sandy, or sandy loam conditions. Loose material on the surface tends to pile up under the hoof as the bearing edge plows down through it. There certainly can and will be frictional wearing of the sole and frog, under these conditions with compensatory thickening of the cornified epidermis (callus) as a result. Such thickening, however, does not imply that the sole and frog are primary or major weight-bearing structures as sometimes claimed.

Digital Cushion

The role of the digital cushion has been long debated, often in connection with so-called "frog pressure," Bowker *et al* (1998). Dyhre-Poulsen *et al* (1994) showed that the pressure in the cushion dropped during weight-bearing and suggested this was caused by expansion of the hoof without pressure being exerted on the cushion itself. They showed (their figures 2 and 3) that the pressure in the cushion builds up relatively slowly with the foot off the ground and suddenly released as the foot is loaded. This is characteristic of a **relaxation oscillation**, Thompson and Stewart (1986). Dyhre-Poulsen saw an almost immediate, within 30 milliseconds, drop of pressure in the cushion when the foot impacted the surface. My interpretation of this data is that this pressure drop occurred because of squeezing of the extensive venous plexuses in the corium of the hoof, Storch (1894). This squeezing, in turn, forces blood out of the cushion to refill those emptied veins and that explains the drop of pressure in the cushion itself. The pressure drop was largest dorsally and less toward the palmar aspect of the cushion, indicating less squeezing out of blood from the frog area of the solar surface and more under the distal phalanx during the first 30 milliseconds after the impact of the hoof with the surface. This supports the idea that the frog and cushion are not significantly loaded during the initial impact of the foot with the surface.

The value of a relaxation oscillation is that it is: "…ideally suited to control systems in which an input stimulus should produce a response of fixed amplitude but adaptable frequency or repetition rate."(Thompson and Stewart) This is exactly what is needed in the case of the energy absorption action of venous blood movement in the foot.

Dyhre-Poulsen's measurements were done at the walk, trot, and in a standing pony. At greater velocities one might expect larger pressure drops in the cushion as the pastern pressed down, forcing more blood from the cushion. The drop in pressure in the digital cushion, then, is not because the cushion is not being compressed but because compression is forcing blood out of the cushion into the efferent veins. At slower gaits the cushion is compressed by outward expansion of the hoof wall while at faster gaits both outward expansion and the downward pressure of the pastern are causing the compression.

Closure

Certainly one does not ignore the inherent, genetic contribution of hoof wall strength and friction resistance. There is, however, little information available on these factors. Nor can one overlook the role of nutrition in the quality of hoof horn in relation to strength and friction resistance. Again, however, little is presently known. The fact remains, however, that the qualitative wearing pattern of the bare foot is primarily related to friction, the effects of which can be either quantitatively increased or decreased by the genetically and nutritionally determined quality of the horn of the hoof.

This study does not and cannot address the question of how horses should be shod or not shod. Another essay on this site does address some aspects of shoeing.

Footnotes

1: The material in this essay was originally published in the Online Journal of Veterinary Research. It has been extensively rewritten and reillustrated for this site.

2: The foot refers to the digit from fetlock to bearing surface of the hoof wall. The hoof is the horny encasement of the distal end of the foot.

3: The so-called four point shoeing method is based on the results of placing unloaded, inked feral bare feet on a plank and noting that four ink spots were made on the plank one at each heel and on either side of the concavity at the toe. Since this DOES NOT represent the actual dynamic contact of the bearing edge of the hoof wall with the surface, the basic theory of four point shoeing is flawed.

4: You will recognize this as the same pattern seen with the unloaded feral hoof.

Appendix

I know this looks forbidding, but it really is not… if you are willing to take an hour or so to study it. There are two types of force operating on the foot: linear forces operating in straight lines and moments which are turning or twisting movements. The equations given are equilibrium equations showing that when the relevant forces, linear or moment, are balanced that they sum to zero.

Moments

The important moments acting around the coffin joint in the standing horse are shown in **Figure A1** and **Equation 1**:

Equation 1: **DFc-(Fa+CEb)=0**

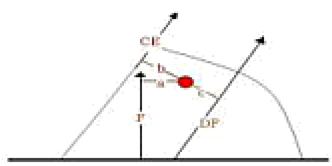

Figure A1

By convention a counterclockwise moment is positive (thus: **DFc**) and a clockwise moment is negative (thus: **-Fa, -CEb**). **DF** is the tensile force in the deep flexor tendon; **F** is the ground reaction force acting on the hoof; **CE** is the tensile force in the combined common extensor tendon and extensor branches of the suspensory ligament. The lower case letters are the *moment arms* of those linear forces and are perpendiculars from the forces to the center of rotation (the red circle) in the distal end of the middle phalanx.

We construct the equilibrium equation and figure for the linear forces, **Figure A2, Equation 2**:

Equation 2: **F+CE+DF-W=0**

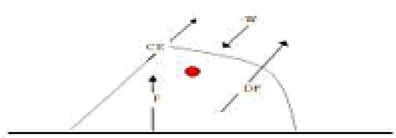

Figure A2

Horn Tubules

We now look at the orientation of the horn tubules in the hoof wall as another aspect of the shape of the hoof.

By convention the upward forces, **F**, **CE**, and **DF** are positive and the equal and opposite force, **-W**, is negative.

Now by the trickery of vector mechanics we can move these force vectors in the plane so long as their directions do not change. In **Figure A3 F, CE,** and **DF** have been so moved and added together by vector addition to give the final vector, W, which is equal in amount and opposite in direction to the body weight vector, **-W**.

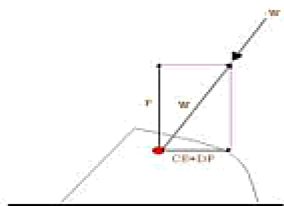

Figure A3

It has been shown that the horn tubules of the hoof wall are normally parallel to the force vectors **W** and **-W**, and that those tubules and the hoof wall will be strongest when the tubules are in line with the resultant force, Rooney (1998). That analysis is not repeated in detail here.

As the horse moves the linear forces change in direction and amount, but no new forces appear and none disappear. The vertical ground reaction force, **F**, appears when the foot impacts with the surface, increases to a maximum at midsupport (halfway through the step) and decreases again to lift-off. This is shown schematically in **Figure A4**.

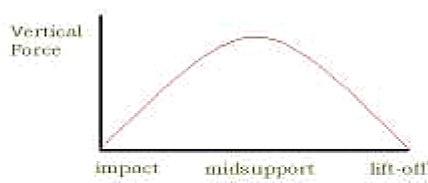

Figure A4

As **F** increases clearly the vector **W** would change direction and not remain in parallel with the horn tubules. As **F** increases, however, so does **CE+DF**, and the resultant force **W** will stay parallel to the tubules. In effect the parallelogram of **Figure A3** does not change shape, **W** remains parallel to the tubules, because as **F** increases, **CE+DF** increases in phase with it.

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