The Human Trebuchet

By Dan Galaz at Galaz Baseball Technologies © 2019

Introduction

To properly analyze the pitching motion, it should be observed like a machine since the pitcher resembles a trebuchet in its function. The trebuchet was one of the most efficient medieval siege weapons (machines) ever designed, and its purpose was to hit its targets at long distances and be highly accurate.[3] The efficiency of the trebuchet's design is in optimizing ratios of the levers and sling and the masses of the counterweight (CW) and projectile **(Dr. Donal B. Siano, 2010)**.[3] Also, the wheels had four purposes; to move the trebuchet from location to location, improve lever arm stall points (LASP) and CW stall points (CWSP) to increase the velocity at release, and reduce the stresses in the structure, giving the trebuchet longevity.[3] It is important to note that LASP and CWSP co-occur and may be used interchangeably in this write-up.

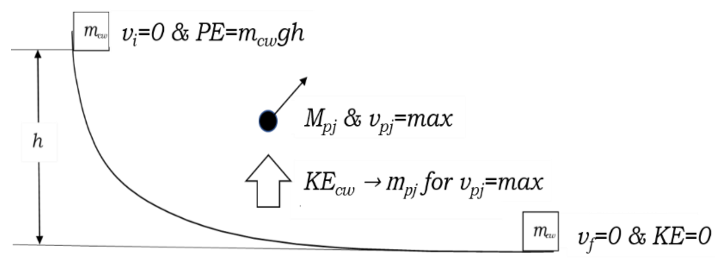
Looking at how a trebuchet functions can give insight into how the pitcher can reduce the chances of injury, improve accuracy, and increase velocity is supported by physics laws. Also, how the trebuchet is constructed and adheres to the optimization ratios mentioned above, similarly, the fulcrum and beam lever structure must be as rigid as possible to prevent vibration during launch, especially in the beam lever.[3] If the beam vibrates under the CW's gravity, it results in an inaccurate shot and shorter distances. This literature about trebuchet physics will give insight into improving accuracy and velocity while preventing injury.

Trebuchet Physics

The physical principle how in trebuchet design transfers energy to the projectile is the '**Conservation of Energy,**' where the **Potential Energy** (*PE*) equals the **Kinetic Energy** (*KE*) written as:[2]

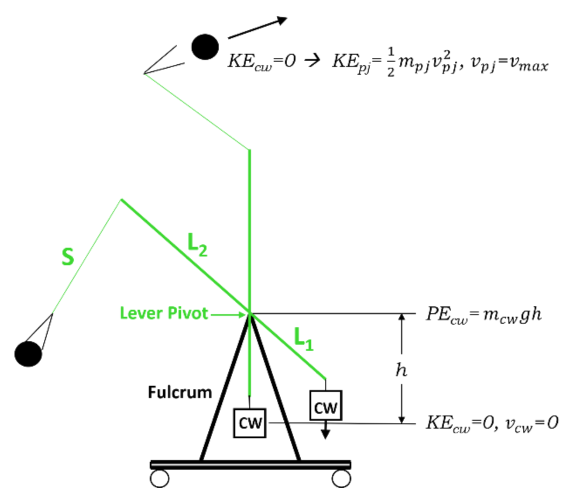
$$mgh = \frac{1}{2}mv^2$$

This equation is best illustrated by the classic frictionless ramp with the CW mass starting at height h with a $PE = m_{cw}gh$ and released converting to $KE = \frac{1}{2}m_{cw}v_{cw}^2$, where the *KE* of the CW mass must be equal to zero (since velocity v must equal 0 when the CW is not moving) at the bottom of the ramp to transfer the entire *KE* of the CW to the projectile due to gravity depicted by the big white arrow, as shown below.[2]



The total *KE* of the trebuchet system written as:[2]

$$KE_{total} = \frac{1}{2}m_{cw}v_{cw}^2 + \frac{1}{2}m_{pj}v_{pj}^2$$



Trebuchet Construction

Trebuchet efficiency has to do with optimum ratios between the levers L_1 and L_2, the sling **S** and L_2, and the masses of the CW m_{cw} and projectile m_{pj}, as shown in the succeeding bullet point ratio list. Also, another thing to point out within these ratio parameters is that the distance between the fulcrum and the projectile must be as large as possible.[2]

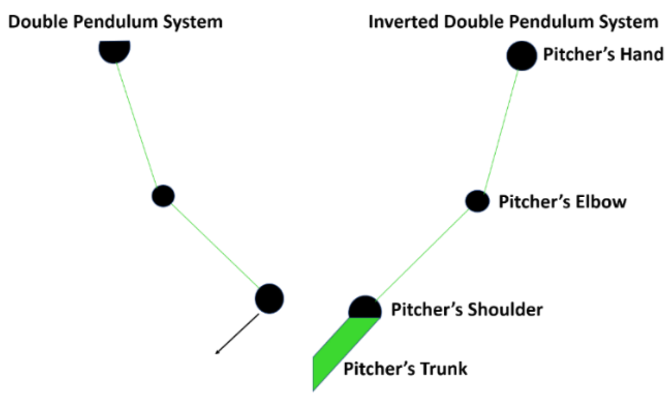
Ratios:

- $L_1:L_2$ → 4:1 & L_2 should be 3.75 times longer than L_1
- $m_{cw}:m_{pj}$ → 133:1
- $S:L_2$ → 1:1

These ratios determine timely LASP and CWSP, which produce maximum distances and accuracy.

Double Pendulum System

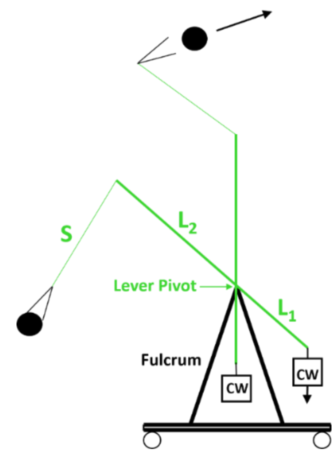
The trebuchet is an invert double pendulum system (IDPS) that uses gravity to launch projectiles similar to the arm pitching motion, as shown below.

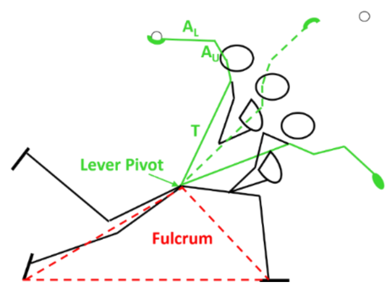


The trunk is equivalent to the lever, and the arm to the sling, making the pitcher an IDPS. A typical DPS swings downward due to gravity is inverted to resemble a pitcher's arm. The shoulder, elbow, and hand are in position just after the ball's release. The similarities of how the DPS and pitcher's arm moves are that they both hinge at the nodes represented by the black balls. The motion of the DPS is initiated when released from some height allowing gravity to cause the motion. The pitcher's arm is forced to move due to muscle involvement in shoulder internal rotation (IR) as the trunk rotates forward after front foot strike. The differences in how they produce energy to increase the projectile's velocity, the trebuchet does it by increasing the projectile and CW's mass ratio using the conservation of energy. The pitcher by prolonged passive loading of the arm by shoulder maximum external rotation (MER) and muscle contraction.

The Structural Comparisons of the Pitcher & Trebuchet

Observing how a trebuchet functions, one can envision the similarities when comparing it to how a pitcher throws a baseball. In making their comparison, we may gain insight into how the pitcher may release the baseball with more efficiency. While looking into how a trebuchet is optimized, one can see a similar lever system in both, as shown below.

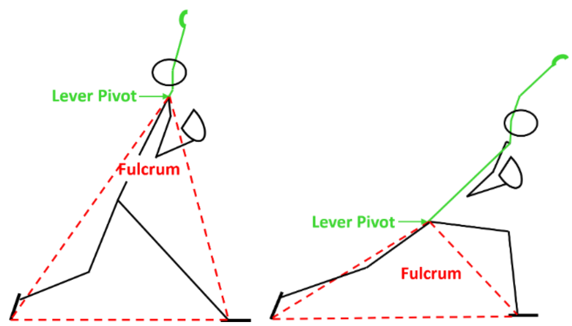




Lever L_2 coincides with the pitcher's trunk **T** from the top of the fulcrum, and the sling corresponds with the upper arm A_U and lower arm A_L. When comparing both fulcrums, the trebuchet's fulcrum is constructed rigidly on the front and back, forming an isosceles triangle with the base. The pitcher's fulcrum starts to develop at the front foot strike, which must also be rigid to efficiently transfer energy from the lower extremities to the upper and, ultimately, the ball. Front leg stability is crucial for producing forward trunk acceleration through ball release. After ball release, the trunk should continue to rotate to allow more time for the arm to decelerate to reduce the deceleration stresses in the shoulder and elbow. At this point, the larger muscles are getting involved in the eccentric deceleration of the trunk and arm (quadriceps, glutes, and latissimus dorsi). The body is stronger eccentrically than concentrically.[1] Therefore, pitchers must train more eccentrically to help in the deceleration phase of the arm. Besides, the further the pitcher finishes over the front thigh, the closer to home plate he is releasing the ball, giving the hitter less time to it, and the better he can place the ball for better accuracy due to full trunk extension. Not to mention increased leverage since the trunk is further involved in the pitcher's lever system. The difference is that the trebuchet is designed for maximum distance and accuracy, while the pitcher wants improved velocity and accuracy.

The front knee must not hyperextend for front leg stability where the front leg fully straightened or collapsed beyond the front foot's shoelaces, as shown in the series of three frames below.

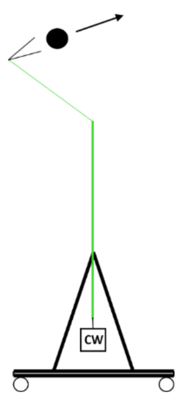
When the front knee collapses forward, energy starts to dissipate before it gets to the trunk. When the front leg fully straightens, the pitcher decelerates the torso too early; therefore, the arm also. Besides, when the trunk stops bending forward, it forces the lever pivot of the fulcrum to be at the shoulder, as shown in the first image below. Also, optimizing trebuchet launch distances and pitchers is increasing velocity; the distance between the fulcrum and the projectile must be as large as possible. In the first image below, since the fulcrum is at the shoulder, it shortens the lever system, therefore, decreases velocity, according to **uniform circular motion theory**. As opposed to the second image, the fulcrum starts at the hips, increasing the throwing arc's range of motion. Hence, increasing velocity.



Hypothetically speaking, the shoulder complex would have to do most of the arm's deceleration in the first image. When the pitcher fully extends the front leg, it restricts the torso from bending forward correctly, done properly in the second image. It also jeopardizes the hamstring muscle on the landing leg as it tries to slow down the trunk’s forward rotation eccentrically. It's a hamstring rupture waiting to happen. A low percentage of pitchers have the mobility to forwardly rotate the trunk to where the chest is parallel to the ground while throwing on a fully extended front leg. Therefore, pitchers with reduced mobility in this region should refrain from practicing this type of maneuver.

LASP & CWSP of a Trebuchet

The theory of LASP and CWSP is essential for trebuchet design. As mentioned earlier, to transfer the entire *KE* from the CW entirely to the projectile, the CW, L_1, and L_2 velocity must be equal to zero at launch. It is important to note that the sling is a very efficient energy transfer system and not just a release mechanism. Optimizing a trebuchet requires using the suggested optimum ratios mentioned earlier in the trebuchet construction section. These suggested ratios allow for timely LASP and CWSP for maximum distances and accuracy. The trebuchet is most efficient when the lever L_1, L_2, and CW are shown below at launch. Trebuchet launch optimization occurs when these elements line up in a perfect verticle position, as shown below.



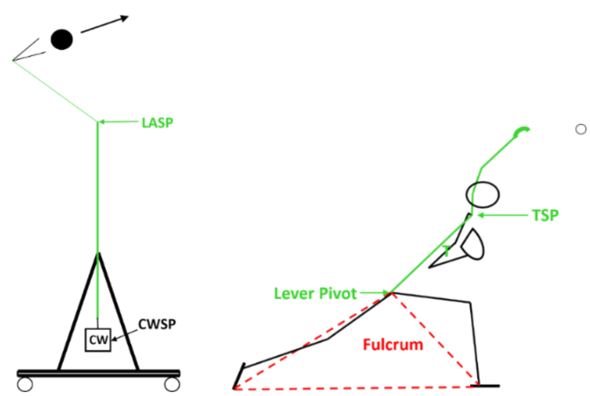
The mathematics involved in trebuchet design is more tedious and complicated than the conceptual grasp of how it functions but serves its purpose of how a pitcher should throw a baseball.

Comparing Trunk Stall Points of the Pitcher to the LASP & CWSP of a Trebuchet

The knowledge of optimizing ratios of lengths, masses, and LASP and CWSP in a trebuchet may give us the secrets to efficient pitching mechanics. Efficient in the sense of improving accuracy and increasing velocity while preventing injury. There seems to be a consensus by pitching experts that improving velocity and accuracy while preventing injury can not be accomplished simultaneously. The trebuchet, as mentioned earlier, may give us the answers to this dilemma.

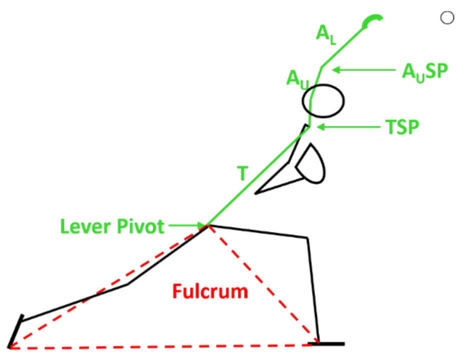
Achieving maximum output with minimum wasted effort is the goal when designing a machine. As mentioned earlier, to analyze the pitching motion properly, we should address the pitcher like a machine. When designing or tuning a machine, it is vital to have the right timing as momentum transfers from link to link of the dynamic structural system, which prevents high stress that may lead to a failure somewhere in the structure's weakest link. As for the pitcher, lengths and mass ratios are what they are – the trunk being the lever and the arm as the sling and cannot be changed. It may very well be that the optimization of the LASP and CWSP in trebuchet design gives us the answers to successfully addressing improved accuracy, velocity, and injury prevention.

The trebuchet meant to launch projectiles in a parabolic pattern, and the pitcher a straight line toward home plate. Hypothetically speaking, this means that the trunk stall point **TSP** occurs later than the trebuchet's **LASP**, as shown below. One can ascertain that these stall points resemble each other although different launching angles.



As mentioned earlier, perfect verticle alignment of the L_1, L_2, and **CW** and optimal **LASP** and **CWSP** enhance the distance and velocity of a projectile launched from a trebuchet. The conservation of energy illustrates the energy system of the trebuchet. In contrast, the pitcher utilizes passive arm loading to reach shoulder MER, muscle contraction in the abdominal region (hip flexion) to accelerate the trunk forward and down rotationally. Although gravity is involved since the torso has mass, its effect is negligible.

Realistically, including the **A_U** and the **A_L**, as shown below, it would produce another stall point at the upper arm **A_USP** at the elbow as it transfers momentum from the **A_U** to the lower **A_L**, as shown below.



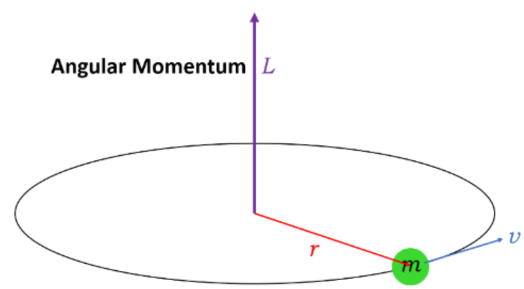
For the **TSP** and the **A_USP** to occur in a timely fashion, the trunk and arm must move as one for optimum results.

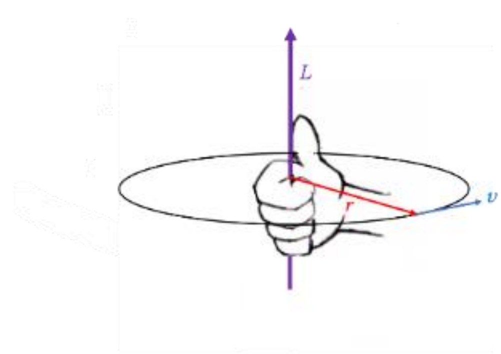
<u>The Application of Trebuchet Theory & Angular Momentum</u>

As we observe the trebuchet's lever system's effortless motion and efficient output, one can ponder how this insight of trebuchet physics theory may apply to the pitching motion. The trebuchet's smooth action involves the lever movements that stay perfectly straight to take advantage of each lever's full length while adhering to the **LASP and CWSP theory**. The same smooth action should apply to the pitcher's lever system and allow TSP to occur later, which would enable seamless transfer of energy from one link to another of the kinetic chain. In other words, the longer the movements, the faster and accurate the pitch. Contrary to this, the quicker the motion does not allow the complete transfer of energy from one body part to the next because the movements are too short. It also does not adhere to the principle of **simple harmonic motion** not covered in this material but crucial to understanding this concept.[4] Put another way, slow movements are more extended movements, and fast movements are less extended. Therefore, to increase velocity would suggest that we use a longer lever system. The physics to support this fact comes from the law of **angular momentum** written as:

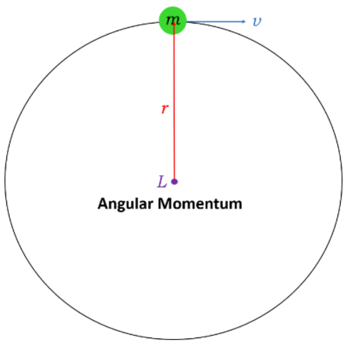
$$L = mvr$$

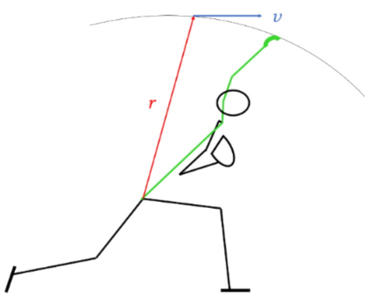
Where m is the mass of the rotating object, v is the linear tangential velocity at the circle, r is the radius from the axis of rotation to the mass m, and L is the purple arrow that points upward according to the right-hand thumb rule as shown below. Thus, the fingers would point along with the velocity v, and the thumb would point upward along with angular momentum L, as shown in the image below.



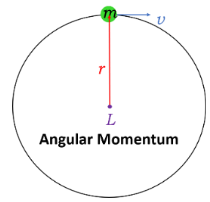


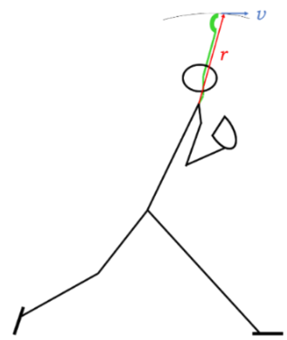
Suppose the image above is tilted upward to resemble the pitcher's arc path while throwing the ball, as shown in the first image below. In this case, if we use the right-hand rule, the angular momentum L points into the paper where the radius r is the trunk and arm working together as one link in the kinetic chain, as shown in the second image below. The velocity *v* is the ball's speed at release, and its increase depends on the length of *r*; the larger it is, the greater the speed.





Therefore, a proper understanding of this principle of the pitching motion can help protect pitchers from injury while safely increasing velocity. If the radius *r* is from the hip to the hand is more significant, it reduces the shoulder's acceleration and deceleration loading. As in the following images, a shorter radius *r*, starting from the shoulder, caused by front leg extension, would create more stress in both shoulder and elbow in the throw's acceleration and deceleration phases. The shoulder would have to do most of the acceleration and deceleration of the arm. As mentioned earlier, shortened movements caused by quicker movements contradict the principle of simple harmonic motion. The words 'harmonic motion' can also mean harmonious movements, not depicted in the latter illustration in the following image.





Conclusion

There seems to be a consensus by pitching experts that improving velocity and accuracy while preventing injury can not be accomplished simultaneously. The trebuchet may give us the answers to this dilemma. Trebuchet theory can be the answer to injury prevention, improved accuracy, and velocity. Understanding timely transfer of energy due to appropriate LASP and CWSP can give insight into this concept. The reason is that the movements are not rushed but are sequential and timely since no muscle contraction can fire at the wrong time. If muscle contraction fires in a timely fashion, trebuchet theory would revolutionize how pitchers are trained.

References

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