Biomechanical Efficiency
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The horse is an amazing athlete, with great speed and endurance considering his body size and weight. For the past 20 years, researchers have evaluated what makes the equine locomotive system so efficient for racing and other strenuous performance activities. But why are some horses better, more efficient movers than others?

Hilary Clayton, BVMS, PhD, Department of Large Animal Clinical Sciences, Michigan State University, has done extensive research evaluating equine locomotion. She defines biomechanical efficiency as the efficiency of converting chemical energy from the horse's food into mechanical energy as locomotion. The goal is for the limbs to move the animal as far or as fast as possible for the smallest amount of food intake (like a fuel-efficient vehicle). Unique structural arrangements make leg movement more efficient, such as being able to use elastic springs (tendons) instead of having to use fuel energy in the muscles. Using the leverage of the leg is another factor.

Energy-Efficient Leg Movement

One thing that aids biomechanical efficiency is the way the horse swings his legs forward. "Energy is needed to accelerate the leg and then decelerate it before it hits the ground," says Clayton. "If you envision the horse on a treadmill, where the 'ground' is moving but the horse's body is not, the leg rotates backward underneath the stationary body as the hoof is carried back by the moving treadmill belt. He pushes off against the treadmill, then accelerates the limb through the air so that it overtakes his stationary body, then decelerates it again relative to his body before it hits the treadmill belt."

When the horse is traveling over ground rather than on a treadmill, the hoof is stationary when it is on the ground and the body keeps moving forward. Then in the swing phase he must move the whole leg forward faster than his body is moving before he places his foot on the ground again.

"The amount of energy he uses to thrust off and swing the leg is an important factor," says Clayton. "At the middle of its swing phase, the hoof will be moving forward at a little more than double the horse's forward velocity. So if the horse is galloping at 40 miles per hour, the hoof is going close to 100 miles per hour during the swing phase. This includes the forward velocity of the horse's body. There are two components to the speed the hoof is moving--the speed it is moving just because it is connected to the moving body, and the additional speed it must make as it swings forward. At a racing gallop, the horse is taking about 2.5 strides per second. This means 10 times per second one of the hooves is being accelerated and decelerated.

"Then we look at which joints are involved in swinging the leg," Clayton continues. "In the front legs it's mainly the elbow. In the hind leg it's mainly the hip joint (the pivot point for the leg). The front leg is a bit more complicated than the hind because there is no bony connection between the front leg and the trunk."

Instead, the ribcage hangs between the front legs via muscle attachments. The muscles around the shoulder are primarily designed for stabilizing that front leg/trunk connection, and that's why the elbow is responsible for the swing of the leg. When the leg is on the ground, the shoulder muscles work to stabilize the leg, rather than being concerned with the movement, she says.
Moment of Inertia

Several factors affect how much energy the horse uses to swing the leg forward, Clayton explains. The resistance of the leg to forward movement depends on its moment of inertia (tendency of something to resist acceleration). The amount of energy used to swing a leg depends on its resistance to rotation due to inertia. The moment of inertia depends on the mass of the limb and the distribution of that mass (and weight) relative to its point of rotation.

"It's like swinging a baseball bat," she says. "If you pick it up by its skinny end, it's harder to swing than if you pick it up by the larger, heavier end. This is because the center of gravity is closer to the heavier end of the bat. The closer you can get the center of gravity to the pivot point (your arm), the easier it is to swing the bat because there is less weight farther out."

The same principles apply to the horse's leg. Several conformational features ensure that the center of gravity is in the upper part of the leg, close to its point of rotation. Clayton explains this is why all the big muscle masses are high up on the limbs, and only lightweight structures--tendons and bone--are present in the lower limb (below the knees and hocks). The largest muscles in the front limb are around the shoulder and elbow, with smaller muscles on the forearm. Below the knee there is virtually no muscle tissue.

"Long tendons transmit the forces from the muscles to the lower limb," she explains. "Tendons are much lighter than muscles. Thus the front cannon, pastern, and hoof account for less than 1% of the horse's weight."

Another adaptation along these lines is that when the early horse evolved, his multiple toes were reduced to one. This single toe is lighter than even a cloven hoof.

With this weight distribution principle in mind, Clayton reminds us that horse owners and trainers must be concerned about what is put on a horse's legs. For example, if we put on wraps or protective boots or shoes, we add more weight way down on the leg, which makes the swing phase of the stride more energy-consuming.

"The horse can easily carry the same amount of weight on a saddle pad, and he uses much less energy to compensate for it than if you put the weight on his shoes," says Clayton. "That's why lightweight aluminum shoes are used on racing Thoroughbreds. But for endurance horses, aluminum shoes may not be sturdy enough to protect the foot. So endurance riders use the lightest shoes that will still do the job for the horse."

Clayton says another thing horses do naturally to aid locomotive efficiency is fold the leg joints as they swing their legs forward. "The amount of folding increases with speed," she says. "This brings the leg closer to its pivot point and reduces that moment of inertia. So what you want is a leg that's long when it's on the ground so the horse pivots farther forward over the leg (more leverage for powerful movement), but then becomes short in the swing phase to make it easier to swing it. That's where having flexible joints is a huge advantage."

Tendon Recoil

Another advantage to the horse's build is that some leg muscles are adapted into long, elastic tendons. "These tendons are stretched when weight is on the leg; then as the horse takes weight off the leg, the tendons recoil like elastic," Clayton explains.
Elasticity is the ability of an object to rebound after being pushed, pulled, or twisted out of shape. Tendons can stretch when a tensile force is applied to them, then recoil when the tension is released. The stretching process stores mechanical energy, which is released during recoil; elastic energy is stored as the limb is loaded, then released when the limb is unloaded, she explains. That released energy is used to move the joints, rather than the horse having to actively use his muscles to move them, she explains. This avoids expending energy to contract the muscles, giving the horse more economy of motion.

"A tendon in the biceps brachii muscle flexes the elbow, and it acts almost like a catapult to pull the leg forward as soon as the weight comes off the front hoof," she says.

The digital flexor tendons and the suspensory ligament that run down the back of the leg act the same way, stretching as the fetlock extends when the limb is loaded, then recoiling as the leg leaves the ground, Clayton explains. As the horse goes faster, there's more loading of the leg and stretching of the tendons when it's on the ground, and more recoil and flexing when it comes off the ground.

This helps the limb move faster and also helps flex the leg to bring it closer to its point of rotation, which reduces that moment of inertia. This happens naturally, because the extra loading of the elastic structure in that phase of the stride bounces the leg higher off the ground.

**Push-Off**

"When a leg is on the ground, the horse uses muscles to create leverage at the hoof so it can push harder against the ground for more thrust," says Clayton. "If you look at the ultimate determinant of speed, it's not the ability to swing the leg forward more quickly, it's the ability to push harder against the ground."

The hind legs give much of the driving power, and the front legs aid somewhat in pulling the horse along.

"Depending on what sport you are doing, the front leg does different things," says Clayton. "In dressage horses, the front legs help create self carriage by pushing the forehand up and backward. Racing horses roll right over that front leg and use it as part of the pushing forward apparatus, for more momentum."

All the muscles down the back of the hind leg--the hip extensors, hamstrings, etc.--are very important for pulling the hind legs back (for thrust) as the hind hooves are on the ground.

**Biomechanical Studies**

Some studies to evaluate equine locomotion are done on treadmills and some on the ground. "We've collaborated with Drs. Don Hoyt and Steve Wickler at California State Polytechnic University in Pomona (Cal Poly) to look at effects of different speeds of trot on the horse's locomotion (how it affects the way the horse uses his legs), and whether the horse is trotting uphill or down," says Clayton.

Different speeds at the trot (whether on level ground or not) affect how a horse moves his legs, the way he pushes against the ground, and how much stress is put on certain joints or how much concussion is imparted to the leg.

"Steve has published a study on the effects of adding a certain amount of weight either to the horse's back or equally distributed on the four limbs in bell boots," says Clayton. "It shows the basic principle that horses can carry weight more easily on their backs than on the peripheral parts of the limbs."
Dead weight (a saddle or added padding) is easier for the horse to carry than the unpredictable weight of a rider that moves around. It's easier for the horse to compensate if he knows where the weight is going to be, she says.

Some studies use force plates to measure the hoof's push against the ground. "Forces reflect both the weight of the horse and the activity of the muscles," she says. "The same horse generates higher forces if he uses his muscles to push harder against the ground, which will project him higher into the air, say in a trot stride, and also cause him to come down more heavily when he lands."

The impact and concussion that occur immediately after the hooves hit the ground can also be affected by the horse's conformation and action, as well as things like speed and the type of surface he's working on (whether he's trotting on hard ground or pavement, or something softer like loose dirt or sand). Hard surfaces and higher speeds always have higher impact forces.

**Take-Home Message**

Knowing how horse's limbs function can be advantageous to the horse owner who is using a horse strenuously. Understanding the horse's biomechanical structure, and how ancillary add-ons such as shoes, boots, and saddles affect movement, can help you keep horses sounder, longer.

*Editor's Note: Clayton recently published the book The Dynamic Horse: A Biomechanical Guide to Equine Movement and Performance (published by Sporthorse Publications), and one of the chapters is devoted to muscle leverage.*

**Studies at California State Polytechnic University**

**Maximum Efficiency**

Steve Wickler, DVM, PhD, university veterinarian, director of lab facilities, and associate director of equine sciences in the Department of Animal and Veterinary Sciences at California State Polytechnic University in Pomona, Calif., has done a number of studies to evaluate what makes the equine locomotor system so efficient.

"We've looked at two different aspects," Wickler says. "One project, started by my colleague Don Hoyt, PhD, director of the Minority Biomedical Research Support Program, special assistant to Provost for Research, and professor of biological sciences in the Department of Biological Sciences, looked at the metabolism of different animals and how they move. Don measured the preferred speed at the walk, trot, and canter, using ponies, to find their behaviorally chosen speed," he says.

"Don measured the metabolism of the ponies and calculated the costs of locomotion--the amount of energy it takes to move a given distance," he continues. "He found that if the animals walked slower than their preferred speed, the costs went up. If they walked faster, the costs also went up. The minimum metabolic cost coincided with the speed the animals chose. When they are roaming free, they'll walk at a certain speed, and when they go to a trot they go directly to their preferred speed--which turns out to be right in the middle of their trotting range.

"We repeated the study with horses and found the same thing; the speed they walked was the most economical and so was their preferred trotting speed," he continues.
Even if a horse is bred to trot, it becomes metabolically expensive to do an extended trot. At a certain point, it is more economical to switch to a canter rather than trot faster. Horses also tend to change gaits in order to reduce concussion forces.

"We've also been doing some incline studies, looking at the effect of grade--how trotting uphill or downhill makes a difference in metabolism," says Wickler. "If you weight the animal with 20% of its body weight (200 pounds of rider and tack on a 1,000-pound horse), its metabolic rate goes up by 20%. If you take the same animal and make it trot up a 10% grade (a 10-foot rise in 100 feet of distance), the 10% grade elevates the horse's metabolism 250%.

If the horse is working 2.5 times harder, this factor must be taken into consideration when conditioning him. The metabolic rate of horses in research trials is determined by measuring oxygen consumption. The animals are all trained to wear oxygen consumption masks while doing the various activities, says Wickler.

"One of our studies has been looking at the shifts in force production on various grades," he says. "On the level, most of the forces are taken by the front legs. When the horse goes up a 10% incline, however, there must be more thrust from the hind leg."--Heather Smith Thomas