ORIGINAL ARTICLE

Factor analysis of the improvement of bat energy in baseball hitting

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ABSTRACT

Baseball hitting involves multiple biomechanical variables, and understanding their impact on bat energy is crucial for improving performance. However, no studies have explored how biomechanical features affect hitting performance from the perspective of bat energy. This study aimed to systematically investigate the influence of lower limb biomechanical variables on bat energy using factor analysis and stepwise regression methods. Sixteen right-handed baseball players participated in the study. Bilateral lower limb kinematic and kinetic features were calculated and exported using a motion capture system and force platform. Six key factors (F1–F6) were extracted from the 28 biomechanical features. Factors F1 and F5 are correlated with the rotation of the trailing and leading limbs, respectively; F2 correlates with energy production of the leading limb; F3 correlates with linear momentum production; F4 correlates with body posture control; and F6 correlates with body linear movement in the anterior direction. To enhance bat energy, hitters should step towards the incoming ball more rapidly to increase ground reaction force on the leading limb. They should also maximize extension and external rotation of both the leading and trailing limbs, stabilize the trailing limb during body rotation, and ensure proper weight distribution between the leading and trailing limbs.
Keywords: Biomechanics, Baseball biomechanics, Factor analysis, Baseball training, Baseball performance.

Cite this article as:
Yang, C., & Jin, P. (2025). Factor analysis of the improvement of bat energy in baseball hitting. *Journal of Human Sport and Exercise, 20*(2), 381-393. https://doi.org/10.55860/df8j1d03

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Submitted for publication September 15, 2024.
Accepted for publication November 07, 2024.
Published January 03, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/df8j1d03

INTRODUCTION

Baseball hitting is considered one of the most difficult skills to master in all sports. Hitters must accurately judge the timing and direction of their swing within a fraction of a second to successfully hit a baseball traveling at over 140 kilometers per hour. The question of how to achieve the maximum speed of a hit baseball has existed almost since the inception of the sport. Faster bat speed is strongly correlated with higher on-base rates and home run rates, making it a key factor in winning games (Horiuchi et al., 2024).

Some researchers have studied how to maximize bat speed. One study quantified the impact of shoulder, elbow, and torso movements on bat swing speed, finding a positive correlation between the moment of shoulder adduction/abduction and the angular velocity of torso rotation with bat speed (Koike & Mimura, 2016). This rotational force originates from the ground reaction force exerted by the feet, which hitters can use to increase the moment at the hip and knee joints, achieving faster torso and upper limb rotation (Ae et al., 2017). Additionally, since the ground reaction force of the leading limb is an important energy source for torso rotation (Howenstein et al., 2020), a larger stride will help increase the linear momentum during the step forward (Ramsey et al., 2014), and enhance the absorption of the ground reaction force by the leading limb, increasing the kinetic energy of torso rotation. Thus, greater extension of both lower limbs is also an important factor affecting hitting power. Howenstein used computer simulation to find that greater barrel-side shoulder abduction, knob-side elbow flexion, and torso right lateral flexion around ball impact can significantly increase bat swing speed from 36.5 to 40 m/s (Howenstein et al., 2020). These studies confirm that many kinetic and kinematic variables influence bat swing speed.

However, bat swing speed is only one factor affecting hitting power. Powerful swing requires transferring as much of the bat's energy to the ball as possible at the moment of contact. Specifically, the bat's kinetic energy is the sum of its translational energy, rotational energy, and potential energy. Translational energy is determined by the bat's mass and linear velocity, rotational energy is determined by the moment of inertia and angular velocity, and potential energy is determined by the bat mass, gravitational acceleration, and vertical displacement. These energies depend on the hitters ability to generate mechanical energy (Ae et al., 2020). During hitting, the greater the mechanical energy generated by the hitters body, the more energy is transferred to the bat per unit time, resulting in faster swing speed (Szymanski et al., 2010). Surprisingly, no researchers have directly examined the relationship between the mechanical energy of the bat and kinetic and kinematic characteristics. Moreover, the current problem in this field of research is that when researchers attempt to examine the relationship between a bat speed and several independent variables, they rely on their experience to select the kinematic or kinetic indicators (independent variables) to analyze. This is overly subjective and cannot comprehensively examine the relationship between all potential features and swing speed. Additionally, different studies may choose different features, resulting in non-complementary findings. Overall, theories on how to increase bat mechanical energy to enhance bat speed are fragmented. Previous studies have used factor analysis method to quantify key independent variables related to performance in cutting maneuvers and take-off performance in pole vaulting (Li et al., 2022; Welch et al., 2021). The advantage of this method is that it can include many independent variables at once, filtering out the truly useful ones through dimensionality reduction, and then performing regression analysis with the dependent variable. This comprehensively quantifies the correlation between independent and dependent variables, reducing the risk of bias from subjective selection of variables.

In summary, we collected kinetic and kinematic data from the leading and trailing limbs during a baseball swing. We then applied factor analysis for dimensionality reduction on the independent variables. After extracting the relevant factors, we conducted stepwise multiple linear regression analysis to explore the associations between these independent variables and bat energy during the swing.

METHODS

Participants

Sixteen right-handed baseball players participated in this study (age:23.6±2.4 years, experience: 7.8±1.5 years, height: 178.65 ± 3.11 cm, weight: 77.52 ± 13.21 kg). Each participant had been formally training for over six years. The inclusion criteria for the participants were as follows: male, accustomed to the automatic pitching machine, and maintaining regular training within the past six months. The exclusion criteria included having chronic or acute lower or upper limb injuries in the past three months, such as shoulder impingement syndrome, lumbar strain, knee osteoarthritis, and hip surgery. Each participant signed an informed consent form before the experiment, and the experimental procedures complied with the Helsinki Declaration. This study was approved by the Ethics Committee of Qufu Normal University (grant number: LL-20230009).

Procedures

The experiment was conducted in a rectangular area of approximately fifty m^2. Two force plates (sampling rate: 1000 Hz, model: BP600900, AMTI Inc, USA) were placed in the center of the field. Surrounding the field, a three-dimensional motion capture system consisting of 12 cameras (sampling rate: 200 Hz, model: Vantage V5, ox-ford Inc, UK) was set up. Before the formal test, 41 markers were attached to the subjects' bodies and 5 markers to the bat (Figure 1). The hitters then performed a static capture under the guidance of the experimenters. During the formal test, the subject's right leg (trailing limb) was positioned on force plate 1, while the left leg (leading limb) was on force plate 2. The leading limb is defined as the limb that steps towards the incoming ball during the hitting, while the trailing limb refers to the another limb (Lis et al., 2022). An automatic pitching machine (model:777BH, Furlihong Inc, China) was placed 16 meters directly in front of the subject, which launched fast baseball (weighing approximately 140 grams) towards the subject at a speed of 105 kilometers per hour. The subjects used a bat (model: B5 Pro, Easton Inc, USA) weighing approximately 850 grams to hit the baseballs, performing at least five effective hits.

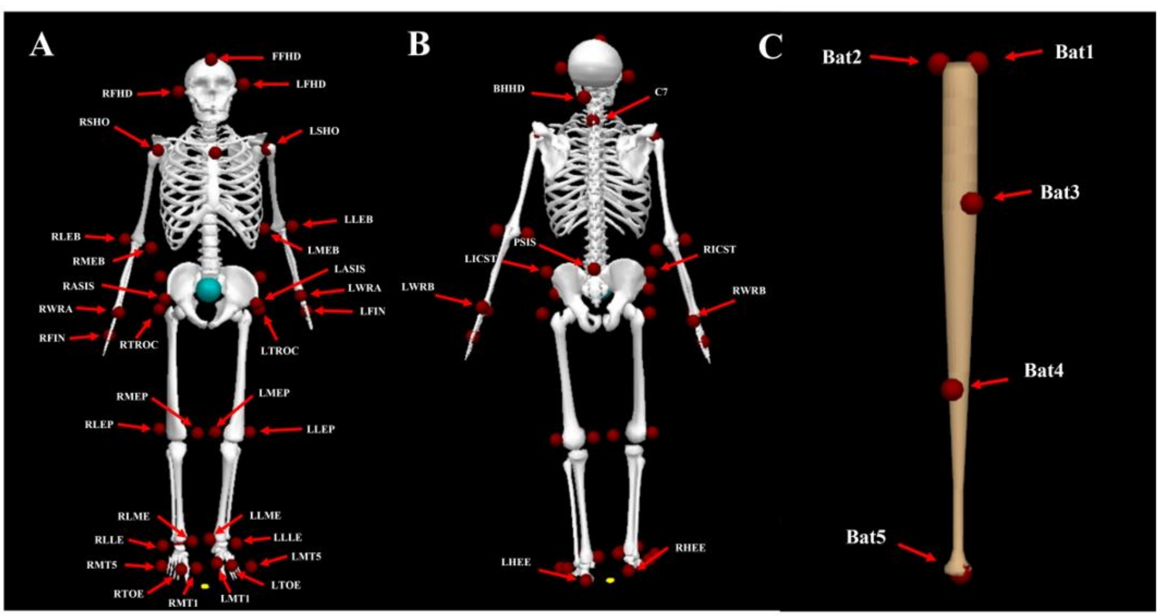

Figure 1. Marker protocol. A: front view. B: back view. C: marker placement in bat.

The force plates and the motion capture system were synchronized using a sync cable. The laboratory coordinate system was set as follows: the Y-axis represented the anterior-posterior direction, with the positive direction pointing towards the pitching machine; the X-axis represented the medial/lateral direction, with the positive direction being to the subject's back side (in the ready stance for hitting); and the Z-axis represented the vertical direction, with the positive direction pointing upward.

Data analysis

Each subject's static calibration file was imported into the Visual 3D biomechanical analysis system (version: V6 Professional, Has-Motion Inc, Canada). Based on the static files, a rigid body model of the human body and a rigid body model of the bat were established and saved as MDH format files. The model files were then applied to the motion capture files. The calculation method for bat energy is described in Equations (1) to (4):

$$M_{energy} = \mathrm{R}_{energy} + \mathrm{T}_{\mathrm{energy}} + \mathrm{P}_{energy} \quad (1)$$

In the above equation, M_{energy} is the Energy in the bat, R_{energy} is rotational energy of bat, $\mathrm{T}_{\mathrm{energy}}$ is translational energy of bat. P_{energy} is the potential energy.

$$\mathrm{T}_{\mathrm{energy}} = \frac{1}{2} * \mathrm{Mass} * (v_x * v_y + v_y * v_z + v_x * v_z) \quad (2)$$

In the above equation, Mass represents the mass of the bat, and v_x, v_y, v_z represent the bat's velocity components along the three coordinate axes, respectively.

$$\mathrm{R}_{energy} = \frac{1}{2}\mathrm{I}_{\mathrm{xx}}\omega_x\omega_x + \frac{1}{2}\mathrm{I}_{yy}\ \omega_y\omega_y\ + \frac{1}{2}\mathrm{I}_{zz}\omega_z\omega_z \quad (3)$$

In the above equations, ω_x, ω_y, and ω_z represent the angular velocities of the bat around the three coordinate axes, and I_{xx}, I_{yy}, and I_{zz} represent the moments of inertia of the bat around the three coordinate axes, respectively.

$$\mathrm{P}_{energy} = \mathrm{Mass} * 9.81 * COM_z \quad (4)$$

In the above equations, COM_z refers to the center of mass of the bat, which is approximately 52.6 cm from the handle along the longitudinal axis. Mass represents the mass of the bat.

Using function of "*LINK_MODEL_BASED*" in Visual3D, the following parameters was calculated: the joint moments of the bilateral hip, knee, and ankle joints; center of gravity (COG) speed at anterior[+]/posterior[-], medial[+]/lateral[-] and up[+]/down[-] direction; step length (distance between leading limb and trailing limb at foot contact);the ground reaction force components in the anterior[+]/posterior[-], medial[+]/lateral[-] and up[+]/down[-] directions from the two force plates. The anterior direction points towards the pitching machine, the medial direction points towards the subject's back (in the ready stance for hitting), and the superior direction points towards the sky. The calculations of joint moments was based on the Cardan Sequence, see Table 1, a standard method for representing joint motion recommended by the International Society of Biomechanics (Wu et al., 2005). All independent variables were processed using a zero-lag 4th-order lowpass filter with cutoff frequencies of 10 Hz for kinematic variables and 20 Hz for kinetic variables (Escamilla et al., 2009b), 30Hz for force plate data.

Table 1. Instructions of cardan sequence in this study.

Joint	Segment (Distal)	Segment (Proximal)	Sequence X	Sequence Y	Sequence Z
Ankle	Foot	Shank	PF [-]/DF [+]	EV [+]/INV [+]	ER [+]/IR [-]
Knee	Shank	Thigh	EXT [+]/FLE [-]	VAL [+]/VAR [-]	ER [+]/IR [-]
Hip	Thigh	Pelvis	EXT [-]/FLE [+]	ABD [+]/ADD [-]	ER [+]/IR [-]

Abbreviation: PF = Plantar flexion. DF = Dorsiflexion. EXT = Extension. FLE = Flexion. EV = Eversion. INV = Inversion. VAL = Valgus. VAR = Varus. ABD = Abduction. ADD = Adduction. ER = External Rotation. IR = Internal Rotation.

The swing phase was defined according to Shaffer et al.'s definition, where the beginning of this phase was marked by the end of the Wind-up and the end is marked by the moment of impact (Shaffer et al., 1993). Event detection commands were written in Visual 3D to accurately locate the start and end of the phase. For the phase start, the event tag was defined as the time point when the vertical ground reaction force exceeded 20N as the subject's stride limb stepped onto force platform 2. Since reflective markers were not attached to the ball, it was impossible to determine the exact time point of impact. According to previous research, the time point of contact usually occurs very shortly before the bat's resultant velocity reaches its peak (Mcintyre & Pfautsch, 1982). Therefore, in this study, the impact event was defined as the time point when the bat's resultant velocity reached its maximum value, with a backward adjustment of 30 milliseconds. All independent variable data within the swing phase were calculated, including the means, maximum, and minimum values, to be used for downstream analysis.

In this study, principal component analysis method was employed to perform dimensionality reduction on lower limb biomechanics features during hitting. This process yielded factors, which were subsequently iteratively incorporated into a linear regression model until convergence. Specifically, the linear regression model can generally be expressed by the following formula, where a_0 represents a constant, a_n denotes regression coefficients computed using the least squares method, and x_n represents independent variables:

$$Y = a_1 x_1 + a_2 x_2 + \cdots a_n x_n + a_0 \tag{5}$$

When incorporating the factors, the equation transforms into:

$$Y = a_1 * F1 + a_2 * F2 + \cdots a_n * F_n \tag{6}$$

Here, $\mathrm{F_n}$ encompasses a dataset of multiple independent variables transformed into a new dataset containing several uncorrelated factors, specifically:

$$F1 = a_{11} x_1 + a_{12} x_2 + \cdots a_{1n} x_n \tag{7}$$
$$F2 = a_{12} x_1 + a_{22} x_2 + \cdots a_{2n} x_n \tag{8}$$

Thus, incorporating factors into the regression equation provides linear regression coefficients between all independent variables and the dependent variable, without issues of multicollinearity among the independent variables. Therefore, we can obtain the correlation of each independent variable with the dependent variable (energy in the bat).

Statistical analysis

SPSS (version 26.0, IBM Inc., USA) was used for principal component analysis to obtain factors for dimensionality reduction of the independent variables. Subsequently, stepwise multiple linear regression analysis was conducted to examine the correlation between the reduced factors and the dependent variable (bat energy). The significance level for this study was set at $p < .05$

RESULTS

Table 2 shows the mean values of all features during the swing phase, based on data from 39 hits by 16 hitters.

Table 2. The descriptive data of the 28 features from 16 athletes.

Features	Mean	Std	Maximum	Minimum
Leading knee moment (Nm/kg)				
Extension	0.192	0.154	0.770	-0.291
Varus	-0.217	0.180	1.084	-0.344
External rotation	0.198	0.060	0.449	-0.028
Leading hip moment (Nm/kg)				
Extension	-1.011	0.375	-0.149	-2.589
Adduction	-0.115	0.154	0.559	-0.601
Internal Rotation	-0.287	0.105	0.031	-0.695
Leading ankle moment (Nm/kg)				
Plantar flexion	-1.023	0.196	-0.421	-1.926
Eversion	0.085	0.116	0.775	-0.105
External rotation	0.056	0.049	0.353	-0.080
Trailing knee moment (Nm/kg)				
Extension	0.112	0.166	0.646	-0.355
Varus	-0.455	0.137	-0.004	-0.956
External rotation	0.575	0.166	1.231	0.044
Trailing hip moment (Nm/kg)				
Extension	-0.661	0.281	0.706	-1.624
Adduction	-1.135	0.278	-0.163	-1.868
External rotation	0.426	0.115	0.894	-0.114
Trailing ankle moment (Nm/kg)				
Plantar flexion	-0.368	0.105	-0.027	-0.984
Inversion	-0.205	0.092	0.511	-0.521
Internal Rotation	-0.143	0.063	0.095	-0.324
Force plate contact by leading limb (N)				
Posterior	-337.521	83.249	-98.923	-584.039
Medial	151.917	37.795	280.863	30.278
Vertical	912.862	188.291	1697.592	321.643
Force plate contact by trailing limb (N)				
Anterior	57.701	30.522	110.559	-96.095
Lateral	-104.016	19.451	-22.469	-170.551
Vertical	284.460	44.023	494.436	139.878
Center of gravity speed (m/s)				
Anterior	0.691	0.092	1.056	0.373
Medial	0.081	0.064	0.426	0.095
Vertical	-0.067	0.096	0.295	-0.461
Step Length (m)				
Anterior	0.837	0.044	1.047	0.671

The Kaiser-Meyer-Olkin (KMO) score was 0.638, and Bartlett's test of sphericity was significant (p = .000), indicating that factor analysis was appropriate (Table 3). Therefore, dimensionality reduction was performed on the 28 independent variables, retaining only factors with eigenvalues greater than 1, with a maximum of 25 iterations, six principal component factors were extracted (Table 4).

Table 3. Bartlett's and KMO test results.

Bartlett's Test of Sphericity	Value
Approx. Chi-Square	1840.861
df	378
Sig.	.000
KMO Measure of Sampling Adequacy	0.638

Abbreviation: df = Degrees of freedom. Sig.: Significance; KMO: Kaiser-Meyer-Olkin.

Table 4. Total variance explained.

Component	Initial Eigenvalues			Rotation sums of squared loadings		
	Value	% of Variance	Cumulative %	Value	% of Variance	Cumulative %
1	10.878	38.848	38.848	6.371	22.753	22.753
2	4.477	15.989	54.837	4.729	16.889	39.642
3	3.451	12.327	67.164	4.598	16.421	56.063
4	2.982	10.651	77.815	3.976	14.199	70.262
5	2.033	7.261	85.076	3.424	12.230	82.492
6	1.312	4.684	89.760	2.035	7.268	89.760

The six factors explained 89.760% of the variance (Table 4), extracts these six factors is appropriate, because there are explained the most variances. The factors of F1 includes trailing limb ankle internal rotation moment (0.806), knee external rotation moment (0.918), and leading limb hip external rotation moment (0.890), F2 includes leading limb hip adduction moment (-0.812), ankle plantar flexion moment (0.844), vertical force (-0.826) and medial force (-0.828) from force plate contact by leading limb, F3 includes trailing limb knee (0.889) and hip (0.868) extension moment, F4 includes trailing limb ankle plantar flexion moment (0.884) and vertical force (-0.895) from force plate contact by trailing limb. F5 and F6 includes hip external rotation moment (0.952) of trailing limb and body speed (0.882) in anterior direction (Table.5).

Table 5. Rotated component matrix and communalities.

Features	Component					
	1	2	3	4	5	6
COG Speed Anterior	-0.647	-0.118	-0.027	0.435	0.191	0.882
COG Speed Medial	-0.207	0.031	0.323	0.698	0.399	0.220
COG Speed Vertical	-0.187	0.036	-0.006	-0.155	0.275	-0.442
FL Posterior force	0.185	0.712	-0.082	-0.443	0.068	0.424
FL Medial force	-0.414	-0.826	-0.036	-0.096	0.247	0.092
FL Vertical force	-0.207	-0.828	0.129	0.424	-0.094	-0.198
FT Anterior force	0.389	0.206	-0.353	-0.559	0.268	-0.420
FT Lateral force	0.647	0.449	0.405	0.012	-0.115	0.082
FT Vertical force	0.092	0.269	0.092	-0.895	-0.095	0.029
LA Plantar flexion moment	0.456	0.844	-0.149	-0.106	0.124	-0.305
LA Eversion moment	-0.312	-0.251	0.380	0.163	0.784	0.165
LA External rotation moment	-0.212	-0.221	0.746	0.179	0.479	0.071
Step Anterior length	-0.561	-0.085	0.109	0.645	0.030	-0.368
LH Extension moment	0.290	0.429	-0.508	-0.519	-0.284	0.253
LH Adduction moment	0.471	-0.812	0.182	-0.044	0.015	0.028

LH Internal rotation moment	0.890	-0.106	-0.027	0.025	-0.276	-0.075
LK Extension moment	-0.037	0.336	-0.747	-0.074	-0.093	0.193
LK Varus moment	0.046	-0.495	0.479	0.103	0.649	0.257
LK External rotation moment	-0.495	0.670	0.047	-0.089	-0.360	0.103
TA Plantar flexion moment	0.122	0.025	0.257	0.884	-0.018	0.026
TA Inversion moment	0.523	-0.155	-0.471	-0.219	-0.524	-0.139
TA Internal rotation moment	0.806	0.315	-0.206	-0.243	0.077	0.035
TH Extension moment	-0.311	-0.095	0.868	0.274	0.091	-0.100
TH Adduction moment	0.918	0.150	-0.270	-0.060	-0.107	-0.083
TH External rotation moment	-0.151	0.054	0.004	-0.002	0.952	0.019
TK Extension moment	-0.159	0.162	0.889	0.029	0.035	0.185
TK Varus moment	0.782	-0.016	-0.453	-0.130	-0.132	-0.187
TK External rotation moment	0.918	0.054	0.450	0.091	0.426	0.222

Abbreviation: LA = Leading limb ankle. LH = Leading limb hip. LK = Leading limb knee. TA = Trailing limb ankle. TH = Trailing limb hip. TK = Trailing limb knee. FT = Force plate contact by trailing limb. FL = Force plate contact by leading limb. COG = Centre of gravity.

The next step is conducting six factors were analyzed using stepwise linear regression to quantify the relationship between the independent variables and the dependent variable (Table 6), the R^2 of the model was 0.885, and the adjusted R^2 was 0.861. The observed F statistic for the significance test of the regression equation was 14.831, p = .001, therefore, the null hypothesis of the regression equation significance test should be rejected, indicating that the regression coefficient is not zero. A significant linear relationship was found between the explanatory variables and the dependent variable, confirming that the linear model is reasonable. The final regression equation is as follows:

$$Energy = -0.527 * F1 - 0.489 * F2 + 0.374 * F3 \ldots - 0.243 * F6 \qquad (9)$$

Table 6. Linear regression analysis statistics of six factors.

Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob**
Constant	-2.8463E-16	0.062212	0	1.000
F1	-0.527	0.063	-8.347	.000
F2	-0.489	0.063	-7.754	.000
F3	0.374	0.063	5.921	.000
F4	0.325	0.063	5.155	.000
F5	0.252	0.063	3.992	.000
F6	-0.243	0.063	-3.852	.001
R-squared		.885	F-statistic	14.837
Adjusted R-squared		.861	Prob. (F-statistic)	.001

Table 7. Linear regression analysis statistics of six factors.

Features	**Coefficient**	**Features**	**Coefficient**
Leading knee moment		Force from plate contact by leading limb	
Extension	-0.518	Posterior	-0.706
Varus	0.531	Medial	0.617
External rotation	-0.194	Vertical	0.724
Leading hip moment		Force from plate contact by trailing limb	
Extension	-0.853	Anterior	-0.449
Adduction	0.199	Lateral	-0.454
External rotation	-0.471	Vertical	-0.467
Leading ankle moment		Center of gravity speed	
Plantar flexion	-0.588	Anterior	0.649
Eversion	0.639	Medial	0.363
External rotation	0.660	Vertical	0.151

Trailing knee moment		Step Length	
Extension	0.310	Anterior	0.684
Valgus	-0.604	Trailing ankle moment	
External rotation	-0.259	Plantar flexion	0.296
Trailing hip moment		Inversion	-0.546
Extension	0.671	Internal rotation	-0.723
Adduction	0.171	\	\
External rotation	0.289	\	\

Finally, substitute the factor scores of each independent variable from Table 4 into Equation 9, can calculate the correlation between each independent variable and the dependent variable (Table 7).

DISCUSSION

Achieving high-speed hitting is crucial for winning baseball games, and the energy contained in the bat plays a significant role in high-speed hitting. To our knowledge, no studies have comprehensively examined the correlation between lower limb biomechanics and bat energy. In this study, we introduced twenty-eight independent variables, covering nearly all measurable lower limb features during a baseball player's swing. We identified six distinct factors, each playing a unique role in the baseball swing. These findings will be discussed in detail below.

F2 responded for energy transfer between limbs. Results show that the plantar flexion moment of the leading limb ankle has a positive factor score but a negative contribution, while the adduction moment of the hip joint has a negative score but a positive contribution. This indicates that more plantar flexion moment is associated with reduced bat energy, whereas more adduction moment is linked to improved energy. The plantar flexion moment from the leading limb ankle at foot contact is well-documented (Ae et al., 2017). EMG studies have found that the gastrocnemius muscle activates approximately 500ms before ball impact and remains active for about 300ms (Nakata et al., 2013; Nakata et al., 2012). After the leading limb contact the force plate, the body needs to decelerate to transfer forward and vertical momentum to the pelvis and trunk, converting it into rotational components (Orishimo et al., 2023). When hitters move towards the incoming ball, the momentum and force from contact create an ankle dorsiflexion moment at foot contact. This causes the leading limb to move towards the ball's direction, leading to energy loss. Previous studies have shown that the plantar flexion moment plays an important role in decelerating the center of gravity speed during the gait cycle (Orendurff et al., 2008). Undoubtedly, the ankle plantar flexion moment during the swing phase helps hitters decelerate their body and avoid energy loss in this direction. However, the braking force must be carefully controlled, as excessive plantar flexion moment at the ankle can reduce the energy available for rotation. On the other hand, the results that greater hip adduction moment is helpful improving bat energy suggests that hitters should use the leading foot as a pivot when foot contact and control their lower trunk like a pendulum to generate more power during the swing. Previous studies have found that the adduction moment of the leading limb hip joint is the main power producer at swing phase (Ae et al., 2017).

Results show that the vertical force score is negative, but its contribution is positive, indicating that increased vertical ground reaction force from plate contact by leading limb is associated with improved bat energy. A previous study found that the peak vertical force could explain 38% of the variance in ball speed (Orishimo et al., 2023).We believe that hitters should employ a "*controlled fall*" mechanism, similar to pitching, to propel their bodies forward (Campbell et al., 2010). This mechanism accelerates the center of mass toward the leading limb, increasing velocity and incorporating more body mass into the batting motion, thereby producing more force compared to a direct step forward. Moreover, the medial force from plate contact by the leading limb has a negative factor score but a positive contribution, indicating that increased medial force is associated with enhanced bat energy. Note that in the force plate coordinate system, the medial direction points toward the back of the athlete. Medial force means more large energy for body rotational. According to Newton's third law, the medial and lateral force vectors are equal in magnitude but opposite in direction. During a golf swing, players shift their center of pressure (COP) to the trailing limb, activating the ankle eversion muscles to counterbalance the large moment created by ground reaction force (Choi et al., 2016; Marta et al., 2016). Therefore, to provide stable support for the leading limb, it is recommended that hitters use their ankle eversion muscles to generate a moment that stabilizes the foot and counteracts the ankle inversion moment caused by the medial force generated during the body's counterclockwise rotation.

All the variables in F1 have positive factor scores but negative contributions. These results suggest that increased internal rotation moment of the trailing limb ankle joint and external rotation moment of the knee joint are associated with reduced bat energy. When hitters begin to rotate their bodies, an increased internal rotation moment at the trailing limb ankle joint indicates that the foot is rotating internally along with the shank and thigh. If the foot were fixed to the ground and acting as a stable pivot, it would produce more external rotation moment, as the foot would remain stationary while the shank and thigh continue to rotate internally. If the foot undergoes internal rotation that exceeds the rotation of the shank or thigh, stability will be compromised, making it difficult to maintain stable support during rotation. Additionally, if the knee joint produces more external rotation moment during the rotation of the trailing limb, it suggests that the shank is rotating less than the thigh. If the shank were in sync with the thigh, the knee joint would be unlikely to produce external rotation movement. Without a doubt, the un synchronize of shank and thigh will disrupt the rotational rhythm and reduce energy production. Another interesting finding is that an increased internal rotation moment at the leading limb hip joint is correlated with reduced bat energy. Consider this: if the pelvis continues to rotate while the thigh remains stationary, it will create more internal rotational moment at the joint. However, this means the hip joint reaches its maximum external rotation limit faster, potentially leading to premature hip impingement (Sonnenfeld et al., 2021). At baseball pitching, pitcher leans forward to increase shoulder motion range before pitching, as a greater range of motion allows more time for acceleration (Stodden et al., 2005). Therefore, we suggest hitters rotate the thigh in coordination with the pelvis, or even surpass the pelvis's external rotation. This kind of movement strategy will result in a larger external rotation moment at the hip joint and produce more energy.

Another factor related to power production is F5. The results show that the factor scores and contributions are positive, indicating that increased external rotation moment of the trailing limb is correlated with higher bat energy. Baseball swing emphasizes a distal-to-proximal joint movement pattern, constructing the kinematic chain (Escamilla et al., 2009a; Welch et al., 1995). Therefore, these results suggest that the pelvis must rotate degrees should over pass the thigh of the trailing limb. Only then can the hip joint produce more external rotation moment. More pelvis internal rotation means more efficient trunk rotation, it will be helpful produced more bat energy.

F3 is related to the production and control of linear momentum, as all variables are activated in the sagittal plane. Results show that the factor scores and contributions are positive, indicating that increased hip and knee extension moments in the trailing limb enhance bat energy. During the rotation phase, the pelvis rotates nearly 90 degrees towards the incoming ball at a rate of 600-700 degrees per second. To achieve such a large rotation in such a brief time, the hip extensors of the trailing limb must generate significant mechanical energy. In the early phase of foot contact and body rotation, this energy mainly comes from the linear momentum generated by the contraction of the hip and knee extensors of the trailing limb (Liu et al., 2023) (Horiuchi & Nakashima, 2023). EMG studies have also shown that the hip extensor muscles peak in activation before the hitting event (Nakata et al., 2013). This linear momentum generates a large resultant moment at the pelvis, which applies angular acceleration to the trunk and upper limbs. The larger the resultant moment, the greater the angular acceleration of the trunk and upper limbs, and the greater the moment of inertia during the bat swing (Ae et al., 2017). The positive factor score and contribution for the center of gravity speed in the anterior direction indicate that greater speed in this direction is beneficial. These factors emphasize the importance of fully extending both the leading and trailing limb to generate more linear momentum and speed.

F4 is related to body posture control. Results show that the vertical force from plate contact by the trailing limb has a negative factor score and contribution, indicating that increased vertical force is correlated with a reduction in bat energy. A previous study found that the force from plate contact by the leading limb has a strong correlation with energy transfer to the trunk, while the force from the trailing limb does not (Horiuchi & Nakashima, 2023). Therefore, hitters should transfer more body mass to the leading limb. The positive effects of the trailing limb ankle plantar flexion moment on energy also suggest that transferring more body mass to the leading limb is beneficial. Additionally, the correlation between vertical force from leading limb contact and increased bat energy supports our speculation. However, we believe hitters should control their body mass distribution. Previous research has discussed the foot pressure of high-level and amateur hitters during hitting. High-level hitters typically shift their body mass to the leading limb at contact, but the trailing limb still maintains a reasonable portion (Moon et al., 2013). This is crucial for balance control. If hitters are unable to maintain their balance, it can cause instability in the bat's axis of rotation due to centrifugal force during the swing. Meanwhile, a balanced distribution of body mass will maintain the ideal position of COG between the COP of the trailing and leading limbs. This will helpful to creates more shear force against the ground and enhances pelvic rotation speed (Welch et al., 1995).

CONCLUSION

We used factor analysis and regression methods to explore the relationship between mechanical energy and 28 lower limb biomechanics features during baseball hitting, identifying six key factors. To enhance bat energy, hitters should step towards the incoming ball more rapidly to increase ground reaction force on the leading limb. They should also maximize extension and external rotation of both the leading and trailing limbs, stabilize the trailing limb during body rotation, and ensure proper weight distribution between the leading and trailing limbs.

AUTHOR CONTRIBUTIONS

All authors, Chen Yang, Pengfei Jin, have made substantial contributions to the conception and design of the work, the acquisition, analysis, and interpretation of data, and drafting or revising the manuscript. Each author has approved the final version to be published and agrees to be accountable for all aspects of the work. We also confirm that the manuscript has not been published elsewhere and is not under consideration for publication in any other journal. All co-authors have agreed to its publication in JHSE.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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