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ORIGINAL ARTICLE

Diversity and independence of stride strategies in collegiate baseball batters: A descriptive study

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ABSTRACT

The purpose of this study was to quantify the diversity of stride motions in collegiate baseball batters (n = 95) and establish normative data for hitting mechanics. Maximum-effort batting tasks from a tee were analyzed using a 3D motion capture system and force plates. Stride motion was defined by three components: stride width, stride direction, and peak foot height. Pearson's correlation analysis was used to examine the relationships between these components and batting performance metrics, including bat head speed, center of gravity (COG) kinematics, and peak ground reaction force (GRF). The results showed no significant correlation among the three stride components, indicating they are independent strategic parameters. Stride width showed a weak but significant positive correlation with bat head speed (r = .328, p < .001), suggesting it functions as a modulator for swing velocity. Conversely, neither peak foot height nor stride direction correlated with bat head speed, although they were significantly associated with COG kinematics (vertical displacement, r = -.64) and GRF characteristics (mediolateral force, r = .455), respectively. In conclusion, no single "*ideal*" stride motion was identified among elite collegiate batters. The lack of strong correlations between stride mechanics and swing speed supports the concepts of motor redundancy and equifinality in batting. These findings suggest that elite batters can achieve high swing speeds using diverse stride strategies by optimizing subsequent kinetic chains, implying that coaches should accommodate individual stride styles rather than enforcing a rigid form.

Keywords: performance analysis; baseball; batting; stride motion.

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INTRODUCTION

In recent years, the evaluation of baseball batting has become more sophisticated, and batted ball speed has attracted attention as an important performance indicator strongly associated with outcome metrics such as OPS (On-base Plus Slugging) and batting average; it has been reported that the swing speed at impact is heavily involved in this (Sawicki et al., 2003). In the batting motion, the motion of the lower limbs in particular does not directly accelerate the bat, but it is considered to indirectly contribute to performance as the energy source for the entire swing. In a study targeting collegiate baseball players, it has been clarified that there is a positive correlation between lower body muscle strength and the improvement of swing speed (Reyes et al., 2010). Furthermore, Horiuchi et al. (2017, 2023) stated that the left and right hip joints serve as the source of mechanical energy, and the transfer of this energy from the trunk to the upper limbs and then to the bat contributes to an increase in swing speed at impact. Thus, it is extremely important to generate greater energy in the lower limbs and transfer it efficiently.

In the field of batting, there are multiple studies dealing with lower limb motion, reporting on the relationship between ground reaction force (GRF) or lower limb kinematics and swing speed or the amount of energy influx, as well as differences in stride and rotation strategies due to different pitch speed conditions (Ae et al., 2017; Orishimo et al., 2023; Katsumata et al., 2007; Fortenbaugh et al., 2011). However, many of these previous studies have focused on specific mechanical factors or kinetic chains, and studies that systematically quantify the relationship between the variations in the diverse stride motions themselves among individual batters and batting characteristics in a form that can be fed back to practical coaching settings remain limited.

On the other hand, in pitching motion, detailed examinations regarding the actual state of stride motion and the effect of stride length on pitching performance using force plate systems and three-dimensional motion analysis systems have progressed (Smith et al., 2017; Manzi et al., 2022). In contrast, although lower limb motion in batting is a phase where high individuality tends to appear in stride length and stride style, findings that systematically clarify its actual state and relationship with batting characteristics have not been sufficiently accumulated compared to pitching research. Because stride motion in batting possesses high individuality, making simple comparisons or averaging difficult, systematic analysis is hard to advance. Based on this background, quantitatively characterizing stride motion in batting and comprehensively organizing the relationship between its variations and batting characteristics is expected to have practical significance in that it provides objective and quantitative criteria for designing individualized coaching and training according to characteristics such as the player's intention and body size.

The purpose of this study is to quantify the diversity of lower limb motion, namely stride motion, in collegiate baseball batters, and to present to what extent variations in quantitative features (stride length, direction, and peak foot height) are tolerated without hindering performance. Furthermore, by examining the strength of the correlation between stride motion and performance, this study aims to clarify the range of degrees of freedom of motion in technical coaching.

METHODS

Participants

The participants were 95 male collegiate baseball fielders (55 right-handed batters, 40 left-handed batters) (age: 19.8 ± 1.0 years, height: 171.8 ± 6.6 cm, body mass: 72.4 ± 6.6 kg). Prior to the experiment, the participants were fully informed about the content and purpose of the measurements, the confidentiality of the results, and the potential physical risks, and their informed consent to participate was obtained. This study was approved by the Ethics Committee of the National Institute of Fitness and Sports in Kanoya.

Experimental procedure
Figure 1 shows the experimental setup and the recording area for the batting trials. For the trials, a ball was placed on a batting tee, and the participants were instructed to hit the ball toward centre field with maximum effort. The height of the tee was standardized to the height of the greater trochanter, and the participants continued the trials until 10 successful hits were obtained.

Prior to the trials, the participants performed a sufficient warm-up including stretching, followed by 3 to 5 practice swings to familiarize themselves with the experimental environment before the measurements began. After each trial, they were asked to verbally report their subjective feeling of the hit to the examiner on a 5-point scale.

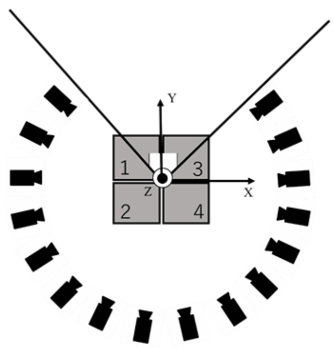

Figure 1. Experimental setup.

Data acquisition and processing
Reflective markers were attached to a total of 58 points: 53 points on the participant's body and 5 points on the bat (Figures 2 and 3). Measurements were conducted using an optical three-dimensional motion analysis system, Mac3D (16 Raptor-E cameras, Motion Analysis Corporation, Santa Rosa, CA, USA; 500 Hz), and four force plates (TF-90100, Tec Gihan, Uji, Kyoto, Japan; 2000 Hz). A soil-filled box (25-015-301, Tec Gihan, Kyoto, Japan) was placed on top of each force plate, and similar to a previous study (Yanai et al., 2017), the inside of the boxes was packed with clay blocks (MoundMaster®, Turface Athletics™, USA), red sand (En-tout-cas Neo, OKU EN-TOUT-CAS CO., LTD., Osaka, Japan), and black soil (Satsuma Hayato, Osumi Kurotsuchi Hanbai). After laying the clay blocks, a mixture of red and black soil was used to cover the clay blocks to form the surface layer. Water was sprinkled over each area, and the surface was firmly tamped down to compact the soil.

Force plate data were output from a central relay board (Tec Gihan, Kyoto, Japan) and acquired using Cortex 8.0 software (Motion Analysis Corporation, Santa Rosa, CA, USA) for Mac3D via an A/D converter (USB-6259, National Instruments Corporation, Texas, USA). The obtained three-dimensional coordinate (body) data were smoothed using a fourth-order Butterworth digital filter with a cutoff frequency of 13.4 Hz (Escamilla et al., 1998). Considering the rapid deceleration of the bat head upon impact with the ball, the bat data during the batting trials were not smoothed (Tabuchi et al., 2007).

In this study, a global coordinate system was defined with the X-axis directed from the right batter's box toward the left batter's box, the Y-axis directed from home plate toward the pitcher, and the Z-axis pointing vertically upward. The origin was set at the centre of the four force platforms (Figure 1). For the trials selected for analysis, referring to the method of Ae et al. (2017), the trials in which the ball was hit toward centre field and had the highest subjective score among those rated 3 or higher (on a 5-point scale) by the participant were targeted. If there were multiple applicable trials, the one with the fastest swing speed among them was selected for analysis. Prior to the trials, the participant's height, body mass, and body fat percentage were measured using a body composition monitor with a stadiometer (DC-217A, Tanita Corporation, Tokyo, Japan) to calculate BMI and lean body mass (hereafter referred to as LBM).

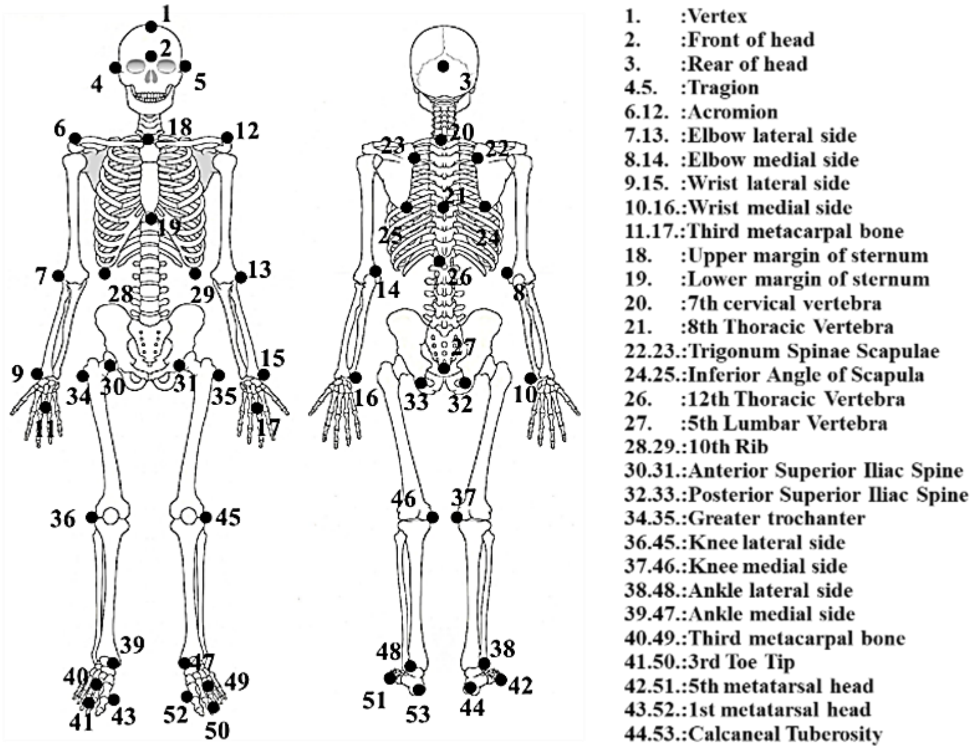

Figure 2. Landmarks of body.

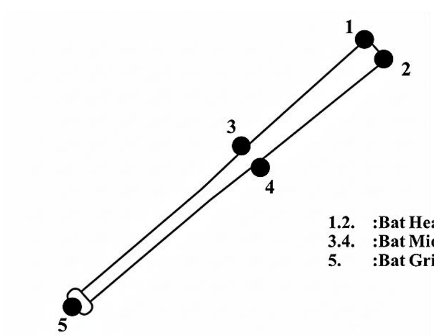

Figure 3. Landmarks of bat.

Definition of stride motion

In this study, the stride motion during the batting motion was defined by three components: "*stride length*," "*peak foot height*," and "*stride direction*," using the coordinates of the midpoint between the medial and lateral malleolus markers of the stride leg (hereafter referred to as the ankle joint centre). The stride length and stride direction were defined as the X and Y coordinates of the ankle joint centre at the time of stride foot contact, respectively. The peak foot height was calculated as the difference between the maximum Z coordinate of the ankle joint centre during the phase from the start of the batting motion to stride foot contact, and the corresponding Z coordinate during static standing. For all parameters, the unilateral lower limb length was calculated as the sum of the line segment connecting the greater trochanter to the lateral knee and the line segment connecting the lateral knee to the lateral malleolus during static standing, and the values were individually normalized by dividing them by the lower limb length.

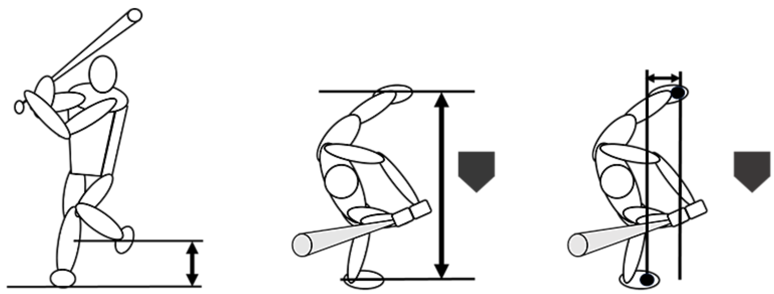

Figure 4. Definition of hitting stride motions.

Analytical parameters and calculation methods
For the swing speed, the resultant velocity for the five frames immediately prior to impact was calculated using the midpoint of the reflective markers attached to the tip of the bat, and the average value was adopted (Tsuchikane et al., 2017). The body's centre of mass (COM) was estimated for each participant using the body segment inertia parameters by Ae (1996).

Regarding the COM displacement and COM velocity, the analysis phase was defined as the period from the moment the Y-coordinate (pitcher-catcher direction) of the COM reached its minimum (i.e., became closest to the catcher) to the moment of impact (Takagi et al., 2008). The COM displacement (X, Y, Z, and resultant) was calculated as the difference between the maximum and minimum values of each component during this analysis phase. The COM velocity (X, Y, Z, and resultant) was calculated as the maximum value (peak velocity) of each component during this analysis phase.

The peak ground reaction force (GRF) values were calculated as the maximum (peak) values of each component (X, Y, and Z) and the resultant value of the GRF obtained from both the stride foot and the pivot foot during the analysis phase from the moment of stride foot contact to the moment of impact.

Statistical analysis
For each calculated parameter, the values for left-handed batters were first converted to correspond to those of right-handed batters, and then the average values for all participants were calculated. Descriptive statistics were presented as mean ± standard deviation (SD). For the statistical analysis, Pearson's product-moment correlation coefficients were calculated using the stride motion parameters—peak foot height, stride length, and stride direction—as independent variables, and swing speed, COM displacement, maximum COM velocity, and peak ground reaction force values of the stride and pivot feet as dependent variables, respectively. In this study, the statistical significance level was set at less than 5% (p < .05) for all tests, and

the statistical software IBM SPSS Statistics 26 (IBM Corporation, New York, USA) was used. Additionally, to control the influence of physique, a multiple regression analysis was performed using leg-length-normalized stride length and lean body mass as independent variables, and swing speed as the dependent variable.

RESULT

Characteristics of stride motion

Table 1. Descriptive statistics of parameters during the stepping motion.

		mean ± SD	min	max
Peak foot height / Leg length	(m/m)	0.32 ± 0.13	0.11	0.61
Stride length / Leg length	(m/m)	0.93 ± 0.07	0.77	1.15
Stride direction / Leg length	(m/m)	-0.07 ± 0.11	-0.34	0.14

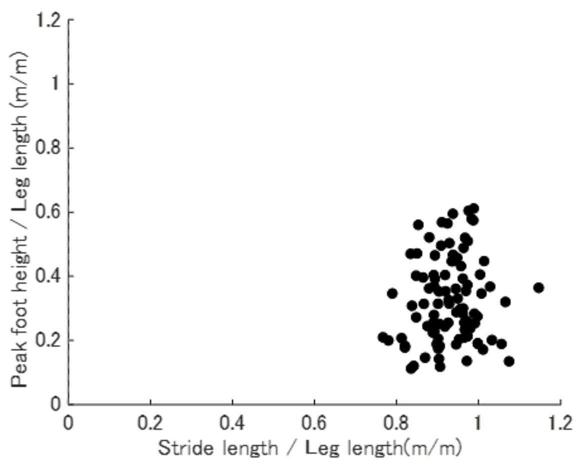

Figure 5. Relationship between leg-length-normalized stride length and foot height.

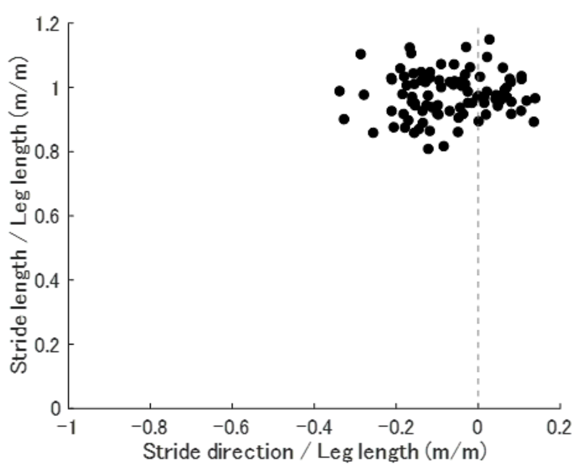

Figure 6. Relationship between leg-length-normalized stride width and stride direction.

Table 1 shows the descriptive characteristics of the stride motion. In addition, Figure 5 and Figure 6 show scatter plots of the leg-length-normalized stride length versus the leg-length-normalized peak foot height, and the leg-length-normalized stride length versus the leg-length-normalized stride direction, respectively.

As shown in Table 1, individual differences were observed in the stride motions of the 95 collegiate baseball players. The leg-length-normalized stride length averaged 0.93 ± 0.07 m/m, and the leg-length-normalized peak foot height averaged 0.32 ± 0.13 m/m, with an approximately 5.5-fold difference confirmed between the minimum value of 0.11 m/m and the maximum value of 0.61 m/m. The leg-length-normalized stride direction averaged -0.07 ± 0.10 m/m; although the mean value was close to 0, the standard deviation was 0.10, indicating that diverse stride directions were adopted, ranging from an open step (minimum value -0.34 m/m) to a closed step (maximum value 0.14 m/m). Furthermore, the relationships among the stride motion variables were examined using scatter plots (Figures 5 and 6). As shown in Figure 5, no clear correlation was observed between the leg-length-normalized stride length and the peak foot height. Similarly, in Figure 6, no significant relationship was observed between the leg-length-normalized stride length and the leg-length-normalized stride direction.

Relationship between peak foot height and batting motion characteristics

Table 2. Correlation coefficients between stride motion and batting motion characteristics.

	mean ± SD	Peak foot height (r)	Stride length (r)	Stride direction (r)
Bat speed (m/s)	130.77 ± 7.00	.04	.33**	.04
COG velocity (m/s)				
X	0.28 ± 0.07	-.05	-.06	-.22*
Y	1.01 ± 0.17	.19	.22*	.31**
Z	0.56 ± 0.12	.12	.11	-.06
Resultant	1.14 ± 0.15	.22*	.27**	.30**
COG displacement (m)				
X	0.01 ± 0.05	-.09	-.13	.05
Y	0.37 ± 0.07	.25*	.19	.31**
Z	-0.09 ± 0.04	-.64***	-.20	-.10
Resultant	0.39 ± 0.07	.31**	.21*	.34**
Stride Leg GRF Peak (N/kg)				
X	3.71 ± 1.01	.03	-.16	.45***
Y	6.40 ± 1.93	-.02	-.05	-.07
Z	17.99 ± 2.74	.11	-.16	.07
Resultant	19.19 ± 2.92	.10	-.15	.06
Pivot Leg GRF Peak (N/kg)				
X	2.50 ± 0.57	-.20	-.20	-.01
Y	2.06 ± 1.11	.02	-.08	.25*
Z	10.12 ± 1.01	.16	.00	-.08
Resultant	10.21 ± 1.03	.16	-.01	-.07

*Note. * $p < .05$, ** $p < .01$, *** $p < .001$.*

Among collegiate baseball players, no statistically significant correlation was observed between peak foot height and swing speed (r = .04, $p > .05$). However, as a kinematic feature, a strong negative correlation was found (r = -.64, $p < .001$), indicating a tendency for players who lift their foot higher to drop their COM lower than during the take-back phase. Furthermore, peak foot height showed significant positive correlations with moving the COM further forward during the subsequent translational motion (r = .25, $p < .05$), generating a larger resultant displacement (r = .31, $p < .001$), and increasing the resultant velocity of the COM (r = .22, $p < .05$), respectively. On the other hand, regarding the peak ground reaction force (GRF) values, which are kinetic features, no statistically significant correlations were observed with any components for either the stride leg or the pivot leg (n.s.).

Relationship between stride length and batting motion characteristics

Table 2 shows the results of the correlation analysis between the leg-length-normalized stride length and each batting motion characteristic variable. Stride length showed a statistically significant positive correlation with swing speed (r = .328, $p < .001$). Regarding the kinematics of the COM, significant positive correlations were shown with the antero-posterior velocity of the COM (r = .217, $p < .05$) and the resultant velocity of the COM (r = .266, $p < .01$). In addition, a significant positive correlation was observed with the resultant displacement of the COM (r = .208, $p < .05$). Although the antero-posterior displacement of the COM did not reach the level of significance, a positive correlation trend was confirmed (r = .192). On the other hand, no clear relationships were found with the velocity or displacement of the COM in the X and Z directions. Regarding kinetics, the peak ground reaction force (GRF) values showed no statistically significant correlations with any of the X, Y, and Z components, nor with the resultant value.

Relationship between stride direction and batting motion characteristics

In this study, no statistically significant correlation was observed between the leg-length-normalized stride direction (positive for in-step, negative for open-step) and swing speed (r = .04, $p > .05$). However, the stride direction showed clear relationships with the movement characteristics of the COM, as well as the peak ground reaction force values. As a kinematic feature, it was shown that players who step in the in-step direction (positive) tended to have significantly higher values for the Y-direction velocity (r = .305, $p < .01$) and Y-direction displacement (r = .310, $p < .01$) of the COM. Similarly, significant positive correlations were observed with the resultant velocity (r = .299, $p < .01$) and resultant displacement (r = .343, $p < .01$) of the COM. On the other hand, the X-direction velocity of the COM showed a negative correlation, contrary to the in-step direction (r = -.217, $p < .05$). As a kinetic feature, the strongest correlation confirmed in this analysis was with the peak value of the ground reaction force in the X-direction (medio-lateral direction) (r = .455, $p < .001$). No significant correlations were found for the other ground reaction force components.

Influence of physique and stride length on swing speed

Previous studies have shown that lean body mass is an important contributing factor to swing speed (Suzuki et al., 2024), and a similar trend was confirmed in this study as shown in Figure 7. In addition, as shown in Table 3, in the multiple regression analysis of leg-length-normalized stride length and swing speed with lean body mass added as a covariate, stride length showed a weak but significant effect. This indicates that stride length maintains a certain descriptive association with swing speed even after controlling for the influence of physique.

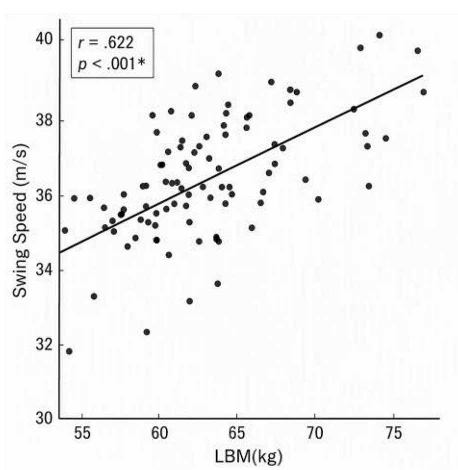

Figure 7. Relationship between swing speed and LBM,

Table 3. Multiple regression analysis with swing speed as the dependent variable and stride width and LBM as independent variables.

Dependent variable: Swing speed (Adjusted R^2 = .408)					
	Unstandardized coefficients		Standardized coefficients	*p*	VIF
	B	Std. Error	β		
Stride length / Leg length(m/m)	5.55	2.39	0.19	.023*	1.06
LBM	0.21	0.03	0.58	<.001***	1.06

*Note. * p < .05, ** p < .01, *** p < .001.*

DISCUSSION

Characteristics of stride motion

One of the purposes of this study was to quantitatively clarify the actual characteristics of the stride motion during batting in 95 collegiate baseball players. The stride motion was classified into three components—"*stride length*," "*peak foot height*," and "*stride direction*"—for analysis. As a result, variations among the players emerged, with an average stride length of 0.93 ± 0.07 m/m, an average peak foot height of 0.32 ± 0.13 m/m, and an average stride direction of -0.07 ± 0.11 m/m. Although the standard deviation of the stride length was smaller than that of the other variables, there was a range (0.38 m/m) from the minimum value (0.77 m/m) to the maximum value (1.15 m/m). When converted using the average lower limb length (0.785 m) of the participants in this study, this range corresponds to a measured value of approximately 30 cm (0.298 m). This can be said to be a large individual difference that cannot be ignored practically in the stride length, which serves as the foundation of the swing. This difference in stride length is also related to swing performance and is considered an important parameter that players intentionally select.

On the other hand, large individual differences were observed in the peak foot height and stride direction. Particularly in the peak foot height, there was a wide distribution ranging from motions close to a sliding step to motions lifting the foot high, and the stride direction was also diverse, ranging from an open step to a closed step. These results suggest that the stride motion is an element where individuality tends to appear in the batting motion. This great diversity highlights the difficulty of uniformly applying an average batting motion in coaching settings, the limitations of describing the tendency of the entire group using only average values, or potential problems in statistical interpretation.

Furthermore, from Figures 4 and 5, no correlations were found among these three variables. Rather than indicating strictly independent neurophysiological control, this lack of correlation suggests that batters exploit motor redundancy and exhibit degeneracy in their movement coordination. In addition, the results of the subjective reports revealed that 76.3% of the players subjectively and intentionally manipulate these motions. The observation that these three elements do not strongly constrain one another suggests the possibility that diverse coordination patterns are tolerated. This flexibility is a factor that allows players to intentionally combine each element as their own motor strategy, and this is considered to reflect the motor redundancy in the batting motion.

For example, this result shows that there is no strong constraint on the kinetic chain, such as the choice to widen the stride length inevitably lowering the peak foot height.

However, it should be noted that this study involved hitting a stationary ball. The use of tee batting simplifies perceptual and temporal constraints, which may significantly alter the role of stride motion compared to real batting situations. For a ball pitched by a pitcher, the stride motion plays a critical role as a timing adjustment function and in adapting to pitch characteristics, so it is highly possible that each component functionally interlocks depending on the pitch speed and pitch type. Therefore, the generalization of these findings to actual game situations is restricted. The descriptive associations and motor redundancy observed here should be carefully interpreted as a baseline specific to constrained, non-reactive conditions.

Nevertheless, this independence of each component is important in understanding the complex movement of stride motion, and it supports the validity of individually examining what kind of functional relationship each component has with swing performance (swing speed, COM displacement, and ground reaction force) in the subsequent analysis of this study.

Relationship between peak foot height and batting motion characteristics

The results of this study showed that peak foot height did not have a direct correlation with swing speed ($p > .05$). This suggests that lifting the foot high is not in itself a decisive factor in increasing swing output. On the other hand, peak foot height showed a certain relationship with the kinematics of the COM. A strong negative correlation ($r = -.64$, $p < .001$) was observed between peak foot height and the vertical displacement of the COM. In this study, the Z-direction displacement of the COM was defined as the displacement from the take-back phase to the time of impact, and the average value was -0.09 m. This indicates that many batters have a tendency to drop their COM during the process of translational motion. Based on this result, it was suggested that batters with a higher peak foot height tend to drop their COM somewhat deeper during the translational motion after the take-back.

Furthermore, peak foot height showed significant positive correlations with the Y-direction displacement, resultant displacement, and resultant velocity of the COM ($r = .25$, $r = .31$, and $r = .22$, respectively). Because batters with a high peak foot height also had a large displacement in the Y component, it is considered that they tend to perform a batting motion accompanied by translational movement. This is consistent, from the perspective of motion trends, with the report in a previous study (Takagi et al., 2008) that the magnitude of COM movement contributes to swing output. In other words, it is considered possible that batters with a high peak foot height are actively using the forward movement of the COM as a strategy aimed at improving swing speed.

Additionally, Takagi et al. (2008) reported that reducing the distance of the COM movement toward the pitcher moves the hitting point more toward the catcher and is a motion that improves batting accuracy. Considering this point, batters with a high peak foot height may be at a disadvantage from the perspective of accuracy due to their large COM movement. The increase in COM movement and the deepening of the drop shown in this study can be interpreted as mechanical factors related to a decrease in accuracy and difficulty in timing adjustment. These findings suggest that in coaching settings, peak foot height can be used as an adjustment parameter according to the player's issues. That is, while coaching to increase the foot height is effective for players who lack translational motion, coaching to suppress the foot height is considered to contribute to the improvement of accuracy for players whose drop is excessive and who lack stability in their motion.

From the above, it is highly likely that peak foot height is not a factor that determines the output itself but rather functions as a kinematic element that characterizes the movement pattern of the COM and the rhythm of the motion.

Relationship between stride length and batting motion characteristics

The results of this study showed a statistically significant positive correlation between stride length and swing speed ($r = .328$, $p < .01$). Although this correlation coefficient is small, it indicates a tendency for batters with a wider stride length to have a higher swing speed. Furthermore, stride length showed significant positive correlations with the antero-posterior velocity of the COM (Y-direction velocity: r = .217), the resultant velocity of the COM (r = .266), and the resultant displacement of the COM (r = .208), respectively. In addition, for the antero-posterior displacement (r = .192), although it did not reach the significance level, a positive correlation trend was observed. From these results, it is considered that batters with a wider stride length tend to move their COM faster and more largely forward (toward the pitcher) from the take-back to impact. Comparing this with the report in the aforementioned previous study (Takagi et al., 2008) that the magnitude of COM movement toward the pitcher contributes to swing output, it was suggested that stride length in this study cannot be concluded as a factor directly determining swing output, but is possibly one of the motion characteristics that tend to increase the antero-posterior displacement and velocity of the COM, consequently showing a descriptive association with higher swing speed.

On the other hand, the peak ground reaction force (GRF peak) did not show significant correlations with any of the components of either the stride leg or the pivot leg ($p > .05$). Therefore, it is hard to say that differences in stride length have a direct effect on the magnitude of the ground reaction force itself. Ae et al. (2019) calculated the moment around the COM generated by the ground reaction force as an evaluation index indicating the superiority or inferiority of lower limb motion and reported that the distance between the COM and the centre of pressure of the ground reaction force (Y-component) was significantly longer in the high group than in the low group. They pointed out the possibility that widening the stride length secures this distance and contributes to more efficient force exertion, and the finding in this study showing the relationship between stride length and the amount of COM movement is consistent with this insight.

As shown in the Results section (Table 3), the relationship between stride length and swing speed remained weakly significant even when controlling for lean body mass. Summarizing the above, stride length is a motion characteristic that promotes the translational movement of the COM and tends to be positively associated with swing speed as a result.

On the other hand, a previous study (Takagi et al., 2008) pointed out that excessive COM movement toward the pitcher shifts the hitting point toward the catcher, potentially reducing batting accuracy. In practical coaching knowledge as well, it is said that widening the stance decreases the probability of making perfect contact but leads to greater batted ball distance. Therefore, it is inferred that while widening the stride length contributes to improving swing output, it is an element accompanied by a trade-off with accuracy.

Although the correlation between stride length and swing speed was statistically significant, the coefficient of determination was low. This suggests that stride length is not the primary factor determining swing speed but rather functions as an adjustment factor for players to fine-tune timing and output. Therefore, coaches can suggest widening the stride length as an option when seeking distance, but it is not an essential requirement for all batters.

In the future, it is necessary to examine the mechanically and functionally optimal range by including aspects of batting accuracy, such as variations in batted ball direction and speed, in addition to kinetic indices like the moment of the ground reaction force. Furthermore, in order to determine whether the correlation shown in this study is based on a mechanical causality generated by manipulating the stride length, validation through interventional studies that intentionally manipulate the stride length will be essential in the future.

Relationship between stride direction and batting motion characteristics

Regarding the stride motion, the leg-length-normalized stride direction (positive for in-step) did not show a statistically significant correlation with swing speed (n.s.). This suggests the possibility that the medio-lateral difference in stride direction is also not a primary factor directly determining swing output. On the other hand, stride direction showed clear relationships with the movement characteristics of the COM and the peak ground reaction force values. Particularly in this analysis, the strongest positive correlation ($r = .455$, $p < .001$) was confirmed between the stride direction and the peak ground reaction force value in the X-direction (medio-lateral direction) of the stride leg. This indicates that players who step in the in-step direction (positive) exert more horizontal force with the stride leg. Ae et al. (2017) reported that the ground reaction force in this direction is important for generating the rotational moment of the body, and it was suggested that the in-step strategy observed in this study is possibly a functionally effective force exertion strategy to increase this force. Furthermore, stride direction was also related to the magnitude of translational motion; players who step in-step showed a tendency for increased Y-direction velocity ($r = .305$) and displacement ($r = .310$) of the COM, as well as increased resultant velocity and displacement. This result indicates the possibility that the in-step strategy is a motion style accompanied by larger translational motion (forward weight shift) of the COM.

Summarizing the above results, it is highly likely that stride direction is not a factor that directly increases swing speed itself, but rather a variable that characterizes the motion pattern and force exertion strategy when transitioning from translational motion to rotational motion. This interpretation is supported by practical coaching knowledge. According to an instructional book (Williams and Underwood, 1971), an open stance is effective for inside pitches or when pulling the ball, while a closed stance is effective for outside pitches or when hitting to the opposite field. In particular, it was strongly suggested that the in-step strategy is a functionally effective force exertion strategy that is consistent with the mechanical mechanism (generation of rotational moment by medial-lateral GRF) demonstrated by Ae et al. (2017). However, it should be noted that these relationships are correlational and do not determine causality. Furthermore, since the measurements in this study were conducted with the pitch location set to the centre, further verification is required in the future regarding the relationship between differences in pitch location and the choice of stride direction, as suggested by instructional books, and the causal relationship of the stride direction itself on performance.

Feedback to coaching settings and future directions

In this study, we quantitatively clarified the actual characteristics of the stride motion during batting in 95 collegiate baseball players and examined their relationship with batting motion characteristics. As a result, although statistically significant relationships were observed between the three components of stride motion and the batting motion characteristics, none of the correlation coefficients showed high values, indicating no strong tendencies. This suggests the possibility that the style of the stride motion does not uniformly determine the swing output, but rather that diverse optimizations are being performed according to the individual physical characteristics and batting strategies of the players.

Therefore, in coaching settings, rather than uniform form correction, instruction that understands the characteristics of the stride motion as the player's individuality and supports efficient force exertion and timing acquisition within that context is required. Furthermore, the findings obtained in this study are strictly correlational; in order to clarify the causal effect of stride motion on batting performance, analyses based on motion manipulation experiments and longitudinal data will be necessary in the future. Moreover, research that controls and expands upon external factors, such as competition level and pitch conditions, is also cited as a future task.

CONCLUSION

In conclusion, it was quantitatively demonstrated that an extremely large diversity exists in stride motion even among elite collegiate batters, and that a specific stride style does not guarantee swing speed. This finding provides a scientific basis suggesting that coaches should not impose a uniform ideal form on players but should rather accommodate and encourage diverse stride strategies based on individual physical characteristics and sensations.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Junya Kuwabara. Methodology: Junya Kuwabara, Kanzi Ohyama, Masafumi Fujii, Akira Maeda. Formal analysis: Junya Kuwabara, Kanzi Ohyama, Masafumi Fujii, Akira Maeda. Investigation: Junya Kuwabara. Data curation: Junya Kuwabara, Akira Maeda. Writing – original draft: Junya Kuwabara. Writing – review & editing: Kanzi Ohyama, Masafumi Fujii, Akira Maeda. Supervision: Akira Maeda.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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