Spring 2017

Equines and Equations: A Mathematical view of Equine Movement and Lameness

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Recommended Citation

Schoeggl, J.M., "Equines and Equations: A Mathematical view of Equine Movement and Lameness" (2017). *All Regis University Theses*. 819.
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EQUINES AND EQUATIONS: A MATHEMATICAL VIEW OF EQUINE MOVEMENT AND LAMENESS

A thesis submitted to
Regis College
The Honors Program
in partial fulfillment of the requirements
for Graduation with Honors

by

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May 2017

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Director, University Honors Program

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Preface and Acknowledgements

There are so many people to thank and acknowledge that it is simply impossible to name them all, but the following have had a profound impact on the final product you see before you.

Completing this thesis would not have been possible without the support of Dr. Howe and Dr. Kleier of the Honors Program. Thank you for pushing me to do my best and showing me just what I'm capable of.

Dr. Trenary, thank you for being the best academic advisor anyone could ask for. Your unwavering support through my time at Regis has meant more to me than you could possibly know. Your help as my reader has made this thesis far less *lame* (get it?).

Dr. Springer, thank you for your endless patience and support through the years, not only in regards to my thesis but to life in general. Life will always change but I know I can always count on you to give me a helping hand or just listen to my rants. You are an incredible role model and I hope I can be as cool as you when I grow up.

Thank you to my parents, Jim and Nancy, for indulging my 4-year-old-self's obsession and signing me up for horseback riding lessons. And thank you for continuing to support me when you realized that I would still be obsessed with horses long after that.

And finally, thank you Kasper.

Introduction

It all started with a big gray horse named Kasper. After years of training, we were only two weeks away from beginning our pilgrimage to Oklahoma City to compete in the American Quarter Horse Youth Association World Show, a huge competition bringing together young riders from all over the world to compete in a variety of different events. Kasper and I were going to compete in Equitation over Fences, Working Hunter, and Jumping.

One morning, two weeks before we planned on leaving, I got on Kasper for a training ride and started trotting around. He always started out a little stiff because he had arthritis. But something was wrong. He didn't feel like himself, and his steps were weak. Sure enough, onlookers commented that he looked "off" on his left hind leg. This wasn't an uncommon occurrence, but as we continued to trot he wasn't getting any better. Dejectedly, I dismounted and realized that we would need to schedule an appointment with the vet. Because he was out of town, a barn-mate offered to let us take her place with a different vet later that day.

Figure 1: Kasper, the one who started it all

Dr. Owens examined Kasper and determined that he had a tear in his suspensory ligament, one of the most important structures to support the lower leg. She recommended that Kasper have 6 months off and charted an extensive treatment plan.

I was devastated. After years of planning and training, I wasn't going to be able to go to the World Show. And, I knew that Kasper wouldn't be likely to remain sound enough to go back to the same level of competition. Even if his suspensory ligament healed perfectly, he still had arthritis which made it harder and harder to keep him comfortable. Just like that, my dreams were dashed. I also felt guilty that I potentially caused Kasper's injury by riding him in unsuitable conditions and made sure to ride in a different arena if at all possible.

The event that didn't happen ended up being one of the most defining moments of my life. I learned far more from Kasper's injury and recovery than I would ever would have from showing in Oklahoma. It instilled in me an even deeper passion for my four legged friends and partners, and prompted my interest in equine lameness.

We did everything we could to treat Kasper's injury, and it healed acceptably well. However, he was never able to get back into full riding again. Shortly after his suspensory ligament healed, he suffered another soft tissue injury in a different leg, and then developed severe arthritis in yet another. Despite all of these injuries, Kasper was perfectly happy to hang out in a field for about a year until he started developing some severe (and unrelated) lameness issues that caused the joint in his foot to begin to collapse. After several months of trying to manage his pain levels, we made the difficult decision to euthanize my big gray friend. It was, and still is, the hardest decision of my life. I miss him every day and wish there was something that we could have done to alleviate his pain.

As if Kasper's lameness issues weren't enough, my current horse, Vashon, has had his fair share of injuries too. When we bought Vashon, we did what is called a pre-purchase exam where the vet examined Vashon's movement to make sure he didn't have any lameness problems. They also took x-rays of his legs to make sure there was no arthritis or bone chips. Even though his x-rays were clean and he showed no signs of lameness, he developed injuries that make him unable to jump again, some of which might have also been caused by poor footing.

Watching Dr. Owens and Dr. Latimer conduct countless lameness exams made me think about the way they were able to determine whether or not the horse was lame. In some cases, Kasper and Vashon displayed pain in multiple limbs so it was hard to distinguish which legs were really injured. This phenomenon, called compensatory lameness, makes an already difficult job that much harder. Sometimes, when a different vet would look at Vashon, they would detect a different lameness than Dr. Latimer. I wondered about the accuracy of each vet's analysis and wondered again what went into their decisions when declaring a horse lame in a certain leg. I also wondered what effect the surface the horses were moved had on their findings.

As I began my thesis process, I knew that I wanted to do something that involved analyzing equine motion in a mathematical way. It fascinates me to see the way horses move while competing in events or simply while in the pasture. I also wondered why horses have different gaits like the walk, trot, canter, and gallop, and how different footing affected the way a horse moves. As I began to do my initial research, I came across a company called Equinosis® that uses inertial sensor data to detect lameness. So many of the things that I was interested in collided that it seemed to be a great place to start my research. As I learned more about Equinosis® I discovered that one of its founders, Dr. Kevin Keegan, has extensively researched the use of inertial sensor data to evaluate lameness in horses. I eagerly read his work since it was the perfect balance of mathematical work and locomotion analysis. In the following pages, I've summarized the research done on inertial sensor data as well as added my own spin on findings.

Finding a new way to conduct lameness exams would not only make life easier for the veterinarians, but it would also considerably lower the cost of such exams for owners, increasing the chance that owners won't be afraid to call their vets if their horse is only slightly off. That way, slight injuries can be detected before more serious ones develop. The ultimate goal is to increase the quality of life for the horse. They bring our lives so much joy that we owe it to them to keep them happy and healthy.

A Machine with a Soul: A Basic Explanation of Equine Locomotion

"The horse is a machine. But a machine with a soul." – Captain V.S. Littauer

We have always been fascinated with the way horses move. In fact, it's the reason we have motion pictures today. In 1878, Leland Stanford placed a bet with his friends that a galloping racehorse has a phase of motion where all four legs were off of the ground, called "unsupported transit" (Lesile, 2001). In order to get a definitive answer, Stanford hired Eadweard Muybridge to capture instantaneous images of a racehorse galloping. The resulting images, shown in figure 2, proved that there is a portion of the gallop where the horse is completely suspended in the air, without any support.

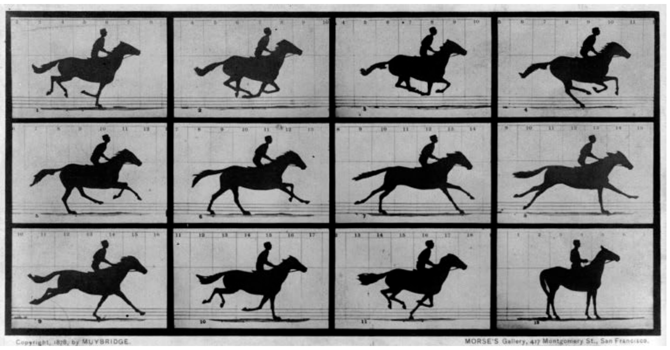


Figure 2: Eadweard Muybridge's images of a galloping racehorse paved the way for modern video cameras

While the technology invented for this discovery led to the creation of film and video, it also gave birth to a brand new field of knowledge: animal locomotion, the study of how animals move. Doing so requires that we think of animals as a "machine" of sorts, or one that will be able to generate the type of motions that produces movement. We also began to ask questions about the efficiency of movement and why horses change gaits – why would a horse walk instead of trotting or galloping?

The Stationary Horse

Before we begin to think about such complex questions, we should start with basic equine anatomy. At first glance, horses look nothing like humans, but our skeletal structures are actually quite similar (along with most other mammals). Figure 3 shows a comparison of bone structures within the human and horse. As we can see, the horse actually walks on what would be considered a finger or toe. We also notice that while we share the same bone structures, the proportions are wildly different. Take a look at the femur, which is colored dark red in Figure 3. In a human, it's the longest bone in the body and makes up approximately half of our legs. However, in a horse the femur sits so far up that we wouldn't even think to consider it a part of the leg. In fact, the equine equivalent of the knee, known as the stifle, sits at the beginning of the leg. In figure 4, we can see the names of common human joints and their equine equivalents.

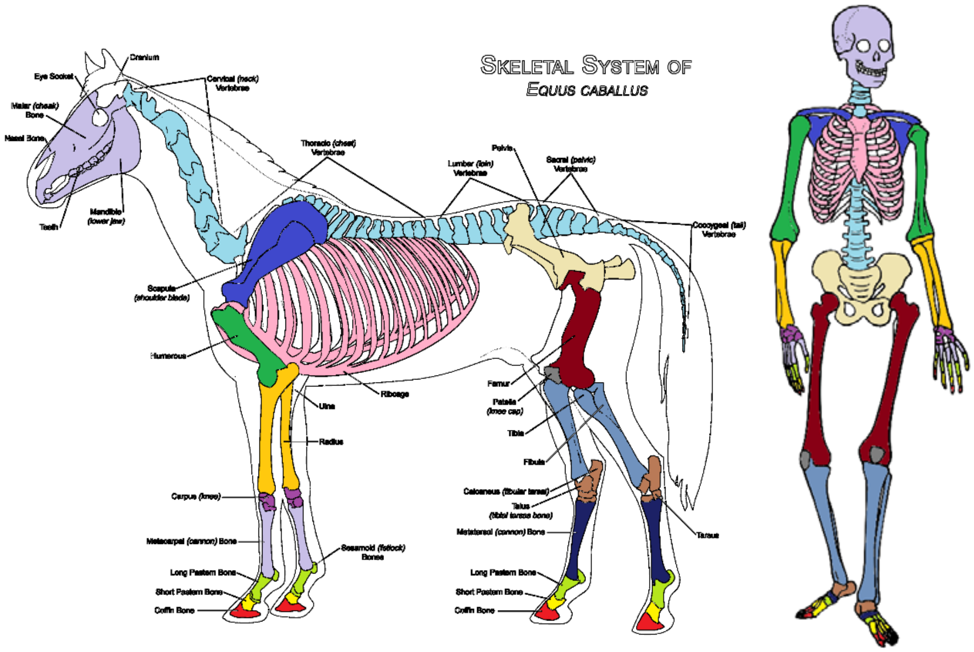


Figure 3: Skeletal Comparison of a Human and a Horse

HUMAN JOINT	EQUINE EQUIVALENT
SHOULDER	Shoulder
ELBOW	Elbow
WRIST	Carpus
FINGERS/METACARPALS	Pastern and coffin
SACRUM	Sacroiliac joint
KNEE	Stifle
ANKLE	Hock
TOES/METATARSALS	Pastern and coffin joint

Figure 4: Table of Equine Joints and their Human Equivalents

While humans and horses have similar skeletal structures, there are several critical differences. First of all, the horse does not have a clavicle, or collar bone, so the scapula is not connected to the rest of the skeleton. This allows the horse to have a greater range of motion in the scapula, which in turn allows a greater stride length. Another huge difference is the ratio between various bone lengths. We can see that the femur and tibia/fibula, while taking up most of a human's leg, only account for about half the length of a horse's hindlimb. Additionally, the horse's neck, a huge percentage of their body, is far larger than that of a human's.

Efficiency is the Name of the Game

So why are horses and humans built so differently? The answer is relatively simple. As horses evolved, their need for speed became greater and greater so that they could run away from predators. In order to increase efficiency, their legs grew longer and became less thick. This allowed them to use less energy with each movement since a skinnier leg is easier to move than a thick one. This explains the remarkable fact that from halfway down a horse's leg there is no muscle to be found, only bone, tendon, and ligament. In fact, the distal limbs of the horse account for less than 1 percent of the horse's total body weight (Clayton, 2004). Furthermore, the incredible tendon and ligament structures of the distal limb act as springs to transmit forces from the muscles to the ground, making muscles unnecessary. Of course, the lack of muscle in the lower leg makes it very susceptible to injury because it is not as well protected as the rest of the body. This will come into play later when we talk about lameness.

Another engineering trick horses employ is the use of a honeycomb like structure in the bones of their lower leg, particularly the cannon bone, which is the longest bone in the lower leg. As Stephen Budiansky notes in his book *The Nature of Horses*, the cannon bone has been designed to withstand intense longitudinal forces due to the shape of the bone structure. This makes the bone light and strong, but "because the bone is designed to resist longitudinal forces only, it is also dangerously vulnerable to transverse forces – for example if the leg strikes an object" (Budiansky, 1997). This paired with the lack of muscle make the lower leg a very delicate, yet efficient, structure.

Adding more muscle to increase strength and range of motion, and to add additional protection is not necessarily the answer. Adding muscle adds precious weight, but despite the fact that they are nowhere near the lower leg, muscles in the horse's body have an important effect on how the lower legs move. Since the horse's scapula is not connected to a clavicle-like bone, allowing it to rotate freely, the horse may extend its front leg farther by moving the axis of rotation farther forward on the scapula. This allows the horse to achieve a greater stride length. The muscles in this area work in two different ways. As humans have flexor and extensor muscles, so do horses. Let's look at the example of a horse bending its carpus joint, more commonly known as the knee. The combined effort of the flexor muscles (located closer to the tail of the horse) and the extensor muscles (located towards the front) is much stronger than a single muscle working on its own. By using the strength of two muscles working in opposite directions, the horse is able to achieve optimal performance with minimal effort and weight.

Putting it all Together

Figure 5: Here Vashon's left forelimb and right hindlimb are in the swing phase, while the other two legs are in the stance phase.

Now that we have the basics of the horse's anatomy and can describe why horses are built the way they are, we can begin to talk about how each part works together to create motion. Equine movement (and most other animals) can be split into two phases: the **stance phase** where the leg is weight-bearing and in contact with the ground, and the **swing phase**, where the leg is soaring through the air with no attachment to the ground.   We can further divide the stance phase into two separate pieces, the first of which begins when the heel touches the ground and ends when the leg is in mid-stance (where the leg is in a vertical position). This is called the **deceleration phase** because the leg is absorbing forces used to propel the horse forward. Once the leg passes through mid-stance, it enters the **propulsion phase**, where the leg creates a propulsive force used to continue the horse's forward motion (Leach, 1984). The point at which the limb moves from the deceleration phase to the propulsion phase is called the **breakover**.

As mentioned previously, the horse's scapula is unattached to the rest of the skeleton, allowing it to move freely. This allows the front legs to rotate around a point in the scapula instead of at the clavicle. Throughout the stance and the swing phases of the stride, the horse's leg acts as a lever to propel the horse forward. In the horse's lower leg, "the bones act as levers and the muscles act as torque (force) generators… the majority of limb muscles act as third-class levers, which are characterized by having the force and resistance acting on the same side of the fulcrum, with the force arm shorter than the resistance arm. The effect of leverage is to increase the range or speed of motion, which is effective for protracting the limb through a wide arc during the swing phase, when resistance to movement is small" (Clayton, 2004).

When stance and swing phases of the legs move in a certain pattern, we call that a **gait**. The most common gaits are walk, trot, canter, and gallop, but there are others gaits that special breeds called gaited horses use such as the running walk, the tolt, and the pace. Gaits are either symmetrical, where "the left and right feet of each front and back pair strike the ground at evenly spaced intervals, with each foot remaining in contact with the ground for the same time" or asymmetrical, where "the cycles of the left and right feet of each pair are different; a movie of one would *not* look like a mirror image of the other" (Budiansky, 1997). The walk, trot, and pace are symmetrical whereas the canter and gallop are asymmetrical. One easy way to remember asymmetrical gaits is to think of the way riders classify these gaits. A horse can be on either a right or left lead canter or gallop, but it cannot have a "left lead" trot. This distinction may be confusing to non-riders, but it is immensely helpful for those who have ever tried to get a horse to canter on a specific lead.

But why do horses have different gaits? If a horse needs to move faster why doesn't it just move its legs faster or increase its stride length? The answer to this is really quite fascinating. A researcher by the name of R. McNeill Alexander analyzed many different animals and the speed at which they transitioned to different gaits. When comparing the animal's stride length (as a percentage of leg length) to what is known as a **Froude number**, the relationship is linear, meaning that as the stride length increases, so does the Froude number. The Froude number "is the ratio of the centrifugal force pulling the body's center of mass upward as it swings over the arc described by the leg, to the force of gravity acting to pull that mass down" (Budiansky, 1997). In other words, the Froude number can be expressed as follows: $F = \frac{v^2}{lg}$, where v = velocity, l=leg length, and g = acceleration due to gravity ($9.8\frac{m}{s^2}$) .

Figure 6: The Froude Number is the Proportion between Centrifugal Force and the Force of Gravity

Using this equation, we can see the when $F < 1$, the gravitational force is larger than the centrifugal force, meaning that the pendulum of the leg is held down by gravity and the horse remains on the ground. If $F > 1$, that means the centrifugal force is greater than the force of gravity, so the pendulum (and the horse) will lift off of the ground. When this occurs, it becomes impossible for the legs to remain on the ground at the same time. So the animal must move into a gait with an airborne phase like the trot, canter, or gallop. This explains the transition from a walk to a trot, but why do horses canter or gallop?

This took further research to discover. Claire Farley and C. Richard Taylor discovered that there was a range of speed in each gait where animals consumed the least amount of energy. In fact, horses travelling one kilometer at a walk, trot, or canter all expend the same amount of energy (measured by the amount of energy it takes to move one kilogram of bodyweight one meter) with the caveat that the animal was allowed to choose its own speed (Farley, 1991). The reason behind this is still contested, but many believe that is has to do with the resonant frequency of the “springs” of ligaments and tendons found in the horse’s body. Additionally, horses will go from the trot to the canter once the force with which their legs strike the ground reaches a peak level.

What is lameness?

As veterinarians gained a greater understanding of the kinematics of equine movement, the applications of this knowledge grew. Most commonly, vets can apply their knowledge to help one of the most common problems horses face: lameness. The American Association of Equine Practitioners defines **lameness** as “a change in gait, usually in response to pain somewhere in a limb, but also possibly as a result of mechanical restriction on movement. We all think of lameness when a horse is obviously limping, but lameness may only cause a subtle change in gait, or even just a decreased ability or willingness to perform” (Thal, 2016). It is important to note that lameness is not a diagnosis but merely a symptom of an underlying problem.

While it may seem intuitive to say that lameness in one leg corresponds to an injury or problem with the same leg, this is not always to case. Because the horse’s gaits involve the complex task of moving the legs in a different pattern, the same injury can appear in many different ways in different gaits. In the case of compensatory lamenesses, a horse can show lameness in one leg even though the injury is in another due to overloading the sound leg. Different types of lamenesses present themselves at different parts of the stride. For example, when a horse presents **supporting limb lameness**, it is caused from “pain during the weight-bearing phase of the stride,” which is responsible for most lameness conditions (Ross, 2003). Ross argues that the supporting limb lameness, while occurring during the stance phase, should not be called stance phase lameness because the swing phase of the step is also altered. Secondly, **swinging limb**

lameness “describes lameness that primarily affects the way the horse carries the hind limb. However, most horses with painful lameness conditions alter the swing phase of the stride in a typical and repeatable fashion, and it is difficult to make a clear separation between supporting and swinging limb lameness…most lameness can be considered **mixed lameness**, with changes in gait during weight bearing or the stance phase and during the swing phase of the stride” (Ross, 2003). Ross notes that “it has been suggested that swinging limb lameness is caused by muscle injury, supporting limb lameness is caused by bone, tendon, and ligament injury; and mixed lameness is caused by joint, tendon sheath, and periosteal injury” (Ross, 2003). While these terms help us understand where in the stride the abnormality occurs, it does little to tell us about the cause of the lameness.

Causes of Lameness

Just as lameness presents itself in a myriad of ways, so too are the causes of lameness countless. Due to the lack of muscle protecting the bone and fibrous tissues, the lower leg is particularly vulnerable to both acute and chronic injury. While injures to other areas such as the neck and sacroiliac joint are possible and are diagnosed more regularly, most lameness is caused by pain in the distal limb. These injuries can be primarily split into two different categories, colloquially known as hard tissue and soft tissue injuries. Hard tissue primarily refers to changes in the horse’s skeletal structure, the most dramatic of which are bone fractures. Most of us are familiar with fractures, which occur when the bone experiences forces too strong to support. One of the most common fractures for thoroughbred racehorses occurs in the cannon bone, because the ground reaction force is simply too much for the bone to handle. In most cases, cannon bone fractures are catastrophic and end in euthanasia. Fractures do occur in other parts of the body, but the leg is the most susceptible.

Another type of “hard tissue” injury that effects up to 70% of sport horses is degenerative joint disease, or DJD. More commonly known as arthritis, DJD affects the places where two bones meet and is often characterized by a lack of cartilage, insufficient joint space, or abnormal bone growth. When two joints meet, the end of the bones are covered by a cushioning material known as cartilage. Damage to the cartilage can cause “lameness, poor performance, stiffness and joint swelling and inflammation” (House). Causes of DJD are varied and contested, but the most common are “age, type of performance, conditioning, trauma, [and] development diseases” (House).

Not too long ago, a large majority of injuries diagnosed by veterinarians were labeled “hard tissue” injuries. After technology made other structures more visible, it became apparent that soft tissue injuries are quite common. The “soft tissues” include muscle, tendons, and ligaments. A **tendon** is a spring-like mechanism that connects a bone to a muscle, allowing the muscle to actually move the bone. A **ligament** acts in a similar fashion but connects bone to bone. One of the most important ligaments in the horse’s leg is the **suspensory ligament**, which supports the horse’s pastern joints and aids in energy conservation. It is not possible to see soft tissues on radiographs. However, ultrasound is particularly effective at imaging soft tissue areas.

Another less common cause of lameness stems from neurological issues where the horse’s brain sends incorrect messages to its body. Neurological defects such as

Wobbler's and Shivers cause the horse to walk as though they were "drunk" in an uneven and very uncoordinated gait. Unfortunately, most cases of neurological lameness are not treatable through traditional methods.

Lameness originating in the fore and hindlimbs present themselves in similar yet different ways. Because of the complex way horses move, hindlimb lameness tends to be more difficult to spot. We will examine the reasons why below.

Lameness Treatment

The treatment options for hard and soft tissue injuries are very different in some regards but very similar in others. No one will argue that the most beneficial treatment for any injury is time. However, there are other ways veterinarians can treat injuries, or in the case of DJD, increase the horse's comfort for long periods of time.

One of the most common treatments for DJD is intraarticular injection of corticosteroids and/or hyaluronic acid, more commonly known as joint injections. Steroid injections are the oldest and most common, which work by masking the pain that a horse is feeling. This can help the horse in the short term (6months-1year) but prolonged use of steroid injections can have a negative effect on the quality of the joint, causing further problems down the road.

It is well known that stem cells and plasma hold great healing power and veterinarians search for ways to successfully integrate them into their treatment regimens. A new alternative to steroid injections is IRAP, which stands for interleukin-1 receptor antagonist proteins. IRAP is made individually for each horse by drawing blood and extracting the plasma by putting it in a centrifuge. Once the plasma is separated, it is placed in a syringe that “stimulates production of the antagonist protein” (House). These antagonist proteins work by “preventing IL-1 from binding to IL-1 receptors on tissues within the joint, and therefore blocks the action of and stops the damage caused by the IL-1 in the joint” (House). IRAP is much better for the long-term health of the joint and shows promise to even improve the quality of joints instead of masking pain, or even making the joint worse. Similar procedures are used to treat soft tissue injuries, including platelet-rich-plasma and others.

Another option, mostly for DJD issues, is surgery. Arthroscopy, which is a minimally invasive surgery, allows veterinarians to look inside the horse’s joint to see any abnormalities. In the case of a tear in the meniscus or abnormal bone growth, the vet can clear the area to eliminate the source of pain. Like all the treatments mentioned, this is not always effective, but has been shown to improve the comfort of many horses.

More and more technologies are developed for treatment of injury of the sport horse, ranging from traditional Western medicine like steroid injections to alternative practices like chiropractic and acupuncture. Much like the human world, there are many “snake oil” salesmen that argue that their product will cure all injuries. From vibrating plates to magnetic therapy, these treatments are often quite expensive and have little peer-reviewed evidence to support their claims. Similarly, oral joint supplements have little scientific evidence supporting their effectiveness in treating or maintaining comfort in sport horses. Owners should be willing to listen to their veterinarians who can share their thoughts on the efficacy of any of these alternative treatments.

Now that we have a better idea of the types of injuries that cause most lamenesses and their treatment options, we can take a closer look at the way horses change their gait depending on the type of lameness.

Forelimb Lameness

Forelimb lameness is primarily characterized by a change in the way the horse carries its head. When a sound horse moves, “the head moves up and down in a sinusoidal, temporally symmetrical pattern, with amplitude equivalent cycles corresponding to each half of the full stride cycle”, however, “in most weight-bearing lameness conditions, the downward head movement during weight bearing of the painful limb is reduced to that in the sound limb” (Kramer J. a., 2014). Mike Ross agrees and notes that “the horse appears to be elevating the head and neck just before the lame limb hits the ground, and then, during the later portion of the support or stance phase, the head and neck nod down.” (Ross, 2003). To put it simply, the horse will raise its head higher just before the lame limb enters the stance phase of the stride and will nod its head farther down when the sound limb begins to enter stance phase. Most veterinarians simply refer to this pattern as “down on sound”, indicating that the horse will move his head lower when the **bilateral** (opposite) forelimb hits the ground.

However, horses just don’t move their heads differently for the fun of it. The primary reason horses lift their heads higher when the injured limb is in stance phase is to lessen the **ground reaction force** the horse experiences. The ground reaction force is the “external force exerted by the ground against the hoof” (Clayton, 2004). A smaller ground reaction force means that less force is put on the painful limb, so the horse experiences less pain. This small concept is vital for the current diagnosis of lameness, as it is responsible for the visible and consistent differences in vertical head displacement used in lameness diagnosis.

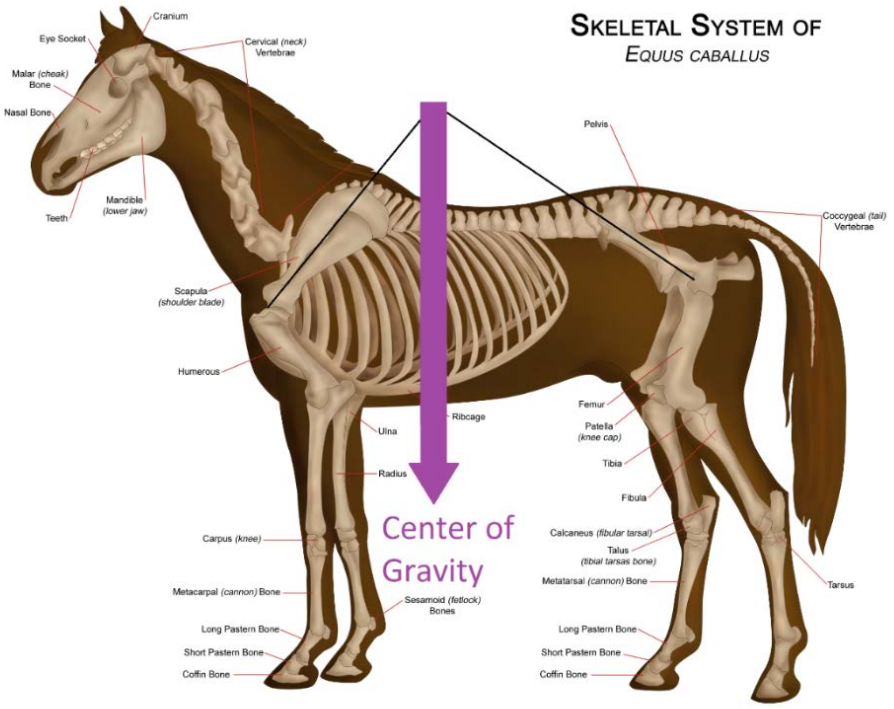


Figure 7: A horse's center of gravity is closer to the frontlimbs, so they carry more weight than the hindlimbs

Hindlimb Lameness

It is much harder to determine hindlimb lameness than forelimb lameness. However, there are similar patterns at play while evaluating hindlimb lameness. Much like a horse with a forelimb lameness will present an asymmetrical movement of their head, horses with hindlimb lameness will present a "pelvic hike", meaning that the movement of the pelvis is asymmetrical and rises different amounts when each hind leg enters the stance phase. The reason for this pelvic hike is the same as that of the change in head movement for forelimb lameness. The horse will raise its pelvis higher in order to lessen the ground reaction force on a painful hindlimb. Veterinarians can identify what is colloquially known as “hip hike” in several different ways. One of the most common is to compare the motion of the tuber coxae (the bony protrusion of the pelvis) and note any abnormalities. Another way is to examine the vertical displacement of the top of the pelvis, known as the sacrum, at each phase of the stride. While these methods are different, they tend to show the same results. A study showed that viewing the horse’s pelvis and the tuber coxae showed similar outcomes in lameness diagnostics, noting that the “rigidity of the equine pelvis results in tightly linked movement trajectories of different pelvic landmarks”, even though variations in diagnosis existed between mild lameness cases (Starke S. M., 2015). Although both can be used to analyze pelvic hike, it is still recommended to observe both the pelvis and the tuber coxae in order to gain the most information possible.

Compensatory and Multiple Limb Lamenesses

In many cases, horses will present lameness in more than one leg. Veterinarians split multiple limb lameness into three categories: compensatory lameness, secondary lameness, or two or more primary lamenesses. Compensatory lameness occurs from “overloading of the other limbs as a result of a primary lameness…[it] develops as the result of a predicable compensation a horse may make *over time* for a primary lameness in a single limb” (Ross, 2003). Compensatory lameness is perhaps one of the most difficult aspects of evaluating lameness as it is incredibly challenging to discern what movement abnormalities are stemming from the original injury versus the compensatory pain or stiffness. While the definition notes that compensatory lameness derives from predictable compensation, diagnosing compensatory lameness requires the acknowledgement that some horses may react to pain in different ways.

Not to be confused with compensatory lameness, secondary lameness is an additional lameness that is caused by the first lameness. This may be due to overloading the **contralateral** (diagonal) limb. Thirdly, the horse may have multiple primary lamenesses, or more than one issue causing the horse to be lame.

One of the great challenges when diagnosing lameness is the ability to notice the existence of a compensatory lameness and its relationship to the primary lameness. It has been shown that inducing lameness in a hindlimb can cause changes in locomotion common to lameness in other legs (Kelmer, 2005). One of the most common ways to distinguish between a primary and compensatory lameness is using the "**Law of Sides**". Dr. Kevin Keegan, an expert in equine lameness, says the first part of the rule states that "when a horse is trotting, an apparent ipsilateral lameness e.g., a right forelimb and right hindlimb lameness, is most likely a primary hindlimb lameness with a compensatory, and therefore false, forelimb lameness" (Keegan K. , Law of Sides, Why I Use Lameness Locator on Every Case, 2011). In short, in the case that a horse shows lameness in both right or both left limbs, it is most likely just a hindlimb lameness. The second part of the Law of Sides states that a "primary forelimb lameness will sometimes cause a compensatory contralateral hindlimb lameness, <u>and</u> that the contralateral hindlimb lameness is a pushoff type," meaning that when a diagonal pair of legs both present lameness, it is usually primarily a forelimb lameness (Keegan K. , Interpreting Lameness Locator: Second Part of the "Law of Sides", 2011). Because contralateral limbs have the same stance and swing phases at the trot, it makes sense that if a forelimb is in pain the diagonal hindlimb will also change its movement.

The Law of Sides demonstrates just how complex equine movement is. It is based on the fact that all the movements of the horse and the changes to those movement due to lameness are all interrelated. Nothing works in isolation, so a problem in one area can (and often will) affect other aspects of the horse's movement. It is important for veterinarians to keep the Law of Sides in mind when performing lameness evaluations, and it can help track "ghost" lamenesses where more than one limb appear lame at different times. Veterinarians must be cautious when evaluating the horse for lameness and take all different changes of locomotion into account, for they may demonstrate a larger problem.

Other Kinematic Markers of Equine Lameness

When evaluating a horse for lameness, it might be tempting to focus on the movement of the lower legs because that is where most injuries originate. However, because there are no muscles below the carpus and hock joints, most of the changes take place closer to the center of the horse's body. As our knowledge of equine kinematics has increased, we have learned more about specific kinematic markers that signify lameness that do not always present as problems with the path of the horse's limbs. When a horse is experiencing pain in a certain leg, there are specific characteristics of the way they change their movement. Front limb and hind limb lamenesses show different changes, but these changes are based on the same simple assumption that horses will try to reduce the ground reaction force on their injured limb.

While the most common indicator of lameness is the head nod or pelvic hip hike, other parameters can be used to evaluate the degree of lameness present in the horse, most of which are associated with the horse decreasing the ground reaction force on the injured limb. Some examples include fetlock drop, which changes in the bilateral limb (the opposite limb): “the fetlock joint of the sound limb drops farther when this limb is weight bearing than does the fetlock of the lame limb, because the horse is attempting to spare the lame limb by increasing load in the sound limb” (Ross, 2003). The fetlock drop is a further symptom of an attempt to lessen the ground reaction force on the injured limb. In addition to fetlock drop, veterinarians can use the sound of the horse’s footfalls to discern lameness. Horses with lameness will “land harder on the sound limb, resulting in a louder noise” and presenting another pattern easily recognizable by the clinician (Ross, 2003). Finally, horses will also drift away from the lame limb in an effort to decrease load bearing of the painful limb. Different lameness may present different drifting patterns. For example, racehorses will drift away from the lame limb, but jumping horses may drift towards the lame limb because they put more weight on the sound limb, propelling them towards the lame limb, so it is important to include other lameness marker in conjunction with drifting.

Lameness caused by neurological disorders has different markers completely. As the change in movement comes from incorrect signals from the brain, the manifestation of lameness patterns is markedly different. Traditional lameness markers do not typically apply to neurological lameness.

Most of these markers of lameness relate to the lessening of the ground reaction force of the injured limb, but it is also important to note that there may be other factors that impact changes in movement. One of the most obvious is range of motion, which can be limited due to inflammation, pain, or other arthritic changes in the joint. Since inertial sensor data is the focus of this paper and it relies on head nod and pelvic hip hike, the author has not researched these other indicators of lameness as thoroughly. More extensive research is needed to determine other indicators of lameness and if they are as clinically relevant as head nod and pelvic hip hike.

How Veterinarians Currently Diagnose Lameness

While each veterinarian has their preferences for lameness evaluation techniques, they all follow the same basic format. Each examination begins with determining the baseline lameness by analyzing the horse's kinematic movement, and then uses analgesic aids to eradicate the symptoms. Finally, imaging like radiographs or ultrasound is used to make a diagnosis. This process was shown to be the most effective with the current technological tools available to veterinarians.

The Procedure

Mike Ross, a professor of surgery at the University of Pennsylvania School of Veterinary Medicine, states that the first step in a lameness exam is for the veterinarian to establish the baseline lameness at the walk and trot. The **baseline lameness** is "the gait abnormality before flexion or manipulative tests are used," or, in other words, the way the horse moves before the veterinarian does anything that might change the movement of the horse (Ross, 2003). The main goal of establishing the baseline lameness is fairly simple: the veterinarian needs to be able to see the initial lameness before the next step, which is to "attempt to abolish baseline lameness using analgesic techniques" (Ross, 2003). They might watch the horse trot away and towards them on a hard surface like asphalt or packed gravel, or watch the horse trot in an arena on a small circle both directions. Additionally, if possible, some vets like to see the horse trot a small circle on a slight incline. These different views give the vet a starting point from which they evaluate the horse before and after joint blocks.

Once the veterinarian has establishes the baseline lameness, they perform physical manipulations on the horse, starting with flexion tests. Flexion tests are where the veterinarian holds a leg in a hyper-flexed position so the joints are bent as much as possible for 60 seconds and then has the horse trot off again. The goal of flexion tests is to induce a more dramatic lameness in order to be localize the horse's pain to a certain leg or joint.

There is some debate about the effectiveness of flexion tests as a diagnostic tool. Some claim that the amount of lameness induced by flexion tests is completely dependent on the pressure the vet uses to hold the limb in place. In a study of 50 horses judged to be clinically sound, "20 had a positive response to normal flexion" and "49 of 50 horses had a positive response to firm flexion" (Ross, 2003). While it is important to note that radiographs of 24 of these horses showed abnormalities that could have explained the positive response, we must keep in mind that these horses were judged to be clinically sound before the flexion test. If horses that are sound display lameness with flexion, why do it? Flexion tests may be a sign of future lameness in horses. Ross cites a study of 151 sound horses where 21% of those with a positive forelimb flexion test developed lameness whereas only 5% of those with a negative test developed lameness. Despite their controversy, most veterinarians use flexion tests as a part of the lameness examination because it helps localize the lame limb.

Veterinarians also use other techniques in order to make the lameness more visible. Often they will use hoof testers to see if a horse's lameness stems from sore feet. Hoof testers are used to place pressure on different areas of a horse's foot and heel area.

If the horse reacts more in one spot than another, chances are the horse is developing an abscess or is suffering from thin soles. Hoof testers might not be a specific diagnosis and can create false positives in small horse and ponies, and a horse with very large or hard feet might not respond to any pressure, even though they have foot pain (Ross, 2003).

After using traditional tests like flexion and hoof testers on the horse, vets can take advantage of new technology and employ the use of temporary nerve blocking. Starting at the hoof, vets temporarily block parts of the horse's leg to see if the lameness improves when the horse loses feeling in that part of the leg. This method has its advantages. Once an area is blocked, the horse experiences a temporary loss of sensation. Using the incremental approach where only a small portion of the leg is blocked at a time, vets use the information attained to determine the origin of the horse's pain. This method does not tell the vet what is causing the lameness, but gives them a better idea of where to use exploratory methods like radiographs and ultrasound.

Limitations of Current Lameness Evaluation

Nerve blocking also has many limitations, the first being the considerable cost. Each time the vet has to block another part of the leg the price of the lameness exam increases dramatically. One can imagine how costly a lameness exam could get if the lameness is found to have originated in the stifle, or even worse, a place like the sacroiliac joint which cannot be blocked. Additionally, blocking is incredibly time-consuming. Waiting for the nerve blocks to reach full effect takes up a large majority of the lameness exam.

As if the time and costs were not enough deterrent, nerve blocking often leads to inaccurate results. The whole basis of nerve blocking is to compare the horse before and after the nerve block, but a vet's interpretation of the severity of lameness can change even though there might not be a change in the horse's gait. Just imagine a vet that has been watching the same horse trot for three hours after a long day of being on call. That vet is going to be primed to look for a sounder horse after a nerve block. This isn't the vet's fault, but is merely a side-effect of being human.

It should also be noted that the speed of the horse plays a role in the identification of lameness. It has been shown that "a slow trotting speed can enhance the visual detection of subtle asymmetry and should therefore be added to the gait examination in cases of uncertainty" (Starke S. D., 2013). Keeping a consistent speed will also maintain other kinematic markers that should be kept in account. Changing the speed of the trot will change stride length, limb angles, and trunk flexion angles, among other things, which could potentially create a change in movement not contributed to analgesic effects (Starke S. D., 2013). Variability in speed could account for differences in diagnosis between different veterinarians or handlers trotting the horse.

Another downside to the traditional lameness exam is the lack of quantifiable data. Lameness is graded on a scale of 0-5, where 0 is totally sound and 5 is non weight-bearing (see the scale in Figure 7). Even though each number on the scale is given certain criteria by the AAEP (American Association of Equine Practitioners), there is still a lot of variation between what two different vets might consider a "grade 2" lameness. Finally, multiple vets looking at the same horse may end up with different results based on their vantage point, past experience, or even previous knowledge of the horse (if one knows the horse has had issues with certain leg in the past, they might be more susceptible to seeing lameness in that leg). It is impossible for a human to be completely objective in their evaluation of the horse.

NUMBER	**EXPLANATION**
0	Lameness not perceptible under any circumstances.
1	Lameness is difficult to observe and is not consistently apparent, regardless of circumstances (e.g. under saddle, circling, inclines, hard surface, etc.).
2	Lameness is difficult to observe at a walk or when trotting in a straight line but consistently apparent under certain circumstances (e.g. weight-carrying, circling, inclines, hard surface, etc.).
3	Lameness is consistently observable at a trot under all circumstances.
4	Lameness is obvious at a walk.
5	Lameness produces minimal weight bearing in motion and/or at rest or a complete inability to move.

Figure 8: AAEP Lameness Scale

As if the inaccurate results with one veterinarian is not enough, there is little consensus among even experienced veterinarians as to the location and severity of lamenesses. Dr. Kevin Keegan et al showed that “veterinarians agree that a forelimb or hindlimb is lame greater than 9 out of 10 times” for lameness greater than a 1.5 on the AAEP scale, and for lameness less than 1.5, “veterinarians agree that a forelimb is lame about…2 out of 3 times, and that a hindlimb is lame just over…half the time” (Keegan K. , 2010). Overall, veterinarians agreed 93% of the time when the mean AAEP lameness score was over 1.5, and they agreed 61.9% of the time when the mean AAEP lameness score was less than or equal to 1.5 (Keegan K. , Repeatability of Subjective Evaluation of

Lameness in Horses, 2010). In the worst case scenario, agreement among practitioners was only 8% greater than chance, showing a dramatic need for a more objective lameness program.

All of these reasons lead me to believe that equine veterinarians should try to find a more quantifiable and unbiased way to examine lameness in horses. Additionally, this is a common consensus among research veterinarians. Researchers say that “if evaluation of the horse in motion is important clinically for diagnosis of lameness and horses do change the way they move because of lameness, the current standard of practice of subjective evaluation of lameness is not acceptable for horses with mild lameness…a search for … a more objective and reliable method of lameness evaluation for use in the field…is justified and should be encouraged and supported” (Keegan K. , Repeatability of Subjective Evaluation of Lameness in Horses, 2010). It is fair to say that it has been proven that horses do change their gait consistently due to pain, so it is time for veterinarians to search for a better way to objectively evaluate these changes.

Using Technology to Diagnose Lameness

From the previous section, it is pretty clear that there is a need for objective lameness evaluation. In order to provide a solution, veterinarians began to experiment with different ways to collect data on lameness in horses. Force plates, camera analysis, inertial sensor data, and other methods have all been used to find lameness in horses. All methods have their benefits as well as downsides, but the general consensus is that that inertial sensor data is the most effective and convenient way to objectively evaluate lameness in horses.

Comparison of Different technologies

The basis of using inertial sensors lies in information obtained in tandem with data from other types of technology which have also proved important in analyzing lameness. It is important to note that while inertial sensors have been determined to be the most effective, this would not have been possible without the use of other technologies. Here, we explore the strategies used for each type of objective lameness evaluation and compare their accuracy and convenience.

Force Plate

A force place is a tool that is used to measure the ground reaction forces exerted by a body standing or moving across them. Force plates give the veterinarian a plethora of information about the amount of force the horse is putting on each leg. As the most common indicator of lameness is a decrease of ground reaction forces on the lame limb, the force plate is a natural tool to analyze lameness. Data from force plate analysis allows practitioners to observe the ground reaction forces being exerted on each leg. Using this technology, it is easy to see the immediate results; no extrapolation is needed. Because of this, force plate analysis has long been considered the gold standard in objective lameness evaluation (Keegan K. G., 2011).

Despite the incredible data that can be obtained from force plates, they have some significant disadvantages that make them impractical for use in a clinical setting. The biggest concern with force plates is the inability to collect data from multiple strides at a time. This makes it difficult to notice consistent patterns in the horse's movement. Collecting data from only one or two strides does not provide enough information for veterinarians to make an educated diagnosis, since those one or two strides could have simply been an abnormality. It is even possible that the differing surface of the force plate changes the way the horse moves and makes all the data collected in this manner obsolete. Furthermore, force plates are not portable and cannot be taken to other facilities as the other technologies can. Force plates have an important role in research facilities, but are simply not practical for use in clinical setting.

Photographic Analysis

The most intuitive method of objective lameness evaluation is the use of a camera. Because veterinarians use their eyes to visually see changes in movement, the use of a camera to detect such movements is a natural progression. Most camera setups face the same problem as force plates in that they can only capture a few strides at a time, and collecting data from contiguous strides is essential for accurate analysis of movement. Despite this, camera based analysis is "reliable, accurate, and sensitive for detecting and evaluating lameness if two conditions are met: (1) multiple, contiguous strides must be collected…and (2) the size of the field of view compared with the size of the subject must be controlled and kept as small as possible for constant and precise spatial resolution" (Keegan K. G., 2011).

Like force plates, cameras are not very portable and can only really be used in a research setting. The alignment of the cameras must be incredibly precise in order to gather meaningful data, making it an unlikely candidate for clinical use. Most camera analysis systems also take on the great challenge of converting a three dimensional movement into a two-dimensional plane for ease of analysis. Even though it appears as though horses move in one direction, and the horse's legs can only move in one plane of movement (forward and backwards), their bodies are constantly rotating and changing in ways it is incredibly difficult for a two-dimensional analysis to make sense of. While portable, cameras are very difficult to set up and have a great potential to spook the horse. Therefore, despite their use in analysis of kinematic markers of lameness, cameras are not the best option for clinical lameness evaluation.

Inertial Sensors

Researchers regularly and consistently prove that the two most important indicators of lameness are the position of the head and pelvis in relation to the horse's gait. Researchers take advantage of the fact that lameness in all corners of the horse can be detected by two different kinematic markers through the use of inertial sensors positioned to analyze vertical displacement of the head and pelvis. Use of inertial sensors is quick, highly portable, and non-invasive. It is also capable of picking up data from however many strides are needed so the primary problem with force plates and cameras is eliminated. Additionally, data is collected wirelessly, so no unruly cables are necessary, further simplifying the process.

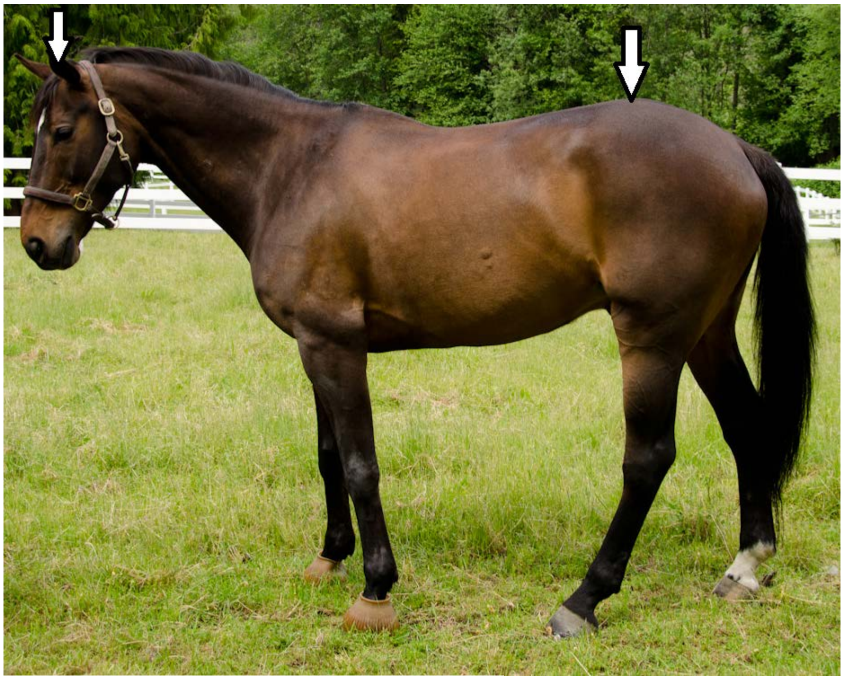


Figure 9: Location of Inertial Sensor Placement

As noted previously, one of the most consistent indicators of lameness is the flight pattern of the horse’s head and pelvis. To take advantage of this, inertial sensors are placed on the horse’s poll and pelvis in order to observe the changes in movement in these areas.

The Mathematics Used in Inertial Sensor Data Collection

The primary goal of inertial sensor data is to discern which changes in movement correspond with lameness in particular limbs. Once the data has been collected, it needs to be analyzed and transformed into information that the veterinarian can interpret. The **Fourier series** allows the data collected from the inertial sensors to be put in context with the kinetic markers of lameness. While the Fourier series is most famous for its use in radio and telephones, but its practical applications are more far-reaching than that. Many image compression methods employ principles of the Fourier series in order to make image files significantly smaller while still maintaining a high quality image. In terms of the inertial sensor data, the Fourier series is used to split the pattern into interrelated patterns of sine and cosine waves. By doing this, researchers can find an estimate of the equation of motion.

To understand how this works, we must first have a basic understanding of the Fourier series and why it is important. The Fourier series is defined to be:

$$f(t) = \sum_{n=0}^{\infty} \left(A_n \cos \frac{2n\pi}{T} t + B_n \sin \frac{2n\pi}{T} t \right)$$

Where A_n and B_n are constants. What this means is that most periodic functions $f(t)$ (those that have a finite number of finite discontinuities and no vertical asymptotes) can be represented using a unique combination of sine and cosine waves of different frequency and magnitude. A periodic function is one that repeats the same behavior over and over again. A pendulum swinging back and forth has periodic motion, and the horse's vertical head and pelvis displacement are both functions that would follow periodic behavior.

The Fourier series is just another way to represent a function. Sometimes it helps to have a function in terms of periodic functions (like $\sin x$ and $\cos x$), Ideally, we would be able to use infinitely many terms to express the function, but that is not physically possible, especially in a clinical setting like a lameness exam. So, we make due by truncating the values of n but the larger the n the more accurate the estimation will be.

Knowing that we can use the Fourier series to estimate a function is nice, but ultimately not very helpful if we cannot find the magnitudes, A_n and B_n. To find them, there are some hypotheses that need to be true. Let us examine what happens with several different integrals containing sine and cosine functions.

Using the fundamental theorem of calculus and trigonometry properties, we see that there are three potential solutions to the integral:

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} \cos\left(\frac{2\pi m}{T}t\right)\cos\left(\frac{2\pi n}{T}t\right)dt = \begin{cases} 0, & m \neq n \\ T, m = n = 0 \\ \frac{T}{2}, m = n \neq 0 \end{cases}$$

We can also show that:

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} \sin\left(\frac{2\pi m}{T}t\right)\sin\left(\frac{2\pi n}{T}t\right)dt = \begin{cases} 0, m \neq n \text{ } or \text{ } m = n = 0 \\ \frac{T}{2}, & m = n > 0 \end{cases}$$

And finally, we see that:

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} \sin\left(\frac{2\pi m}{T}t\right)\cos\left(\frac{2\pi n}{T}t\right)dt = 0 \; \forall \; m, n \in \mathbb{R}$$

These results will be helpful in determining the equations for the A_n and B_n coefficients.

Now let's find A_n. To do this, we need to begin with the original definition of the Fourier series and work from there. We will multiply both sides of the equation by $\cos(\frac{2k\pi}{T}t)$:

$$f(t)\cos(\frac{2k\pi}{T}t) = \sum_{n=0}^{\infty}\left(A_n\cos(\frac{2k\pi}{T}t)\cos\frac{2n\pi}{T}t + B_n\cos(\frac{2k\pi}{T}t)\sin\frac{2n\pi}{T}t\right)$$

Now we will integrate each side on the interval $(-\frac{T}{2},\frac{T}{2})$ with respect to t to yield:

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\cos(\frac{2k\pi}{T}t)\,dt = \sum_{n=0}^{\infty}\left(\int_{-\frac{T}{2}}^{\frac{T}{2}}(A_n\cos(\frac{2k\pi}{T}t)\cos\frac{2n\pi}{T}t + B_n\cos(\frac{2k\pi}{T}t)\sin\frac{2n\pi}{T}t)dt\right)$$

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\cos(\frac{2k\pi}{T}t)\,dt = \sum_{n=0}^{\infty}A_n\int_{-\frac{T}{2}}^{\frac{T}{2}}\cos(\frac{2k\pi}{T}t)\cos\frac{2n\pi}{T}t\,dt + \sum_{n=0}^{\infty}B_n\int_{-\frac{T}{2}}^{\frac{T}{2}}\cos(\frac{2k\pi}{T}t)\sin\frac{2n\pi}{T}t)dt$$

From the previous results, we know that $\int_{-\frac{T}{2}}^{\frac{T}{2}}(\cos\left(\frac{2k\pi}{T}t\right)\sin\frac{2n\pi}{T}t)dt)$ is always 0, so now we have

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\cos(\frac{2k\pi}{T}t)\,dt = \sum_{n=0}^{\infty}A_n\int_{-\frac{T}{2}}^{\frac{T}{2}}(\cos(\frac{2k\pi}{T}t)\cos\frac{2n\pi}{T}t\,dt$$

Let us examine the case when $k = 0$. We know that $\cos(0) = 1$ so this becomes

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)dt = \sum_{n=0}^{\infty}A_n\int_{-\frac{T}{2}}^{\frac{T}{2}}\cos\frac{2n\pi}{T}t\,dt$$

Now, we can see that the only term of the infinite sum that remains is when $n = 1$, as any other value for n results in multiplying A_n by 0. So now we see that when $k = 0$ we are left with the following:

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)dt = A_0T$$

$$A_0 = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)dt$$

We now have an equation for the first term of the series. To see what happens in the other cases, let us consider what happens when $k > 0$. Note that we do not need to worry about $k < 0$ because $f(x) = \cos x$ is an even function; that is, $\cos(-x) = \cos(x)$. When $k > 0$, only the k^{th} term will survive. All the other terms will go to 0, so now we have:

$$\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\cos(\frac{2k\pi}{T}t)\,dt = A_k\frac{T}{2}, or\ A_k = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\cos\left(\frac{2\pi k}{T}t\right)dt$$

In a similar manner, we can see that we can find each constant coefficient B_k as follows:

$$B_k = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\sin\left(\frac{2\pi k}{T}t\right)dt$$

Finding the values of the coefficients A_n and B_n means that we now have a value for the magnitude of each periodic component. In short, the magnitude tells us “how much” of each component is needed to make the total function. For example, a function with high frequencies might need more of a higher frequency periodic component, or a function with few changes might need a majority of low frequency components. The weight each frequency is given comes from information gathered from the original function as well as its dependence on $\sin x$ and $\cos x$ for different values of x. When the two are combined, it provides us with an overall representation of the function.

All of these equations are rather complicated and are much better understood with a simple example. Let us consider the following function:

$$f(t) = \begin{cases} t, -1 \leq t \leq t \\ 0 \; otherwise \end{cases}$$

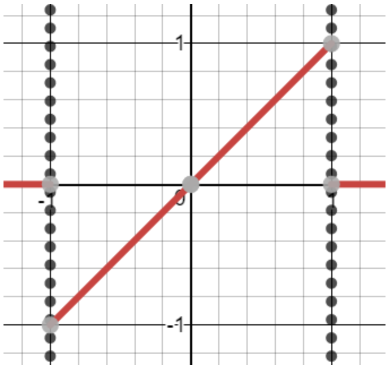


Figure 10: Graph of f(t). Image created with desmos.com/calculator

We can find a series of sine and cosine graphs to estimate it. The period T of $f(t)$ is 2, the width of the main window from which the function is being defined. Now, to calculate A_0 we use:

$$A_0 = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)dt \text{ or } \qquad A_0 = \frac{1}{2}\int_{-1}^{1} t\, dt$$

Using the fundamental theorem of calculus to integrate we see that $A_0 = \frac{1}{2}\left(\frac{1}{2} - \frac{1}{2}\right) = 0$. Likewise, using the equation for find values for A_k tells us that all $A_k = 0$.

$$A_k = \int_{-1}^{1} t\cos(\pi kt)\, dt$$

We can use integration by parts. Let

$u = t$	$dV = \cos(\pi kt)\, dt$
$du = dt$	$V = \frac{-\sin(\pi kt)}{\pi k}$

So we get

$$A_k \frac{-\sin(\pi kt)}{\pi k} t\Big|_{-1}^{1} - \int_{-1}^{1} \frac{-\sin(\pi kt)}{\pi k} dt$$

$$A_k = \frac{-\sin(\pi k)}{\pi k} - \left(\frac{-\sin(\pi k)}{\pi k}\right) - \int_{-1}^{1} \frac{-\sin(\pi k t)}{\pi k}\, dt$$

$$A_k = -\int_{-1}^{1} \frac{-\sin(\pi k t)}{\pi k}\, dt$$

$$A_k = -\frac{1}{\pi k} \int_{-1}^{1} -\sin(\pi k t)\, dt$$

$$A_k = -\frac{1}{\pi^2 k^2} (\cos \pi k t \,|_{-1}^{1})$$

$$A_k = -\frac{1}{\pi^2 k^2} (\cos \pi k - \cos \pi k)$$

$$A_k = 0.$$

This result tells us something very important about the graph of $f(t)$. Because $A_k = 0$ for all values of k, this means that no cosine harmonic functions are needed to represent the graph. Strictly speaking, this means that $f(t)$ is an odd function, meaning that it reflects about the *x* and *y*-axis.

Now, to find the values of B_k, we will use the following:

$$B_k = \int_{-1}^{1} t \sin\left(\frac{2\pi k}{T} t\right) dt$$

Following similar steps as before, we get the following result:

$$B_k = \frac{2}{\pi k} (-1)^k$$

Now we can see that the Fourier series of the function $f(t)$is:

$$f(t) = \frac{2}{\pi} \sin(\pi t) - \frac{1}{\pi} \sin(2\pi t) + \frac{2}{3\pi} \sin(3\pi t) - \cdots$$

Looking at the table below, we can see that the more terms we add to the end of the Fourier series estimation, the more accurate the estimation gets. Here we only went out to $k = 3$ but imagine how accurate this estimation would get as $k \to \infty$.

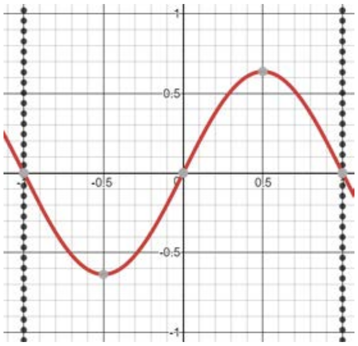
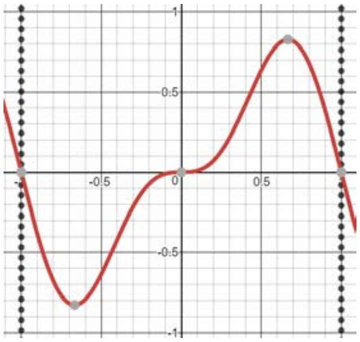
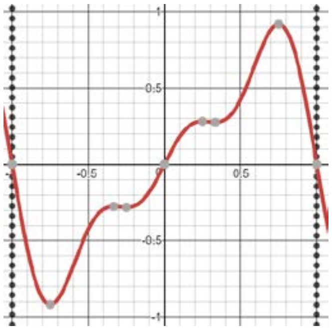
$f(t) = \frac{2}{\pi}\sin(\pi t)$	
$f(t) = \frac{2}{\pi}\sin(\pi t) - \frac{1}{\pi}\sin(2\pi t)$	
$f(t) = \frac{2}{\pi}\sin(\pi t) - \frac{1}{\pi}\sin(2\pi t) + \frac{2}{3\pi}\sin(3\pi t)$	

Figure 11: Comparisons of Fourier Series Estimations for f(t) Images created with desmos.com/calculator

Now that we've seen how the Fourier series works on a simple function, we can start to think about how we would represent more complicated data, like that obtained from a horse's head or pelvis. The inertial sensors that are placed on the horse's head and pelvis collect data at a high rate, usually 200 frames per second (Keegan K. G., 2011). These data points are then graphed as vertical displacement with respect to time. Once collected, it will look something like the following. Note that this is an approximation and does not represent actual data.

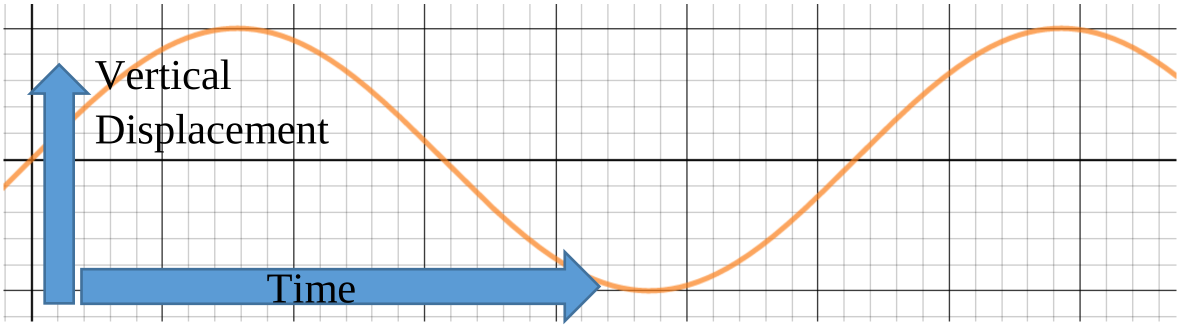


Figure 12: Graph showing vertical displacement with respect to time. Graph made using desmos.com/calculator

The periodic motion represented in the above graph is indicative of that of the head position of a moving horse. At the beginning of the stance phase of a front limb, the head reaches down towards the ground, and once the leg goes into the swing phase the upwards force pushes the horse's head up again. As the swing phase comes to an end, the force exerted by the leg during the propulsion phase is overtaken by the force of gravity, bringing the leg and head back to the ground.

As mentioned previously, the pattern of the head and pelvis changes with lameness. Now, using the Fourier series, we can estimate a function that describes the vertical displacement of the head or pelvis, and use the data to determine lameness.

Again, creating a true representation of the graph using computations is impossible because we can never actually reach infinity. Luckily, researchers found that a relatively small number of frequencies are involved in the vertical motion of the horse's head. If $y(t)$ is the function describing vertical head movement of the horse at different times t, then we can represent $y(\bar{t})$ as a combination of three types of harmonic motion: a) a harmonic component with frequency 2ω that is used to describe the normal vertical head movement, b) a harmonic component with frequency ω that represents the changes in motion due to lameness in one leg, and c) an harmonic component with a low frequency that can be used to represent extraneous head movement. The function $y(\bar{t})$is shown below:

$$y(\bar{t}) = C_1 \cos(\omega\bar{t}) + C_2 \sin(\omega\bar{t}) + C_3 \cos(2\omega\bar{t}) + C_4 \sin(2\omega\bar{t}) + C_5 + C_6\bar{t} + C_7\bar{t}^2 + C_8\bar{t}^3$$

Where $\bar{t} = t - t_m$, t_m being the observed time and t being observed points surrounding the actual point. In order to make a more accurate estimation, researchers used data points around the actual observed time that made E_{rror} the smallest. To calculate the error, the following equation is used, where $y_i = y(\bar{t}_i)$ and Y_i =experimental data at $\bar{t}_i$:

$$E_{rror} = \sum_{i=-N}^{N} \frac{(y_i - Y_i)^2}{1 + \left|\frac{99i}{N}\right|}$$

The denominator represents a weighting constant that makes closer data points of more importance to the error calculation. Once the error has been determined, the coefficients from the equations describing $y(\bar{t})$ are calculated by taking the partial derivative with respect to each respective C_j.

$$\frac{\partial E_{rror}}{\partial C_j} = 0, j = 1,2,3,4,5,6,7,8$$

It is interesting to note that at $\bar{t} = 0$ $(t = t_m)$,

$$y(\bar{t}) = C_1 + C_3 + C_5$$

Meaning that the displacement is the sum of the magnitudes of both components of harmonic motion and the moving average (Keegan K. G., 2000).

The use of these equations is an essential part of using inertial sensors, and without the power of the Fourier series it would be incredibly difficult to estimate vertical displacement of the head and pelvis. The equations behind this have been highly researched and shown to be incredibly accurate, lowering the estimation error from 3% to 0.3-0.5% (Keegan K. G., 2000). With such accurate results, veterinarians are able to capture a much larger set of information about the horse's movement than ever before.

The implications behind the ability to represent vertical head displacement are huge. Now, veterinarians can analyze the magnitude of the periodic component with frequency ω and have a number describing the amount of impact it has one the horse's movement. The larger the value of C_1 and C_2 (the sine and cosine components with frequency ω), the greater influence the unilateral lameness component has on the overall head movement.

Limitations of Inertial Sensors

Inertial sensors are not universally accepted as appropriate replacements for the human eye. Sue Dyson, head of Clinical Orthopedics at the Center for Equine Studies in Suffolk, UK, expresses her concerns about inertial sensor data in her article "Recognition of Lameness: Man versus Machine”. She notes that “while I cannot challenge the potential value of IMUs (inertial measurement units) to detect a unilateral lameness in straight lines, I feel that there are currently many limitations to the use of IMUs for the assessment of lameness in more than one limb, particularly for lameness that is only apparent on a circle, especially if only when ridden” (Dyson, 2014). She also shows concern that what veterinarians are using as a “standard” or “sound” horse isn’t really a sound horse. In a study conducted by Dyson, they examined 506 sport horses that were reported as sound by their owners. However, Dyson discovered that “approximately 47% of the horses had what we believed were pain-related gait abnormalities” (Dyson, 2014). If the normal ranges for these inertial sensor data are obtained with horses that are not sound, that has the potential to skew the data, showing that a sound horse is not sound or vice versa.

Both of the questions Dyson raises are completely valid and are some of the biggest issues facing the use of inertial sensor data in lameness examinations. However, I believe that the benefits of using inertial sensors outweigh the downsides. To refute her claim that the standard for sound horses will not be accurate since not all of the horses are sound, consider the fact that not all horses display lameness in the same leg. Assuming the equine population does not show lameness in one leg more than another, the data collected from horses that are not sound will be cancelled out by horses with lamenesses in opposing legs.

Dyson’s concern about the accuracy of inertial sensors to detect lameness only noticeable on a circle is a bigger concern. Horses will naturally put more weight on the inside legs while traveling on a circle, so the use of inertial sensors to determine head movement will be fundamentally changed on a circle. Not only does the path of the horse have an impact on movement, but the surface is also hugely important in lameness evaluation. A soft, more forgiving surface does not provide as strong of a ground reaction force, meaning that is better for horses with hard tissue injuries, but the deep footing puts more stress on tendons and ligaments, worsening the pain experienced from injuries to those structures. Similarly, on a hard surface like packed gravel or asphalt, the increased ground reaction force enhances the effect of hard tissue pain. At the moment, inertial sensors are not capable of determining the difference between paths or surfaces, so these tools should be used with caution by veterinarians.

Another potential issue with inertial sensors was identified by J.R. Donnell et at. When comparing objective lameness evaluations, inertial sensor data, and a force plate, they found that "variability in ISS (inertial sensor system) data (head movement) between strides was much higher than was found with the [force plate] data collected. Outliers in the ISS data could have influenced the results for lameness detection, potentially identifying more horses as lame" (Donnell, 2015). It makes sense that inertial sensors have more variation than force plates as inertial sensors rely on head movement. While the above method of signal decomposition limits the error due to extraneous head movement, there still remains variability in the data. With only three components to harmonic motion, it is impossible to get a completely accurate model for the movement.

One of the huge assumptions of the model outlined above is that there is only ever one lameness existing at the same time. However, due to our understanding of compensatory lameness we know that this is only the case for a small number of horses. In order to account for the potential of more than one lameness, the model must be modified and further complicated.

To gain a better understanding of a practicing veterinarian, I spoke with Dr. Steve Latimer of Northwest Equine Veterinary Associates, a lameness specialist in the Pacific Northwest. Dr. Latimer has several concerns with the use of inertial sensors in the lameness exam. Firstly, he noted that the time it takes to place the sensors on the horse is limiting in clinical work. He also noted that in order for veterinarians to become fluent in using these products, they must use them on every horse. Dr. Latimer said he believes that inertial sensors are an immensely helpful learning tool for new veterinarians, but does not believe they would improve the quality of his diagnoses. Cost is also a limiting factor while using inertial sensors. There is only one product marketed for veterinarians and its high cost makes in inaccessible for many veterinarians running their own practice.

Finally, one of the largest reasons inertial sensors have not been more commonly used in a clinical setting is practitioner bias against technology. The idea that technology can do their job, and in many cases do it better than them, is disconcerting to not only veterinarians but any professional whose field is saturated with technology. Veterinarians worry that inertial sensor data will take away the art that accompanies lameness diagnosis and make it a skill that almost anyone (thinks) they can do, causing fewer owners to call the vet when their horse is lame. Additionally, there is concern that the use of inertial sensors in veterinary training will have a negative impact of new veterinarian's ability to diagnose lameness. However, it is essential to note that data collected from inertial sensors is nothing without the veterinarians who interpret it.

Potential Solutions

Of the concerns surrounding the use of inertial sensors in a clinical practice, most are answered with the simple response: more research. More extensive studies are needed to gain a better understanding of the way compensatory, secondary, and multiple limb lameness affect equine movement, and with more research will come a greater ability to diagnose more complex lamenesses.

The use of inertial sensors to detect unilateral lameness on a straight line is well documented, but there are so many other situations that need to be studied. For example, compensatory lameness have begun to be more commonly documented and further research is needed to show how it impacts head and pelvis movement. Additionally, it is important to research lameness stemming from places other than the distal limb, like the neck or sacroiliac joint. These lamenesses are becoming more and more common as veterinarians learn how to diagnose them. Research in inertial sensor data for these types of lamenesses would be beneficial to many horses.

In order to counteract the technological bias faced by inertial sensors, proper education is essential. It is of the utmost importance for those selling products using inertial sensors and for those teaching veterinary students to emphasize that the use of inertial sensors is not providing a definitive diagnosis, but rather providing the clinician with more information that can be used to help diagnose lameness.

Conclusion

Writing this thesis has been a true joy. It has not always been fun or easy, but that is what makes it so special. In many ways, this thesis is a culmination of my time at Regis, and in particular the honors program. The research I studied brings up several important questions, not only about horses and lameness but about the way we interact with the world around us. As I said in my introduction, I believe that we owe it to our horses to keep them healthy and happy for as long as possible. Working towards a better understanding of the way lameness works and how it presents itself in horses can make us more aware of discomfort in our equine friends.

While the health and comfort of our horses is of the utmost importance, it is also important to address the bigger questions raised by the use of inertial sensors in lameness diagnosis. Can lameness be diagnosed by a computer? What does this mean about other medical procedures? Will we one day live in a world where our doctors and caretakers are all machines programmed to do their jobs flawlessly?

There is no doubt that medical technology has saved countless lives, and it will continue to do so at a rapidly increasing rate. These changes have bled into the veterinary world too. More and more animals are being given a second chance at life due to life-saving drugs or treatments. By and large, doctors and veterinarians have accepted these changes readily. However, we are seeing a backlash in the equine veterinary community in regards to using inertial sensors to diagnose lameness. Veterinarians are worried that the art of lameness diagnosis will be replaced by computers. They fear that lameness will be broken down into specific components that diagnose horses without applying common sense. It would be wrong to deny cases where technology has led us astray, but the large majority of technology has made our lives much better. Why not take advantage of the world that we live in to make the world a better place? What is the point of researching and discovering if we never use the information obtained?

We can extrapolate all sorts of crazy scenarios where humans have been removed from making important decisions. But at the end of the day, I believe that humans are distinguishable from machines. By bringing our own thoughts, ideas, passions, and yes, errors, into science, humans breathe life into the very topics they study. Not by making them superior to us, but by showing that there is always more beauty and complexity than originally meets the eye. The very thing that makes us human and imperfect is what drives scientific discovery: passion. If humans did not have passion for their ideas and their world, there would be no motivation for us to explore the universe. The inertial sensors used to collect data on lame horses would never have been placed there had it not been for a group of curious and passionate researchers that wondered what would happen if they did just that.

At the end of the day, technology is simply a tool that humanity has created in order to better themselves. It is not sentient nor do I believe it ever will become sentient. Machines and computers are missing that fundamental spark, that curiosity that propels humanity forward. Machines do not experience happiness, pain, loss, anger, or excitement. They have no inner drive, no insatiable thirst for knowledge. They will never know the joy a 4 year old feels the first time she sees a horse. They will never know the pain that a 16 year old girl feels when her best friend is in so much pain he can no longer stand. They will never know that hopelessness that girl feels. And they will never know what it feels like to watch in awe as realms, seemingly unrelated, collide in a way that seems to perfectly represent what someone is feeling. That is what these sensors are missing.

In his book *A Sense of the Mysterious*, Alan Lightman, a physicist and author, writes about the different between science and the humanities. He says simply that "every electron is identical, but every love is different" (Lightman, 2005). Humans, in all their uniqueness, have the opportunity to experience things no one else has ever experienced before. They can bring together ideas that no one else may have thought of, and consider possibilities that a machine could never comprehend. Their completely original life and experiences lend themselves to a single paradigm through which they, and only they, can view the world. This uniqueness is not exclusive to humans. I believe that animals experience it too. Their individuality, the reason that lameness diagnosis is so difficult, breathes life into the partnership between human and horse and makes the emotional bond between the two that much stronger.

We use math everywhere and in everything. While I type this, thousands upon thousands of tiny computations are being made to make the words appear on the page. Math has built the world around us. It's everywhere. So why not use it with horses?

Discovering the equations that can be used to represent equine head movement is only a drop in the bucket. We can use math to estimate flight trajectories, improve our public infrastructure, and optimize the use of precious resources. The possibilities are endless. But the only way these representations can help us is if curious minds seek them out. Math may exist on its own, but its true power lies in its ability to be understood and analyzed by humans. The role of the mathematician and the scientist are similar in that regard. Both are there to express, celebrate, understand, and truly see the workings of the universe. It is only fair that we use that power to make the world a better place.

Glossary of Terms

Term	**Definition**
Baseline Lameness	“the gait abnormality before flexion or manipulative tests are used,” or, in other words, the way the horse moves before the veterinarian has done anything that might change the movement of the horse (Ross, 2003)
Bilateral	The opposite fore or hindlimb. For example, the leg bilateral to the left forelimb is the right forelimg
Biomechanics	Scientific study of living organisms using physical principles. There are several different branches of biomechanics which all form together to make up the broader term.
Breakover	The point at which the limb moves from the deceleration phase to the propulsion phase
Contralateral	The diagonal leg. For example, the leg contralateral to the left hindlimb is the right forelimb
Deceleration Phase	Part of the stance phase of stride, it begins when the heel touches the ground and ends when the leg is in mid-stance (where the leg is in a vertical position).
Fourier Series	
Froude Number	“The ratio of the centrifugal force pulling the body’s center of mass upward as it swings over the arc described by the leg, to the force of gravity acting to pull that mass down” (Budiansky, 1997).
Gait	A sequence and timing of footfalls
Ground Reaction Force	“external force exerted by the ground against the hoof” (Clayton, 2004)
Ipsilateral	The corresponding fore or hindlimb on the same side. For example, the leg ipsilateral to the left forelimb is the left hindlimb
Kinematics	A “branch of biomechanics describing the motion of bodies” (Clayton, 2004).
Kinetics	A “branch of biomechanics describing the forces involved in creating and changing motion” (Clayton, 2004).
Lameness	“a change in gait, usually in response to pain somewhere in a limb, but also possibly as a result of mechanical restriction on movement. We all think of lameness when a horse is obviously limping, but lameness may only cause a subtle change in gait, or even just a decreased ability or willingness to perform” (Thal, 2016).
Law of Sides	Explanation of compensatory lameness patterns. An ipsilateral lameness is usually a primary hindlimb lameness and a

	contralateral lameness is usually a primary forelimb lameness
Ligament	Structure connecting bone to bone
Mixed Lameness	Changes in gait during weight bearing or the stance phase and during the swing phase of the stride" (Ross, 2003). Most common form of lameness
Propulsion Phase	Part of the stance phase of the stride where the leg creates a propulsive force used to continue the horse's forward motion (Leach, 1984)
Supporting Limb Lameness	Pain during the weight-bearing phase of the stride (Ross, 2003).
Suspensory Ligament	Ligament in the horse's leg which supports the pastern joints and aids in energy conservation
Stance Phase	Phase of stride where the leg is weight-bearing and in contact with the ground
Swing Phase	Phase of stride where the leg is soaring through the air with no attachment to the ground
Swinging Limb Lameness	Pain during the swing phase of the stride
Tendon	Structure connecting muscle to bone
Unilateral	Occurs only on one side of the body, or in the case of lameness, in one limb

Bibliography

Barry, E. (1999). Methods, Applications and Limitation of Gait Analysis in Horses. *The Veterinary Journal*, 7-22.

Betram, J. E. (2013). Gait as a Solutions, but what is the problem? Exploring cost, economy and compromise in locomotion. *The Veterinary Journal, 198*, e3-e8.

Budiansky, S. (1997). *The Nature of Horses: Exploring Equine Evolution, Intelligence, and Behavior.* New York, NY: The Free Press.

Chateau, H. e. (2013). Kinematics of the Forelimb in Horses Circling on Different Ground Surfaces at the Trot. *The Veterinary Journal, 198*, e20-e26.

Clayton, H. M. (2004). *The Dynamic Horse: A Biomechanical Guide to Equine Movement and Performance.* Madison, WI: Sport Horse Publications.

Crevier-Denoix, N. e. (2013). Comparision of Superficual Flexor Tendon Loading on Asphalt and Sand in Horses at the Walk and Trot. *The Veterinary Journal, 198*, e130-e136.

Degueurce, C. e. (1997). Variability of the Limb Joint Patterns of Sound Horses at Trot. *Equine Veterinary Journal, Supplement 23*, 89-92.

Donnell, J. e. (2015). Comparison of Subjective Lameness Evaluation: Force Platforms and an Inertial-Sensor System to Identify Mild Lameness in an Equine Osteoarthritis Model. *The Veterinary Journal, 206*, 136-142.

Dyson, S. (2014). Recognition of Lameness: Man versus Machine. *The Veterinary Journal, 201*, 245-248.

Equine Prepurchase Exams. (n.d.). Retrieved from The Horse: http://cdn.thehorse.com/images/cms/2014/08/flexion-test.jpg?preset=slideshow

Farley, C. T. (1991). A Mechanical Trigger for the Trot-Gallop Transition in Horses. *Science, 253*, 306-308.

Keegan, K. (2010). Repeatability of Subjective Evaluation of Lameness in Horses. *Equine Veterinary Journal, 42.2*, 92-97.

Keegan, K. G. (1998). Evaluation of Mild Lameness in Horses Trotting on a Treadmill by Clinicians and Interns or Residents and Correlation of their Assessments with Kinematic Gait Analysis. *American Journal of Veterinary Research, 59.11*, 1370-1377.

Keegan, K. G. (2000). A Curve-Fitting Technique for Evaluation Head Movement to Measure Forelimb Lameness in Horses. *Biomedical Sciences Instrumentation, 36*, 239-244.

Keegan, K. G. (2004). Evaluation of a Sensor-Based System of Motion Analysis for Detection and Quantification of Forelimb and Hind Limb Lameness in Horses. *American Journal of Veterinary Research, 65.5*, 665-670.

Keegan, K. G. (2011). Gait Analysis for the Quantification of Lameness. In *Diagnosis and Management of Lameness in the Horse* (2nd ed., pp. 245-251).

Kelmer, G. (2005). Computer-Assisted Kinematic Evaluation of Induced Compensatory Movements Resembling Lameness in Horses Trotting on a Treadmill. *American Journal of Veterinary Research, 66.4,* 646-655.

Kramer, J. (2004). Objective Determination of Pelvic Movement during Hind Limb Lameness by use of a Signal Decomposition Method and Pelvic Height Differences. *American Journal of Veterinary Research*, *65.6,* 741-747.

Kramer, J. a. (2014). Kinematics of Lameness. In *Equine Sports Medicine and Surgery* (pp. 223-238).

Lameness Exams: Evaluating the Lame Horse. (n.d.). Retrieved from American Association of Equine Practitioners: http://www.aaep.org/info/horse-health?publication=836

Leach, D. (1984). Standardised Terminology for the Description and Analysis of Equine Locomotion. *Equine Veterinary Journal, 16.6*, 522-528.

Lesile, M. (2001, May/June). *The Man Who Stopped Time.* Retrieved from Stanford Alumni: https://alumni.stanford.edu/get/page/magazine/article/?article_id=39117

Mendex-Angulo, J. L. (2014). Impact of Walking Surface on the Range of Motion of Equine Distal Limb Joints for Rehabilitation Purposes. *The Veterinary Journal, 199*, 413-418.

Murray, R. e. (2010). How do Features of Dressage Arenas Influence Training Surface Properties Which are Potentially Associated with Lameness? *The Veterinary Journal, 186*, 172-179.

Orito, K. e. (2007). Identification of Equine Subclinical Lameness Induced by Pressure to the Sole of Fore- or Hind-Limb. *Journal of Equine Veterinary Science*, *27.10*, 429-434.

Poore, L. A. (2011). A Quantitative Review of the Equinalysis System for Equine Locomotion Analysis. *The Journal of Veterinary Science, 31*, 717-721.

Ross, M. W. (2003). *Diagnosis and Management of Lameness in the Horse.* St. Louis: Saunders: An Imprint of Elsevier.

Starke, S. D. (2013). The Effect of Trotting Speed on the Evaluation of Subtle Lamenesses in Horses. *The Veterinary Journal*, *197*, 245-252.

Starke, S. M. (2015). Understanding Hind Limb Lameness Signs in Horses using simple rigid Body Mechanics. *Journal of Biomechanics*, *48*, 3323-3331.

Thal, D. (2016). *Horse Health: Understanding Lameness.* Retrieved from American Association of Equine Practitioners: http://www.aaep.org/info/horse-health?publication=837