The Physical Principles that Interpret Motion in Pitching

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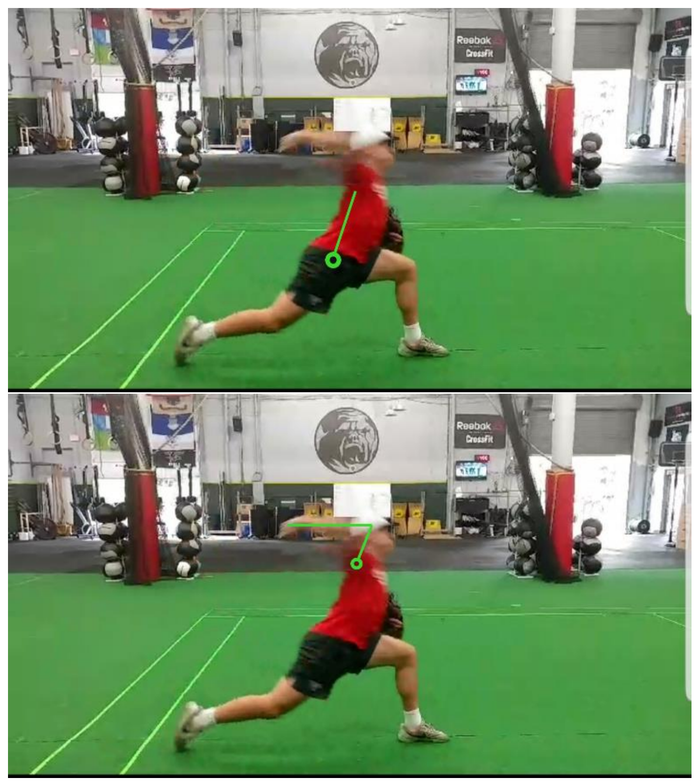
The field of biomechanics is relatively new and has become more prominent since the advent of the computer. Biomechanics is physics applied to the human structure. Since biomechanics requires calculations in research, the computer can accommodate large sums of data in motion analysis. Therefore, research biomechanists have become proficient in computer programming in developing mechanical models of the human body or human parts to gain insight into the behavior of the human kinetic chain. More specifically, to optimize movements that may minimize loads to the joints and better understand mechanisms of injury to prevent them ultimately. The computational analysis utilizes measurements of force, acceleration, angular acceleration, velocity, and moments and moments of inertia as inputs to reach the quantities of interest.

Although human movement experts use quantitative analysis in biomechanics in research, they also have a conceptual understanding of the laws of physics in qualitative analysis of human movement to decide how to intervene to improve motion and prevent injury. Therefore, biomechanics in the qualitative analysis is most effective when integrating it with professional experience, having developed a good eye for sound movement, and combining it with other subdisciplines of kinesiology, such as function anatomy and behavioral and cognitive-motor learning.

This material ventures through the different ways energy can be interpreted as the body moves, specifically, the pitcher. Understanding how a pitcher creates and terminates motion is crucial to improving performance and, most importantly, preventing injury. Also, conceptually utilizing the principles to reach a legitimate conclusion about how a specific law verifies a particular hypothesis.

Motion

To accurately describe the human body's movements in mechanical terms, we must know what causes motion and understand what kind of action is generated. There are two kinds of motion – linear, angular, and a combination of both. Where linear motion is straight, and angular motion is circular where an object rotates about an axis or a point. The object, in this case, is a system of levers called the trunk that rotates about the hip's axis and the arm that rotates about the shoulder's axis. An excellent example of linear and angular motion is when a pitcher throws a ball; his hips move linearly at first as he pushes off the rubber, and his trunk rotates forward as his hips become the axis of rotation, as shown below.



Causes of Motion

For an object to move, there must be a force applied to it. Physics defines a force as a push or a pull on an object in the direction of motion, causing it to accelerate. In this case, the pitcher is accelerated forward by applying a push force from the pitching rubber. Likewise, the pitcher applies a push force of the ball as he releases the ball.

Newton's Three Laws of Motion

Newton's laws must be thoroughly understood to correctly interpret movement to determine actions that may cause injury while improving performance accurately. Sir Isaac Newton developed these laws in the 17^{th} century and has been at the forefront in engineering design, aerospace exploration, astronomy, and other disciplines that deal with forces, mass, and acceleration. These laws govern all aspects of motion and apply in anatomical movement analysis. The pitcher, through his entire motion, experienced all three laws.

The 1^{st} Law (Law of Inertia)

Newton's 1^{st} law states that a body of some mass m in motion remains in motion in a straight line and stays constant or remains at rest unless an outside force acts on it. In other words, an object will not move while at rest or continue in motion unless an external force is introduced into the system.

Where would this law apply during the pitching motion? Just before the pitcher starts his movement forward, his body is at rest until he starts falling toward home plate and then pushes off the rubber. Then, while the pitcher's motion is toward home plate, his body wants to stay in motion, but the plant of the front leg produces an outside force that decelerates his body from moving forward.

The 2^{nd} Law (Law of Acceleration)

Newton's 2^{nd} law states that an object of some mass m accelerates in the direction of the force applied to it and is directly proportional to the force written below.

$$\boldsymbol{F} = m\boldsymbol{a}$$

And the acceleration is inversely proportional to the mass:

$$\frac{\boldsymbol{F}}{m} = \boldsymbol{a}$$

Note: Bold letters represent a vector, and vectors have magnitude and direction.

This law is not useful in these forms but can be helpful to see that force is related to acceleration and necessary to have a force for an object to accelerate. Also, what is essential to understand is that a force must be applied for a period of time to get the object to accelerate.

Where would this law apply during the pitching motion? The push off of the back leg from the rubber to accelerate the pitcher forward, and as the hand pushes the ball to accelerate it toward home plate.

The 3^{rd} Law (Law of Reaction)

Newton's 3^{rd} law states that when object 1 applies a force on object 2, object 2 applies an equal and opposite force on object 1.

Where would this law apply during the pitching motion? When the pitcher pushes off the rubber, the rubber pushes back with an equal and opposite force. Also, when the front foot lands, the ground decelerates the pitcher's body.

Although these are the fundamental laws of motion, other principles were developed to describe motion. These mechanical principles are '**Impulse – Momentum Relationship**,' '**Conservation of Energy**,' '**Linear & Angular Momentum**,' and the '**Conservation of Momentum**.'

<u>Impulse – Momentum Relationship</u>

This principle states that the change in momentum of an object of some mass m is due to an impulse applied to it. Impulse is the duration of time t the force $\boldsymbol{F}$ is applied on an object to change its momentum $m\boldsymbol{v}$.

Impulse = Change in Momentum

$$\boldsymbol{F}t = \Delta m\boldsymbol{v}$$

Where,

- $\boldsymbol{F}$ is the force applied to an object
- t is the duration of time a force is applied to the object
- m is the mass of the object on which the impulse is applied
- v is the velocity of the object
- $\Delta m\boldsymbol{v}$ is the change in momentum of an object

The impulse-momentum principle derived from Newton's 2nd Law of motion ($\boldsymbol{F} = m\boldsymbol{a}$) using calculus shown below.

$$\boldsymbol{F} = m\boldsymbol{a} \;\; where \;\; \boldsymbol{a} = \frac{d\boldsymbol{v}}{dt}$$

Substituting $\frac{d\boldsymbol{v}}{dt}$ for $\boldsymbol{a}$ into Newtonn's 2^{nd} law becomes

$$\boldsymbol{F} = \frac{md\boldsymbol{v}}{dt} \rightarrow \boldsymbol{F}dt = md\boldsymbol{v}$$

If we integrate both sides of the equation, we get

$$\boldsymbol{F}\int_{t_1}^{t_2} dt = m\int_{v_1}^{v_2} d\boldsymbol{v}$$

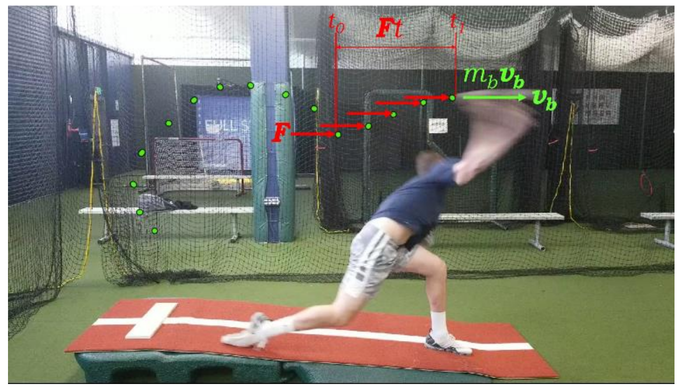
After integrating both sides of the equation, it becomes

$$\boldsymbol{F}(t_1 - t_2) = m(v_1 - v_2)$$

and further reduces to

$$\boldsymbol{F}t = m\boldsymbol{v}$$

The impulse-momentum principle allows us to determine safe gains in velocity. For example, in the image below, the pitcher starts his arm path illustrated by the green dots and begins to exert an impulse $\boldsymbol{F}t$ on the ball at t_0 to t_1, inducing a change in momentum of $m_b\boldsymbol{v_b}$. If the pitcher does not continue to bend as he is doing, it decreases the time t increasing $\boldsymbol{F}$ and decreases $\boldsymbol{v_b}$.



<u>Appling the Impulse-Momentum Principle to Increase Velocity</u>

The critical variable in the equation above is t. The main idea about this formula is that the magnitudes of $\boldsymbol{F}$ and $\boldsymbol{v}$ are dependent on the value t. Thus, if the equation is solved for $\boldsymbol{F}$, one can determine that as t gets larger, $\boldsymbol{F}$ gets smaller, as shown below.

$$\boldsymbol{F} = \frac{m\boldsymbol{v}}{t}$$

Reducing $\boldsymbol{F}$ applied on the ulnar collateral ligament (UCL) starting at shoulder maximum external rotation (MER) to ball release allows for reduced stresses protecting the soft connective tissue at the joints due to violent torques created by the throwing motion, specifically at the shoulder and elbow.

All pitchers want to increase velocity. Therefore, to increase $\boldsymbol{v}$, the value t must increase as well. To clarify this notion, we can solve this equation for the $\boldsymbol{v}$ and simply plug in values, notice that as the numerator gets larger, so does $\boldsymbol{v}$ since m is small.

$$\boldsymbol{v} = \frac{\boldsymbol{F}t}{m}$$

Also, because the ball's mass m is small, it will not take a large $\boldsymbol{F}$ to overcome its inertia. However, it is imperative to note that even though the ball's mass is small, overcoming the ball's inertia too early in the throwing motion increases the magnitude of $\boldsymbol{F}$. Therefore, also increasing the stresses in the joints.

Another way to explain this concept is by writing the impulse-momentum equation signifying the variables' (m being constant) size depicts the preferred magnitudes of the variables, shown below.

$$\boldsymbol{F}t = m\boldsymbol{v}$$

So, this equation illustrates the importance that the value of t must be as large as possible to keep the magnitude of $\boldsymbol{F}$ as small as possible and make the magnitude of $\boldsymbol{v}$ as large as possible. The question that might come to mind is; if the force is kept small, how does a pitcher increase velocity? In a nutshell, a smaller F applied longer can increase $\boldsymbol{v}$ of the ball than a larger $\boldsymbol{F}$ exerted at a shorter period.

Taking longer to release the ball allows the pitcher to create more momentum and store more *PE* to create more *KE* covered later in this material as he goes down the mound. Allowing the pitcher more time t to drive down the mound, increasing momentum, which in turn increases velocity.

Much research has been done to determine what movement mechanisms overload the shoulder or elbow that eventually cause injury. However, the extreme loads exerted at the shoulder and elbow cause injury, but those loads are reduced by allowing more time to load and unload the shoulder and elbow joints.

Angular Impulse-Momentum

Since the shoulder moves angularly and the forearm rotates about the shoulders axis of rotation, we can apply the **angular impulse-momentum**, analog to linear impulse-momentum. Where the torque (rotational force) $\boldsymbol{\tau}$ (tau) replaces force $\boldsymbol{F}$, angular velocity ω (omega) replaces linear velocity $\boldsymbol{v}$, and the moment of inertia (rotational inertia) I replaces mass m, as shown below.

$$\boldsymbol{F}t = m\boldsymbol{v} \rightarrow \boldsymbol{\tau}t = I\omega$$

Without significant calculations with angular impulse-momentum, we can solve for torque $\boldsymbol{\tau}$ and plugin random values for time t in the equation below and see that the torque decreases as time t increases, similar to its linear counterpart covered in the previous section.

$$\boldsymbol{\tau} = \frac{I\omega}{t}$$

Mention earlier, reducing the load by managing the torque's duration at the shoulder and elbow joints.

Conservation of Momentum

This principle states that momentum remains constant in a closed system as long as no external forces are applied to the system.

Change in Momentum in = Change in Momentum out

$$\Delta(mv)_{in} = \Delta(mv)_{out}$$

Biomechanists renamed this principle "**Sequential Summation of Movement**" to appropriately represent how momentum sequentially links the kinetic chain to produce efficient movement. **David Barker** of **Exploratorium Science of Baseball** puts it into his own words in the article "**Putting Something on the Ball**." Although pitchers move linearly and angularly, this quote depicts it linearly but accurately.

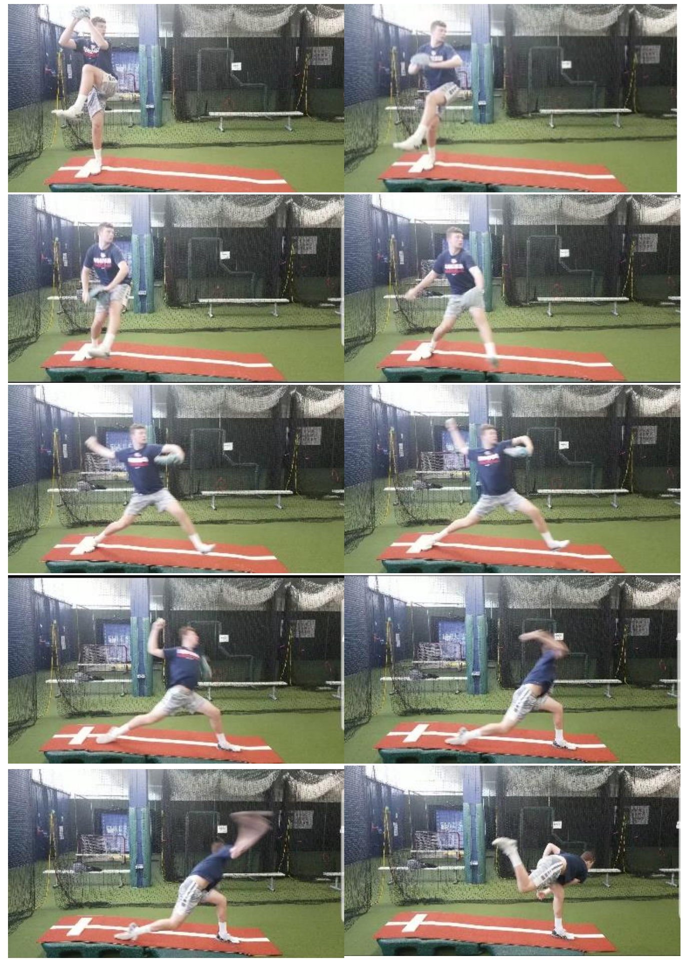
"*This transfer of momentum from the body to ball involves a biomechanical principle called 'sequential summation of movement.' According to this principle, the largest body masses move first, followed by progressively smaller ones, in much the same way a multi-stage booster rocket jettisons a satellite into space: the large booster starts the process, is jettisoned, then is followed by the burning and jettisoning of progressively smaller and faster stages, until finally the small satellite is released at high speed. In baseball, the pitcher drives first with his legs, then his hips, shoulders, arm, wrist, and fingers. As each* *part approaches full extension, the next part in the sequence begins to move, efficiently transferring momentum in a whip-like action. Proper timing is necessary to produce speed and accuracy, and to avoid strain and injury.*"

David Barker's description of this principle is manifested perfectly in the picture below.

Since momentum is the **quantity of movement**, it makes sense why biomechanists changed the name to **'sequential summation of movement'** to accurately represent how pitchers move through the kinetic chain due to the drive off the rubber F_r and the ground shear force F_{grs} when the front foot lands. Other sports apply this principle, like in the golf swing. The movements sum up as momentum moves from links 1-6 representing the stages of each link in sequence to propel the ball efficiently, as shown above. To correctly interpret what is occurring in the image above, we must first know how the pitcher got to this position, which starts the sequential linking or transfer of momentum from larger body parts and ends at the smaller body parts. The links may be reduced to 5 since, realistically, links 1 & 2 is one rigid body at this point and can be considered one link in the motion.

The status quo of those who work with pitchers teach contrary to the knee being in this position. They have a good reason if the pitcher continues to collapse the knee pasted the shoelaces. Still, if the pitcher can maintain that knee position, he can generate more velocity at release.

There are great eccentric loading exercises that strengthen the glutes and quads to keep them in the triangle position. One of the best exercises for this is sprints. Below is an entire pitching sequence demonstrating this concept, and the pitcher holds the triangle position from the time he lands through ball release.



In the last frame, the pitcher's knee remains its position behind the shoelaces of his landing foot.

There are several reasons why the pitcher should finish in this manner.

- Allows the pitcher to release the ball closer to home plate as shown in the 2nd to the last frame (less time for the hitter to see the ball)
- Keeps the throwing hand on the target longer for improved accuracy
- Increases velocity due to the increase in the radius from the hip to the release of the ball

- Increases spin rate due to the longer radius that also increases velocity
- Increases the acceleration & deceleration phase reducing the stresses in the shoulder and elbow
- Less wear & tear on the throwing arm
- Shorter recovery time from start to start
- Safe high pitch counts

Safe high pitch counts might not be understood or excepted since researchers have not solved the mystery of widespread pitching injuries. Higher pitch counts would give an advantage to any organization that understands what is written in this material.

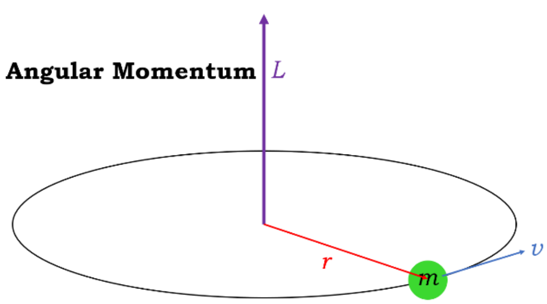
Angular Momentum

Pitchers move linearly and angularly, but the pitcher generates more energy from the rotational energy obtained by the forward trunk rotation and shoulder IR. To determine what increases the velocity of a ball, applying the angular momentum principle clarifies this notion. Angular momentum is the rotational equivalent of linear momentum, and to increase velocity, would suggest we use a long lever system increasing length r in the formula written below:

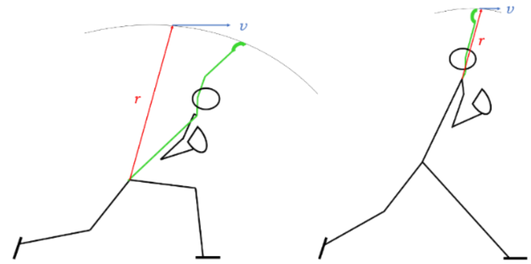
$$L = mvr$$

Where,

- L is the angular momentum of the revolving object
- m is the mass of the revolving object
- v is the linear tangential velocity at the of the circle
- r is the radius from the axis of rotation to the mass



Applying this principle to the pitching motion, as shown below, the key to increasing velocity is to increase leverage or the radius r to the throwing arc starting at the hips. A larger radius reduces stresses in the shoulder and elbow. Conversely, a shorter radius r, starting from the shoulder, would produce more stress in both shoulder and elbow in both the acceleration and deceleration phases of the throw.



The Principle of Conservation of Energy

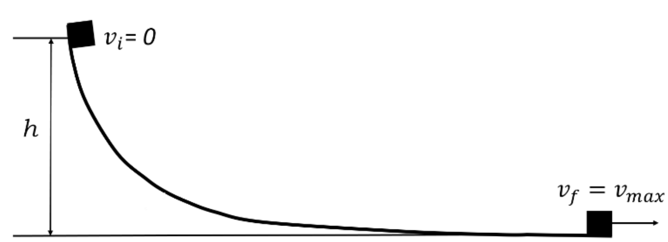
This principle states that the energy of an isolated system remains constant over time and cannot be destroyed but converted to other forms of energy. In this case, *PE* converts *to KE* as written below:

$$PE = KE \rightarrow mg\Delta h = \frac{1}{2}mv^2$$

Where,

- m is the mass of the pitcher's body
- g is the gravitational constant
- Δh is the change in the height of the pitcher's center of gravity (CG)
- v is the velocity of the pitcher's body moving toward home plate

The figure below is a classic example of illustrating the Conservation of Energy. An object of mass m is placed and held on a frictionless ramp at some height h above the ground and released.



An object at this height above the ground is said to have *PE* or stored energy. When the mass m is released from some height h, *PE* is fully converted to *KE* at $h=0$. The two key variables in the conservation of energy principle are Δh and v. The higher the value of h, the larger v_{max} is at $h=0$. Since $h_2=0$ the total height $h=h_1$. Therefore, after an algebraic manipulation of the equation above and solving for v, we get:

$$v = \sqrt{2gh}$$

Similarly, we can apply the conservation of energy to how a pitcher starts and finishes his motion in the following images. The pitcher's CG starts at h_1 and ends at h_2, where the *PE* converts into *KE*.

As mentioned earlier, the higher the value of h, the larger the v. Likewise, the straighter the post leg h_1 is, the larger the value of v. This is because the quantity of the v is only the velocity gained due to gravity acting on the pitcher's CG, pulling him down the mound.

The velocity the pitcher gains due to the conservation of energy down the mound is only to help him fall towards home plate under control and allow the post leg to bend to push off the rubber. In addition, the *KE* increases due to the impulse the pitcher created with the drive of the back leg, illustrated by the yellow dotted line. Two things happen along the way, from the beginning of the yellow dotted line to where CG ends. First, as the back leg drives the pitcher forward, the pitcher gets his arm positioned behind his head and starts to lay back (parallel to the ground) passively due to the impulse created with the drive of the back leg. Second, as the arm is lying back, all the soft tissue pre stretches to eventually unstretch in combination with muscle contraction to throw the ball, illustrated by the circular green arrow, as shown in the image across the page. Therefore, the application of impulse-momentum assists in creating more *PE,* which converts to *KE.*

The Conservation of Elastic Energy of Muscle, Tendon & Ligament

To accurately describe the elastic energy (stored energy) of muscle, muscle fascia, tendon, and ligament, they function similarly to a spring. When a spring is compressed, force $\boldsymbol{F}$ is negative, and when in tension, it is positive. The magnitude for $\boldsymbol{F}$ is positive since the soft tissue concentrically and eccentrically loads in tension. The conservation of energy relationship takes on a different form due to the elastic energy of the soft tissue on the *PE* side of the equation, but the *KE* side stays the same, as written below. U represents the *PE* of a spring, and since the equation of a spring has a subscript ‘*s*’ (U_s), this formulation utilizes ‘*st*’ for soft tissue.

$$PE_{st} = U_{st} = KE_{st} \rightarrow \frac{1}{2}k_{st}x_{st}^2 = \frac{1}{2}m_b v_b^2$$

Where,

- U_{st} is the *PE* of soft tissue
- E_{st} is the elastic energy of the soft tissue
- k_{st} is the soft tissue constant representing their stiffness
- x_{st} is the amount the soft tissue stretched
- m_b is the mass of the ball
- v_{st} is the velocity of the ball

The soft tissue from the lower frontal abdominal area through the shoulder and elbow are stretched and unload like a spring. Thus, hypothetically speaking, in addition to pre-stretching, there is a slight overlap of muscle contraction and unloading of the soft tissue mentioned earlier. The circular green arrow represents this eccentric and concentric overlap, as shown below.

Also, in the above image, the shoulder and elbow are not doing all the work to accelerate the arm. The pitcher's position is ideal for protecting the shoulder and elbow since the eccentric tensile loading is distributed along the entire green arc.

In the following image, the pitcher has most of the load concentrated on the shoulder and elbow illustrated by the smaller circular green arrow, which means that the shoulder and elbow are where the eccentric and concentric overlap is. Hence, the shoulder and elbow are doing most of the work, accelerating and decelerating the arm.

Conclusion

To truly teach any skill in any sport without any knowledge of physics is only putting the athlete in jeopardy of injury somewhere down the road.

“In Russia, no one is allowed to work with their top athletes and dancers without a degree that requires physics or a major in engineering.” ***Anna Karamuzin***

Some downplay physics and how the human body’s ability to produce energy due to its elastic properties and say that it is not circumstantial. We live in a physical world, and there is nothing anyone can do to avoid this fact. Physics is about applying forces to an object to accelerate it into motion. As human body movement specialists, we must understand how the body responds to the forces that produce stresses in the joints and determine the potential for injury, explaining why more pitchers sustain more injuries than ever. Those responsible for managing pitchers lack knowledge of any physics-driven discipline to identify injury mechanisms to eliminate them. Also, they advise pitchers to try something that may help or not and put them in a worse situation than before. Working with pitchers should not be a trial and error – it could be the error in the trial that causes the injury. Anyone who works with pitchers should have enough knowledge of physics to decipher injury mechanisms while improving performance.

Without question, understanding the bullet point list on pages 5 & 6 will help solve the mystery of pitching injuries that have been so widespread at all levels of baseball.