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BIOMECHANICS OF INJURY AND HEALING

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Introduction

The term biomechanics can be used in a casual way to describe movement, but the specifics of this field of science are based in engineering and physics. The definition of biomechanics is the fundamental physical mechanics (physics) responsible for a given action, reaction or result in a biological system.

When an injury occurs, the problem solving begins with a clinical exam and a series of diagnostic tests to determine the structural cause of the problem. Then the biomechanist offers expertise to evaluate the kinetics and kinematics that may be influencing factors. Together the biomechanist and the clinical physical therapist devise an exercise protocol to influence the mechanics of movement, which will address the long-term changes that need to occur to improve healing and minimize reinjury. In addition, prevention of injuries is possible when the understanding of how an injury occurs is improved.

This paper will look specifically at the role biomechanics plays in injury, and recovery from injury, using a several musculoskeletal examples. Human and equine biomechanical research will be reviewed, followed by a discussion of how that research may be applicable in equine rehabilitation to develop healthy movement patterns. These discussions are intended to offer a framework for rehabilitation protocol development so that other professionals can add to this discussion and refine and improve the concepts introduced.

General Biomechanical Terminology

Definitions of biomechanical concepts can be extremely precise. However, in most circumstances a general understanding of the terminology is appropriate. The following is a list of some of the most common biomechanical terms for reference.

Velocity and Speed - In general these two terms can be used interchangeably for practical purposes. However, there are distinct differences between the two concepts; velocity is a vector quantity, and is the rate at which an object changes its position in a specific direction, while speed is a scaler quantity, and refers to how fast an object is moving regardless of direction. For example an object's velocity would be three mph **East,** while the speed of an object would be three mph.

Acceleration - The change of velocity with respect to time. For example, the acceleration of your car is determined by how fast it can go from 0 to 60 mph.

Momentum - Is the product of mass and velocity and is the quantity of motion a body possesses. The greater the momentum the more pronounced an effect the momentum produces on other bodies in its path. It requires more force to change the direction of a body that possesses high momentum.

Force – Is the product and mass and acceleration (gravity). It is what alters a body's state of rest or of uniform motion. Internal forces are within the body and external forces are outside of the body.

Torsion, Shear, Bending and Compression - The diagram below shows the differences between loading of these parameters (Figure 1). Bending is the combination of tension and compression, and in the example of bone loading, is often superimposed on axial compression.

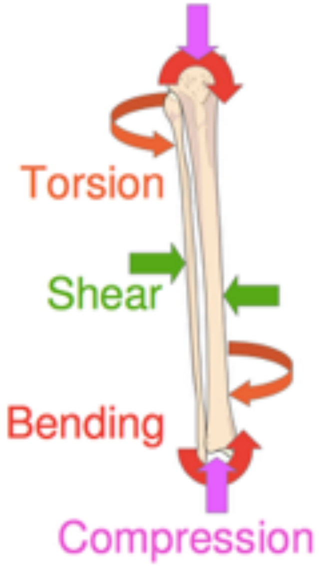

Figure 1. Forces and the direction of action. Courtesy of Dr. James Funk, Ph.D, PE and Biodynamic Research Corporation.

Rotation - Also called angular motion. Movement along a circular path about some line in space. This line can be within the body or external to the body.

The biomechanics of sports injury

Injury occurs when stress (amount of force/area applied) and/or strain (degree of deformation in response to stress) is higher than the tissue can withstand. In addition, the direction the force is applied is related to injury. For example, a limb bone can handle a higher level of force when it is applied during compression, than when that same force is applied during torsion. To reduce injury, the forces need to be managed in a variety of ways to reduce breakdown. Breakdown can occur as a traumatic injury, such as what happens when a horse falls or is kicked, or injury can occur over time as a chronic injury. The focus of this paper will be on the biomechanics of injury and rehabilitation techniques for chronic injuries.

Recently, the understanding of the events leading to sports injury have greatly improved due to the ease of obtaining high-speed video showing the occurrence of the actual injury. Matching the post-injury diagnostics with the injury video data in a real-world situation has helped to refine the knowledge of how injury occurs (Kwon et al, 2010). In addition, research has shown that data from previous cadaver studies are not reproducible as good predictors of injury (Gitajn and Rodriguez, 2011).

Some muscles seem to be more prone to injury than others and eccentric (lengthening) muscle action is frequently the cause of injury (Brockett, 2004). In humans, the hamstrings are a common site of muscular injuries with the biceps femoris muscle being the most frequently injured. In one study, the biceps femoris was the muscle injured in 83% of 154 hamstring injuries (Connell, 2004). It has been proposed that this high injury rate could be due to the biarticular function of the muscle making this muscle more prone to injury (Whiting and Zernicke, 2008). In addition, proximal and lateral injuries to the biceps femoris muscle bellies are common in humans (Garrett et al, 1989) and it has been proposed that this is due to the fact that these muscles have their length determined by the coaction of two joints (e.g. the hip and knee) (Thelen et al, 2005). For example, with the combination of hip flexion and knee extension, the hamstrings are placed in a maximally lengthened state predisposing it to injury (Whiting and Zernicke, 2008).

The development of protocols is a long process and there are always those horses that fall outside of the average response to rehabilitation. However, these caveats should not stop the development of protocol design. The formation of a rehabilitation protocol ‘skeleton’ onto which practitioners can begin to pin their expertise seems to be a useful exercise, and the following discussions are meant to promote that collaborative process.

Human biomechanics and the relationship to equine biomechanics in developing physical rehabilitation protocols

In one study looking at the effects of falling, human subjects were told to “keep their hands as far away from the ground as long as they could” (increasing elbow flexion) during falling and the results were compared to the forces measured when the subjects were allowed to “arrest the fall naturally”. Subjects were able to reduce the force of impact by 27% by flexing their elbows (DeGoede and Ashton-Miller, 2002), which reduced the velocity of the hands hitting the ground as a result of increasing the time over which force was applied. When subjects were then told to fall with “stiff-arms” the forces were increased by 40% when compared to falls were the elbow was flexed (DeGoede and Ashton-Miller, 2002). If changes in movement patterns can reduce impact forces this significantly, the reduction in injury risk can be large. In addition, the authors cited that flexing the elbow during falling was so significant that this movement pattern change was more important than bone strength in reducing injury.

In another human study, knee angle upon landing was correlated with impact forces. It was found that the angle of the knee at contact significantly influenced both peak ground reaction forces (GRF) and acceleration of the tibia, thigh and trunk body segments. In addition, the peak forces and accelerations increased more rapidly when the angles of these body segments were close to full extension, and this is related to the decreased period of time during which the force was applied (Elvin et al, 2007a).

Translating these concepts to equine rehabilitation would indicate that evaluating the degree of flexion of joints during ground contact is important. Developing exercises that improve joint flexion will not only help reduce impact forces, but may also develop a movement pattern to reduce future chances of injury. Examples of exercises that could help lower landing velocity, include slowing the speed of the gait of the horse and then, to increase joint flexion, encouraging higher carpal and hock action. Higher carpal and hock action is also a more natural reaction when the gait is slower. In addition, flexion of the carpal and hock joints results in an associated increase in the flexion of the fetlock in the distal limb. For jumping, tightening the distances between the fences to help slow the horse, while choosing the appropriate height of the fence to obtain the desired joint flexion, could prove helpful rather than just increasing the height of the fences. Another example would be using gymnastics such as bounces, one-strides or two-strides in a gymnastic series at lower jumping heights, while keeping the speed slow to encourage more distal joint flexion, when compared to joint flexion obtained on the flat. The slower speed will also lower the magnitude of the impact forces. Evaluation of the degree of flexion of distal limb joints at stance in both the fore- and hind limbs during a clinical examination could be a valuable tool in a lameness exam.

Emphasizing stronger shortening of the quadriceps femoris and tensor fascia latae muscles in exercises to flex the hip, while not unbalancing the movement, rather than emphasizing hamstring development exercises may also improve “spring,” or the ability to quickly increase vertical acceleration. Contraction of the biarticular rectus femoris head of the quadriceps femoris will flex the hip and pull the patella upward resulting in extension of the stifle. Co-contraction of the cranial muscles of the leg must also occur so that the flexion of the hock is achieved at the same time as flexion of the hip. In addition, lumbosacral flexion will allow the more distal limb flexion to occur. (Denoix, 2014a). Examples of exercises would include hindquarter flexion movements such as piaffe and passage tendencies of the trot, and slower, more stationary canter strides. For both of these, conceptualize exercises that produce a “duck walk” position in the horse’s hindquarters. Of course, sustaining this limb flexion too deeply or for too long of a period of time will be detrimental. Walk approaches to low jumps, if possible, or very slow trot approaches would be more supportive than long, low strides on the approach to the jump. Shorter distances between jumps would also be indicated.

However, if speed is the major consideration, research has shown that the fastest athletes have the lowest vertical acceleration (strides remain close to the ground) and the highest propulsive impulses (the ability to push against the ground) (Hay and Reid, 1982). The propulsive force of the push off by the foot against the ground accounted for 57% of the variance in speed of sprinters (Hunter et al, 2005). In addition, encouraging the athlete to not stride longer than their natural stride length, encouraging a more active foot touchdown (reduced braking during touchdown), with no excessive hip extension and no quick knee flexion, were also associated with higher sprinting speed. The authors cited that the runner's 'normal' stride, which is not artificially lengthened, assists in the maintenance of balance. The reduction in braking during foot contact, which produced higher forward GRF indicative of greater 'push-off', also allowed for a higher running velocity without increasing fatigue. Lastly, flight time should only be long enough for a repositioning of the limbs, and the height of the foot from the ground should be minimal to increase forward acceleration. A longer flight time will decrease the percentage of total time the feet spend in contact with the ground. This reduced foot/ground contact time will reduce speed because the main means the athlete has to apply propulsive impulse is when the foot is in contact with the ground (Hunter et al, 2005). Therefore, increasing the total number of foot contacts by increasing stride frequency are more important to absolute sprint speed than increasing stride length.

Translating these concepts to equine rehabilitation would indicate that strides, which are closer to the ground with less joint flexion, would increase speed. Steps that are too short, or too high are not as helpful to increase speed. However, increasing stride length past the horse's normal range will not necessarily improve top speed and may push the horse out of balance. Poles placed on the ground over an extended distance to encourage a repetitive low stride that feels natural to the horse, but not asking for an increase in the length of the stride, would be beneficial. In addition, gradually asking the horse to cover the same distance with the same length of stride, but at a faster rate could help to improve speed. Pushing the distance between poles longer and longer in an attempt to improve speed would not seem to be useful.

Emphasizing lengthening of the hamstrings and shortening of the quadriceps femoris and tensor fascia latae muscles in exercises to protract the limb (Denoix, 2014a), while not unbalancing the movement, may also improve speed. Also, shortening of the gluteus medius muscle to retract the hind limb could prove helpful. Examples of exercises to train these muscles would include working the horse in longer, but lower strides, and backing up (Denoix, 2014b). More forward approaches to multiple low jumps emphasizing long, low strides on the approach and longer distances between jumps would also be indicated.

ACL Anterior Cruciate Ligament (ACL) injuries have been studied extensively in human rehabilitation. The knee joint is a complex combination of rotational, rolling and gliding movements, therefore the actual cause of the injury can be multifaceted (Boden et al, 2009). ACL injuries have been found to occur at the highest rate when two factors are present; deceleration and changing directions. Internal rotation (torsion) of the tibia relative to the femur and compressive loading during landing were correlated with a higher risk of ACL injury (Meyer and Haut, 2008).

Equine biomechanical research on the muscle-tendon stresses and elastic energy storage showed that changes in gait increased both tendon and muscle stresses more steeply than did steady-state trotting (Biewener, 1998). These data also support the concept that changes in gait should be minimized during early rehabilitation.

Knee adduction or abduction and the role of muscle interaction as a prelude to human ACL injury, has been debated in the literature (Yu and Garrett, 2007). However, the current research is trending in the direction that landing with the knee in abduction, due to a lack of neuromuscular control, is a risk factor for ACL injury (Hewett et al, 2005), and that training programs to reduce abduction of the knee have also reduced ACL injury (Hewett et al, 1999). Reducing abduction by as little as 2 degrees has been shown to be protective (Chaudhari and Andriacchi, 2006).

Translating these concepts to equine rehabilitation would indicate that quick starts and stops should be reduced during rehabilitation. Rather the riders should be instructed to slow or speed up the horse's movement until the horse almost makes a gait transition and then ask the horse to gradually resume the original speed without changing gaits.

To reduce the pathological rotational joint movement and torsion at the stifle, straight lines should be emphasized and turns should look more like an octagon than a curve. A series of straight lines connected by shallow turns would be a better strategy than thinking about a constant arc during movement after injury. Upon landing from a jump, the rider should allow the horse to take a minimum of three straight strides before turning to the next jump to reduce the deceleration and rotational combination. Human research has shown that during walking, people need three strides to reach a steady state of balance (Miller and Verstraete, 1994). Therefore, three strides would be a reasonable number of strides to remain on a straight line before changing directions so the horse will have time to rebalance before the turn.

In another study of human athletes, GRF were compared to vertical jump height. When forces on the athlete were evaluated, landing forces could be as high as 8 times the body weight of the jumper. However, in this study, there was no correlation between jump height and peak vertical ground reaction forces (Elvin et al, 2007b).

Translating this concept into equine rehabilitation could indicate that other issues rather than fence height may be important contributing factors to injury. If higher fence height improves the other biomechanical aspects of the horse's position during jumping, such as distal limb flexion, on approach, take off, flight and landing, then a higher fence height may be appropriate in earlier stages of rehabilitation. However, increasing fence height too much will override any positive outcome by multiplying GRF above acceptable levels.

Distal limb injuries are frequent in equine athletes. Muscles of the distal limb in humans and horses were once thought to generate the power for movement. However, research has shown that these muscles perform little-to-no net mechanical work during level, steady-speed locomotion (e.g. Roberts et al, 1997; Biewener et al, 2000; Daley and Biewener, 2003), while the tendons experience high levels of strain. A consensus from these pioneering works and related studies is that when evaluating the function of the tendon, it is essential that the action of the associated muscle belly must also be evaluated (Butcher et al, 2009), and that muscular imbalances likely effect tendon function (Arampatzis, 2013).

Research on horses has found that in the forelimbs, one head of the complex deep digital flexor (DDF) muscle flexes the fetlock in late swing and, although it is largely a positional control muscle, its fast fiber typing characteristics render it susceptible to fatigue. The DDF muscle/tendon complex stabilizes the hyperextension of the fetlock as well as assisting the superficial digital flexor (SDF) muscle to support the limb during ground contact (Butcher et al, 2007).

In comparison, the SDF muscle belly is more resistant to fatigue than the DDF and undergoes lengthening, resulting in elastic energy storage and recovery by its tendon (Butcher et al, 2009). The long, thin SDF tendon compliments the short, pennate fibers of the SDF muscle belly and allow this muscle/tendon complex to be the main source of elastic energy storage and recovery. This 'spring' effect is best realized at the bouncing trot, and it helps horses save energy, therefore reducing fatigue. The authors cited that when the DDF muscle fatigues, this requires the SDF to bear more load, especially during fast galloping (Butcher et al, 2009).

Looking at the differences in tendon loading across gaits, research found an increase in these parameters on the DDF tendon with a change from walk-to-trot-to-canter (Butcher et al, 2008). The strain, stress and force of the DDF tendon roughly doubled when the walk was compared to the canter. In the SDF tendon, the loading parameters were greater than in the DDF tendon at all gaits (Takahashi et al., 2010). However, in the SDF tendon, the strain, stress and force decreased by 14% from trot to canter, although it is important to note that the SDF muscle/tendon complex loading is overall still high (Butcher et al, 2009). Other research supporting these data found the same 14% reduction in average vertical ground reaction forces when the gait transitioned from trot to canter (Farley and Taylor, 1991).

Translating these concepts to equine rehabilitation would indicate that a progressive increase between gaits from walk to trot and trot to canter may not be appropriate for all injuries. For example, rehabilitation protocols for injuries to the SDF muscle/tendon complex could introduce the canter before the trot to reduce the muscle and tendon loading parameters. Whereas the addition of the trot into the rehabilitation protocol, may help to achieve greater strain for greater elastic energy savings by the SDF muscle/tendon complex.

For DDF muscle/tendon complex rehabilitation, the canter should be utilized at a later time than for SDF muscle and tendon injuries. Activating associated muscles, which could reduce the load on the flexor tendons could prove useful. In addition, when limb acceleration is reduced, the ability to position the foot for correct foot contact with the ground is increased (Jansen et al, 1993).

Equine research has also shown that the biceps brachii muscle (and lacertus fibrosus), is an elbow flexor and has a large isometric force-generating capacity due to the large proximal moment arm making the biceps a strong contributor to shoulder movement. To counter this strong action of the biceps the triceps brachii muscle is thought to have an important stabilizing role during stance (Watson and Wilson, 2007). The development of the powerful lateral triceps of the forelimb to help control the flexion of the elbow joint (Wickler et al, 2005; Hoyt et al, 2005) could be of assistance to compliment the tension in the SDF and DDF muscle/tendon complexes. This tension could then help support the carpus and control hyperextension of the digit (Butcher et al, 2009).

Translating these concepts to equine rehabilitation would indicate that during rehabilitation of the SDF and DDF muscle/tendon complexes, normal function of the triceps brachii would be of initial importance. If instability is found in the triceps, improved function of this muscle would be indicated, followed by evaluation of the normal function of the biceps. Generating a more powerful movement through initial biceps strengthening without having the ability to stabilize that movement could prove to be detrimental. The authors of this review are not familiar with research that has determined exercises for the horse that primarily develop the triceps. However, clinical observation showing hypertrophy of the triceps in racing trotters would suggest that extended periods of trotting with a gradual increase in stride length would be useful. In addition, clinical observation of horses with DDF and SDF muscle/tendon complex injuries shows decreased muscle development in the triceps.

Finally, the sacroiliac joint is a gliding joint and its most important function is for stability, therefore the joint is more susceptible to shearing than to compressive forces (Dalin and Jeffcott, 1986a; Dalin and Jeffcott, 1986b). Pain in the sacroiliac joint has been associated with instability of the joint (Jeffcott, 2009), although the movement in the sacroiliac joint is relatively small and this movement is accompanied by movement of the lumbosacral region (Degueurce et al, 2004). In addition, the sacroiliac joint is responsible for lateral movement and rotation (Dalin and Jeffcott, 1986a; Dalin and Jeffcott, 1986b).

One study found that the activity of the muscles of the back increased with an increase in speed at the trot and showed a decrease in flexion, while extension remained unchanged as speed increased. This is an indicator that the back muscles have a more stabilizing role at the trot as speed increases, rather than inducing movement (Robert et al, 2001). In addition, one preliminary study of 3 horses found that the greatest magnitude of segmental vertebral motion occurred during the canter and the least amount of motion occurred during the trot (Haussler et al, 2001). The trot is such a stabilizing gait that, even compared to the walk, the trot was found to produce more vertebral stability than the walk. Another equine study evaluated motion at the equine sacroiliac joint using pin-mounted sensors and found that the mean walk values for flexion/extension, axial rotation and lateral bending were significantly ($p < 0.05$) greater than the values at the trot (Goff et al, 2010).

Interestingly, in jumping a similar result was found, where too much flexion in the lumbosacral junction as the hind limbs clear the fence can be an aspect of poor performance. Good jumpers show increased extension at the lumbosacral junction. In poor jumpers, increased flexion of the lumbosacral junction and thorax was noted before take-off and during flight. Therefore, lumbosacral extension was less over fences and resulted in poor jumping performance (Cassiat et al, 2004). Another equine study supported this work and found that the rearward extension of the hind limbs, produced through extension at the lumbosacral junction, was one of the kinematic variables found in good jumpers (Bobbert et al, 2005).

Translating this concept to equine rehabilitation would indicate that exercises to develop trunk stability and extension in the lumbosacral region, and perhaps the thorax, would be useful for jumpers with back spasms (hypertonicity). These exercises would include trotting at faster speeds to activate the muscle groups that support trunk stability. A lower and longer frame of the horse will position the center of gravity further forward and, in the authors' opinion, to counter this the horse will increase tension in the lumbar region, which would be beneficial for lumbar stability. However, if the center of gravity is pushed too far forward this position may increase the forces on the forelimbs and over stress the lumbar muscles.

Conclusions

Combining the fields of veterinary medicine, biomechanics, kinesiology, anatomy and physical therapy to produce equine rehabilitation protocols is important. Evaluation of the whole horse mechanics is not only a means to obtain quality healing, but is also a way to prevent injury from occurring. The problem solving begins with a thorough examination and diagnosis of the horse, which is followed by an organized rehabilitation plan.

Some guidelines for equine rehabilitation incorporated from human rehabilitation are listed below.

1. The whole horse body mechanics must be evaluated even when the diagnosis of pathology is a specific bone, muscle, tendon or ligament.
2. Muscles that are in a lengthened state are more prone to injury.
3. Exercises that improve joint flexion will help reduce impact forces include:
    a. on the flat
        i. slow the speed of the gait
        ii. higher carpal joint and hock action
    b. during jumping
        i. tighten the distance between fences to slow the horse
        ii. use gymnastics to slow the horse
        iii. select fence height that increases joint flexion.
4. Exercises that improve strength and ‘spring’ in the hindquarters include:
    a. on the flat
        i. a “duck walk” appearance through piaffe and passage tendency work at the trot
        ii. slower more stationary canter strides
    b. during jumping
        i. very slow approaches to fences with shorter strides
        ii. shorter distances between fences
        iii. increase joint flexion.
5. Exercises that improve speed include:
    a. on the flat and during jumping

    - i. strides that remain close to the ground
    - ii. less joint flexion
    - iii. discourage excessively long strides
    - iv. encourage faster repetitions of the stride
    - v. poles placed on the ground over an extended distance at the horse's 'natural' stride length that are covered at a gradually faster rate
    - vi. backing up exercises.

6. Quick starts and stops should be reduced during rehabilitation with the emphasis on:
    - a. changes of speed within the gaits
    - b. gradual changes of speed between the gaits
7. Steady curves should be avoided in the early stages of rehabilitation with the emphasis on:
    - a. turns should look more like octagons
    - b. turns should be a series of shallow turns and straight lines.
8. Fence height should promote good jumping form.
9. When evaluating distal limb tendon injuries, function of the whole muscle/tendon complex must be considered.
10. Canter work could be introduced earlier in the rehabilitation of the SDF muscle/tendon complex than during rehabilitation of the DDF muscle/tendon complex.
11. Exercises for triceps strengthening which can support SDF and DDF rehabilitation include:
    - a. extended periods of trotting
    - b. gradually increasing the speed of the trot.
12. The trot is a more stable gait, than the walk or canter, and can be used to improve trunk and lumbosacral stability.
13. The canter produces more vertebral movement than the trot, and can be utilized to improve flexibility in the top line.
14. Exercises for rehabilitation of back spasms (hypertonicity) include:

a. exercises to improve trunk stability
    i. lower, longer frame of the horse will increase lumbar tension to help provide trunk stability
    ii. lower, longer frame may also increase forces on the front limbs and over stress the lumbar muscles if the center of gravity is positioned too far forward
b. trotting at faster speeds.

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