MECHANICAL EFFICIENCY IN BASEBALL PITCHING

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Efficient pitching mechanics should maximize ball velocity while minimizing stress on the pitching arm. The purpose of this study was to quantify the relationship between ball velocity and upper extremity kinetics (UEKs) and define the kinematic patterns that achieve the most efficient pitching mechanics. Healthy collegiate and professional pitchers (n=147) threw maximal effort pitches from the wind-up. After determining the overall relationship between ball velocities and UEKs, two subgroups of pitchers were identified as efficient and inefficient. Efficient pitchers had significantly more ball velocity and similar or lower kinetic values. 10 of 23 kinematic variables were significantly different between the groups. It is recommended that coaches and researchers use the efficient group's mechanics as a point of reference when analyzing and teaching pitching biomechanics.

INTRODUCTION: Mechanical efficiency is the ratio of input energy to output energy. Loosely defined in terms of baseball pitching, the input energy can be seen as the mechanical stresses placed on the arm while the output energy is the ball velocity. The mechanical stresses (i.e. forces and torques) placed on the shoulder and elbow joints during baseball pitching routinely approach the limit that those structures can withstand with every pitch (Buchanan, Delp, & Solbeck, 1998; Morrey & An, 1983). To minimize arm strain and reduce the risk of injury, pitchers seek to maximize ball velocity through total body mechanical efficiency, bearing larger loads on the stronger leg and core muscles rather than the weaker arm muscles. Escamilla *et. al.* (2007) found a significant loss in ball velocity without a significant reduction in upper extremity kinetic (UEK) values as pitchers approached fatigue. This means that even though they are in a weakened state from being fatigued, pitchers continue to place extremely high loads on the shoulder and elbow joints. Previous research has confirmed that fatigue is a major risk factor for arm injuries that necessitate surgery (Olsen *et. al.*, 2006).

At least six UEK parameters have been associated with ball velocity: shoulder anterior and proximal force, shoulder horizontal adduction and internal rotation torque, and elbow varus and flexion torque (Stodden *et. al.*, 2005). Positive correlations can be seen in reported pitching biomechanics data between upper extremity kinetics (UEKs) and ball velocity (Fleisig *et. al.*, 1999; Stodden *et. al.*, 2005), though the exact nature of the relationship has yet to be determined. It is assumed that there are at least two main components that establish this relationship: one general and one specific. The general relationship stems from Newton's second law motion that states that force is directly proportional to acceleration given a constant mass. In the case of baseball pitching, this means that more force/torque must be applied to the body, and subsequently to the baseball, in order to accelerate the arm faster and release the ball with greater velocity. From this concept, one might expect to find a nearly perfect linear relationship between upper extremity kinetics and velocity. However, it is very unrealistic to assume that pitchers can apply force that perfectly. This leads to the second component of the relationship, which is what logically separates the efficient pitchers from the inefficient ones. Those who are able to best utilize the kinetic chain to maximize their ball velocity and simultaneously minimize UEKs are placing the least amount of stress on their arms for a given performance level. The first purpose of this retrospective study was to assess the linearity of the relationship between UEKs and ball velocity. It was hypothesized that strong linear correlations between them would be confirmed. The second purpose of the study was to develop a method for determining what constitutes an efficient pitcher and how the biomechanical profiles of mechanically efficient and inefficient pitchers can be differentiated.

METHODS:
Data were collected from healthy collegiate and professional baseball pitchers (n=147) tested at the American Sports Medicine Institute. The biomechanical testing procedures followed a previously reported protocol (Escamilla *et. al.*, 1998). Each pitcher threw up to 10 fastballs with maximum effort at the regulation distance of 18.4m. All available trials were used for analysis, and each pitcher's data were derived from the average among trials. Players' height, mass, ball velocity, and biomechanical variables (23 kinematic, 6 kinetic, and 2 temporal) were measured. The first step in data analysis was to calculate Pearson r correlation values between ball velocity and each of the seven UEK parameters. Next, means and standard deviations (SDs) were calculated for ball velocity and the UEKs. For each variable of each pitcher, values of these parameters were classified as high (greater than one SD above the mean), average (within one SD of the mean), or low (more than one SD below the mean). Efficient pitchers were defined as those in the high velocity group with average or low UEKs and those in the average velocity group with low UEKs, while inefficient pitchers were those in the average velocity group with high UEKs and those in the low velocity group with average or high UEK values. Efficiency levels for each pitcher (efficient, normal, or inefficient) were initially determined for all six UEK values, but the focus was centered on four specific values (shoulder horizontal adduction torque and proximal force and elbow varus and flexion torque). This was done to isolate different phases of the delivery, reduce redundancy, and equally weight the effects of the risk of shoulder and elbow injuries. The pool of pitchers was ultimately reduced to two groups: those with three or four out of four efficient kinetics and no inefficient kinetics (n=16), and those with three or four out of four inefficient kinetics and no efficient kinetics (n=16). Independent t-tests were used to compare the two groups across all biomechanical and anthropometric variables, as well as ball velocity. To help protect against family-wise errors, for all tests, $\alpha=.01$.

RESULTS: The bivariate correlations between ball velocity and upper extremity kinetics for all pitchers with kinetic data (n=145) are shown in Table 1. All six kinetic values were significantly correlated with ball velocity ($p<.01$), with shoulder proximal force and elbow flexion torque showing correlation coefficients greater than or equal to 0.50.

Table 1. Coefficients of correlation between upper extremity kinetics and ball velocity

Upper extremity kinetic (UEK) parameter	Correlation coefficient
Shoulder Proximal Force (N)*	0.57
Elbow Flexion Torque (Nm)*	0.50
Shoulder Internal Rotation Torque (Nm)*	0.48
Elbow Varus Torque (Nm)*	0.48
Shoulder Horizontal Adduction Torque (Nm)*	0.35
Shoulder Anterior Force (N)*	0.22

* $p<.01$

The efficient pitchers had similar heights as the inefficient pitchers (192 cm to 189 cm), but the efficient pitchers had significantly less mass (88 kg to 96 kg) and threw with significantly greater ball velocity (39 $m*s^{-1}$ to 35 $m*s^{-1}$). The comparisons of kinematic, temporal, and kinetic data between the efficient pitchers and inefficient pitchers are shown in Tables 2, 3, and 4 respectively. 10 of the 23 kinematic parameters were significantly different between groups, but neither of the temporal variables was significantly different. Efficient pitchers exhibited significantly greater maximum pelvis, upper trunk, and shoulder internal rotation velocities. They also had greater maximum shoulder external rotation, shoulder horizontal abduction at FC, and forward trunk tilt and elbow extension at BR. Finally, efficient pitchers maintained a shoulder abduction angle closer to 90 degrees at FC and BR and had less lateral trunk tilt at FC. Efficient pitchers had either significantly lower UEK values (shoulder anterior force and horizontal adduction torque) or statistically indifferent UEK values (shoulder proximal force and internal rotation torque, elbow varus and flexion torque) for all kinetic variables.

Table 2. Kinematic differences between efficient and inefficient pitchers.

Variable	Efficient	Inefficient
Stride length ratio (% ht)	83 ± 4	83 ± 3
Lead foot position (cm)	20 ± 10	19 ± 10
Lead foot angle (deg)	14 ± 8	12 ± 11
Lead knee flexion at FC (deg)	43 ± 8	42 ± 7
Pelvis rotation at FC (deg)	33 ± 11	32 ± 12
Pelvis to upper trunk separation at FC (deg)	53 ± 9	46 ± 9
Lateral trunk tilt at FC (deg)*	3 ± 5	9 ± 9
Shoulder abduction at FC (deg)	86 ± 11	96 ± 14
Shoulder horizontal abduction at FC (deg)*	30 ± 11	19 ± 12
Shoulder external rotation at FC (deg)	42 ± 25	53 ± 20
Elbow flexion at FC (deg)	90 ± 9	91 ± 17
Max pelvis rotation velocity (deg/s)*	621 ± 86	535 ± 68
Upper trunk rotation velocity (deg/s)*	1155 ± 71	1058 ± 72
Max shoulder external rotation (deg)*	189 ± 6	176 ± 9
Max shoulder horizontal adduction (deg)	12 ± 7	16 ± 8
Max elbow flexion (deg)	97 ± 10	96 ± 11
Max shoulder internal rotation velocity (deg/s)*	7773 ± 889	6732 ± 1225
Max elbow extension velocity (deg/s)	2346 ± 246	2202 ± 308
Lead knee flexion at BR (deg)	35 ± 14	37 ± 13
Forward trunk flexion at BR (deg)	38 ± 6	33 ± 7
Lateral trunk flexion at BR (deg)	24 ± 11	22 ± 12
Shoulder abduction at BR (deg)*	89 ± 7	99 ± 7
Elbow flexion at BR (deg)*	21 ± 4	27 ± 5

*p<.01

Table 3. Temporal differences between efficient and inefficient pitchers.

Variable	Efficient	Inefficient
Max pelvis rotation velocity (% pitch)	28 ± 15	22 ± 11
Max upper trunk rotation velocity (% pitch)	48 ± 8	46 ± 9

Table 4. Kinetic differences between efficient and inefficient pitchers.

Variable	Efficient	Inefficient
Shoulder anterior force (N)*	271 ± 47	334 ± 49
Shoulder proximal force (N)	1152 ± 200	1147 ± 189
Shoulder horizontal adduction torque (Nm)*	92 ± 17	109 ± 18

Shoulder internal rotation torque (Nm)	84 ± 19	96 ± 17
Elbow varus torque (Nm)	83 ± 179	93 ± 17
Elbow flexion torque (Nm)	47 ± 10	44 ± 13

*p<.01

DISCUSSION AND CONCLUSIONS: The purposes of this study were to define the relationship between ball velocity and upper extremity kinetic (UEK) values during baseball pitching and use these relationships to differentiate mechanically efficient pitchers from inefficient pitchers. The efficient pitching group displayed clear advantages by throwing significantly faster with similar or lower UEK values. They were also capable of accomplishing this despite having significantly less body mass. The efficient pitchers were able to generate greater pelvis, upper trunk, and shoulder internal rotation velocities. It is likely that this optimized use of the kinetic chain is what allowed them to achieve greater ball velocity. The increased upper trunk rotation probably accounted for some of the pitchers' ability to achieve greater maximum external rotation at the shoulder, another factor which has been linked to increased throwing velocity (Matsuo *et. al.*, 2001). They maintained more anatomical stability by keeping the shoulder closer to 90 degrees of abduction throughout the movement, flexed their trunk forward more at ball release to help drive the ball towards the plate, and had more elbow extension to maximize the "whip effect" of the arm in the throwing motion. Efficient pitchers likewise had greater horizontal abduction at foot contact to help activate the stretch reflex in the anterior shoulder and maintained a more neutral lateral trunk position to focus their body's energy toward the plate.

Baseball coaches, clinicians, and researchers are looking for the pitching mechanics that maximize performance while minimizing the risk of injury. Based on the results of this analysis, it is recommended that practitioners use the biomechanical profile of the efficient pitchers in this study as the referential group when assessing an individual's mechanics.

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