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Acceptable timing error at ball-bat impact for different pitches and its implications for baseball skills

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ABSTRACT

In baseball hitting, batters need high precision timing control to hit the ball with bat's sweet spot. Knowing the acceptable range of timing error for hitting the ball in the aimed direction for various pitch types is helpful to understand whether the cause of the batter's mis-hit is a spatial or temporal error and highlight the motor skills required by the batter. The purpose of this study was to determine the acceptable timing error in different baseball pitches and the impact characteristics of mis-hits. Twenty-six high school baseball players hit a ball launched from a pitching machine with three types of pitches: fastballs, curveballs, and slowballs. We recorded the three-dimensional behavior of the ball, bat, and human body (pelvis) using an optical motion capture system. We then defined the optimal impact location based on timing accuracy, and determined the acceptable range of timing error by the interactive relationship between the horizontal orientation of the bat's long axis at the time of ball impact and the horizontal direction of the batted ball. The ± 30° width in the horizontal direction of the batted ball was set as the precondition for the tolerance of timing. The acceptable timing error was ± 7.9 ms for fastballs, ± 10.7 ms for curveballs, and ± 10.7 ms for slowballs, and the optimal timing for outside pitches was approximately 10 ms later than that for inside pitches. The timing error was also explained 38.1% by variation in the impact location along the long axis of the bat ($R^2 = 0.381$, $P < 0.001$) and was minimized at a position close to the bat's sweet spot. These results suggest that the optimal impact location and acceptable range of timing error depend on the pitching course and speed and that timing accuracy is essential to achieve the spatial accuracy required to hit the ball at the bat's sweet spot.

1. Introduction

In the baseball game, the pitcher throws a ball using various pitch types (different speed and trajectory). Pitching courses to get a batter might end up in failure as mis-hits or strikeouts. Therefore, baseball batting is regarded as one of the most difficult skills in sports (DeRenne, 2007; Fleisig & Kwon, 2011), and a batting average of 0.300 is rated as an excellent record at any category. While there are various reasons for the failure of batter (Kirkpatrick, 1963), most result from a lack of accuracy; batters cannot hit the ball with the bat's "sweet spot" that is the specific point defined as a node of vibration or center of percussion (Cross, 1998; Nathan, 2000; Van Zandt, 1992) typically located on the handle side of the bat approximately 15 cm from the barrel end (Cross & Nathan, 2009;

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Fleisig, Zheng, Stodden, & Andrews, 2002).

The coefficient of restitution between the ball and the bat decreases as the ball collides with the location on the bat's long axis away from the sweet spot, so the batted ball speed decreases with the increase of the energy lost by the bat's vibration (Nathan, 2000, 2003). In addition, a batted ball speed varies not only because of the location of its impact on the bat's long axis but also because of its location on the bat's short axis (i.e., the impact on the upper and lower parts of the ball) (Bahill & Baldwin, 2008; Sawicki, Hubbard, & Stronge, 2003; Watts & Baroni, 1989). A batted ball's speed is maximized when the launch angle is 0-10° above the horizontal plane (Nathan, 2016), which requires it to have a nearly "central impact" in terms of its mechanics. Accordingly, the spatial accuracy to hit a pitched ball with a bat's sweet spot is essential for a player to achieve a high batting average.

To accomplish spatial accuracy, a batter must perform an appropriately timed swing motion for every pitch type, considering the moment in which the pitched ball will reach the impact point and the time required for the swing itself. However, there are some limiting factors to execute an accurate swing for the oncoming ball. The visuomotor delay is of the order of 150–250 ms (Day & Lyon, 2000; Le Runigo, Benguigui, & Bardy, 2005), and the swing motion, from the beginning of the forward swing to ball-bat impact, requires 130–280 ms (Escamilla et al., 2009; Inkster, Murphy, Bower, & Watsford, 2011; Nicholls, Elliott, Miller, & Koh, 2003). Visuomotor delay is generally defined as the minimum time taken to correct an ongoing movement in response to new visual information (e.g., Day & Lyon, 2000). Furthermore, the bat's inertia is relatively large. Given that it is difficult to correct the bat trajectory once it has begun to accelerate, the timing of swing initiation is very important for the batter. On the other hand, in order to examine the hitting accuracy, it is necessary to consider the characteristics of a batter's bat swing. Since the bat rotates around its almost vertical axis during impact (Nicholls et al., 2003), the timing of the impact greatly influences whether the ball will travel toward the same or opposite fields. In addition, because the barrel end of the bat collides with the ball at a lower position than the handle end (Nicholls et al., 2003), the horizontal direction of the batted ball may also be altered by oblique impact with the bat's short axis. This suggests that even if the timing of the impact is slightly off, a batter can still hit the ball into fair territory as a ground or fly ball. Even so, to hit the oncoming ball back in a line drive, a batter must control their timing of impact within a small acceptable range, while maintaining spatial accuracy (Bootsma & Oudejans, 1993; Peper, Bootsma, Mestre, & Bakker, 1994).

Although such a successful hit requires both spatial and temporal accuracy, previous studies investigating batting accuracy have investigated these two aspects separately. For instance, Matsuo and Kasai (1994), Matsuo, Kasai, and Asami (1993), Nakamoto, Ishii, Ikudome, and Ohta (2012), and Ohta, Ishii, Ikudome, and Nakamoto (2014) performed the coincident timing task using equipment arranged in a straight line so that the ball trajectory was displayed by LED. The participants swung a bat to coincide with an approaching target (actually, a flashing light). Moreover, Gray (2002a, 2002b, 2004, 2009), Castaneda and Gray (2007), and Ranganathan and Carlton (2007) also performed batting simulations to assess the accuracy of impact. In their studies, participants swung a baseball bat in a virtual environment in which images of the ball, pitcher, and playing field were projected on a screen. These simulated studies using LED stimulus and imaging screen are effective in verifying a specific task, but have not measured the actual ball impact. The mean value of the absolute temporal errors obtained in these studies was frequently over 20 ms; for instance, when the pitched ball speed was 130 km/h, the time of ± 20 ms was equivalent to a travel distance of 1.44 m. It is unknown whether they properly evaluated the optimal impact considering the timing and location. In contrast, Higuchi et al. (2016) asked batters who were wearing visual occlusion glasses to hit an actual ball projected by a pitching machine, and then assessed the distance between the bat's sweet spot and the ball's location at ball-bat impact as spatial accuracy. However, the optimal timing was not clearly defined because the temporal accuracy was assessed by the variability between trials. Therefore, it is necessary to define the optimal timing for the ball-bat impact.

The optimal timing at ball-bat contact is not determined only by the ball speed immediately after ball-release (i.e., pitch types). The spatial location of the ball at ball-bat collision is affected by the pitching course (inside or outside) and is relatively located in the catcher's side for an outside pitch rather than an inside one (Katsumata, Himi, Ino, Ogawa, & Matsumoto, 2017). If the timing of impact can be explained by the spatial impact location into the pitcher-catcher direction, this spatial characteristic indicates that for an outside pitch, batters must slightly delay the impact timing. In that case, depending on the relationship between the spatial impact locations (especially pitcher-catcher direction) and the ball position relative to the bat at ball impact, it should be possible to reveal the interaction between spatial and temporal accuracy. It is very important in understanding the structure of the batter's timing strategy to know the variable factor of the timing of the impact.

However, it is a difficult task for the batter to aim at the gap between the fielders, and it is inadvisable to limit the flight direction of the aim as being too high. Therefore, it is considered that the batter is allowed a certain amount of timing error. Bahill and Karnavas (1993) and Watts and Bahill (2000) theoretically explained that the acceptable error when hitting a ball toward fair territory is within ± 9 ms. However, the acceptable error should be different for the pitched ball speed, there was a great difference in the measured value in previous simulated studies. The acceptable range of timing error for hitting the ball in the aimed direction and the extent to which the optimal timing of the impact is affected by the speed (or pitch types) and course of the pitched ball are currently unknown. Knowing the acceptable error for hitting the ball in the aimed direction for a specific pitch type is helpful to clarify the motor skills required to the batter and establishing whether the cause of the batter's mis-hit is a spatial or temporal error.

The purpose of this study was to determine the acceptable range of timing error for different pitch types based on the spatial impact location and investigate the relationship between the temporal/spatial accuracy and the impact characteristics of mis-hits. We hypothesized that the acceptable timing error is slightly longer than that reported in previous studies (± 9 ms) and is associated with the relative impact location of the bat.

2. Methods

2.1. Participants

Participants were 26 baseball players who belonged to the Saitama High School Baseball Federation in Japan, including 13 right-handed batters and 13 left-handed batters (age: 17 ± 1 years; height: 170.1 ± 4.9 cm; body mass: 66.8 ± 7.1 kg; baseball competition history: 9.8 ± 1.5 years). The experiment was approved in advance by the Ethical Committee of the Japan Institute of Sports Sciences. The participants and their teams were given explanations regarding the purpose of this study, the experimental procedure, and the fact that participation was voluntary. Each participant and their guardian (i.e., legal representative) signed a consent form to participate in this study that conforms to these guidelines, according to ethics committee requirements.

2.2. Experimental procedure

After warming up, each participant performed a hitting trial in the laboratory. We used an air pressure-pitching machine (TOPGUN, KYOWAGIKEN Corp., Fukuoka, Japan) to pitch the balls, which were released 17 m from home plate in one of three types of pitches: fastballs, curveballs, and slowballs. Balls had the following speeds immediately before impact and flight time from release to impact, respectively: fastball 34.3 ± 1.3 m/s (123.6 ± 4.6 km/h) and 462 ± 16 ms, curveball 25.4 ± 1.0 m/s (91.3 ± 3.5 km/h) and 618 ± 21 ms, slowball 25.5 ± 0.9 m/s (91.9 ± 3.3 km/h) and 608 ± 21 ms. Both the curveball and the slowball were slower than the fastball, but the curveball was projected with a topspin, and the slowball was projected with a backspin. The machine was set up so that right-handed batters received right-handed pitches and left-handed batters received left-handed pitches.

We asked participants to make 22 swings at each type of pitch and aim at hitting the ball toward the center of the field, as in an actual baseball game. In twelve trials, the participants were informed about the next pitch type ahead of time, whereas in ten trials, they were not. However, we did not analyze the two conditions separately. All participants used an aluminum bat (DeMARINI WTDX_JHPVE, Wilson Sporting Goods Company, Chicago, USA; length = 83.5 cm, mass = 900 g, center of gravity = 54.2 cm from knob end). We selected a bat with average inertial property such as length, mass, and shape so that it could swing naturally. After the trial, we asked the participants to perform a self-evaluation on whether their timing in regard to the ball's impact was 1) early, 2) well-timed, or 3) late.

2.3. Data collection

During the trials, we recorded the behavior of the ball, bat, and human body using a 20-camera optical motion capture system (VICON-MX, Vicon Motion Systems Ltd, UK) operating at 500 Hz. A phototube sensor (E3Z-T61A, OMRON Corp., Kyoto, Japan) was placed on the pitching machine's release point, and the system recorded a signal as soon as the ball was launched. The analog signals received from the phototube sensor were then inputted into NEXUS software, used with the VICON system.

The data obtained by a motion capture system were regarding a ball, bat, and pelvis. We placed seven circular reflective stickers on a ball with as much distance between each sticker as possible and attached hemispherical reflective markers to the barrel and knob end of the bat. We also attached four spherical reflective markers to each player's pelvis landmark at the left and right anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS).

2.4. Data analysis

We defined the back edge of home plate as the origin, and the orthogonal coordinate system follows: the direction from the right-handed batter's box to the left-handed batter's box was the x-axis, from home plate to the center of the pitching plate was the y-axis, and the upward vertical direction was the z-axis. We reversed the positive and negative values of the x-coordinate for left-handed batters in order to treat their data as identical to those of right-handed batters.

The raw xyz coordinates of each marker, excluding the ball, were smoothed with a fourth-order Butterworth low-pass filter. Because the bat rapidly decelerates immediately after impact, the inclusion of after-impact in the smoothing distorts the coordinates before-impact. Using Giakas, Baltzopoulos, and Bartlett (1997) as a reference, we used a third-order approximate polynomial based on the data of the 20 frames before impact to extrapolate data on the 20 frames following impact and smoothed them together with the raw data before impact. In order to preserve the characteristics of the raw data, the cutoff frequency was set at 35 Hz.

To calculate the velocity of the pitched and batted ball (speed and direction), we estimated three-dimensional coordinates for the center of the ball based on the position coordinates of the reflective stickers affixed to its surface and estimated the center of the ball using the least-squares methods. We then used principal components analysis to fit a linear regression to the position coordinates of the ball for five frames before and after impact. We calculated the pitched and batted ball speeds ($V_{pitched}$, V_{batted}) as the average speed during five frames. The horizontal launch angle ($\theta_{batted/H}$) and vertical launch angle ($\theta_{batted/V}$) were calculated using the trajectory of the ball immediately after impact. For the horizontal angle, the centerline was set at 0° with an opposite-field considered positive and same-field considered negative. For the vertical angle, the horizontal plane was set at 0° with the upward direction considered positive and the downward direction considered negative.

To calculate the impact location relative to the body, we considered the midpoint of the four anatomical landmarks on the pelvis to be the central point of the body. The position coordinates of the ball relative to the pelvis center were calculated as the impact location relative to the body. The impact location of "swing and a miss" was defined as the position at the time the ball passed

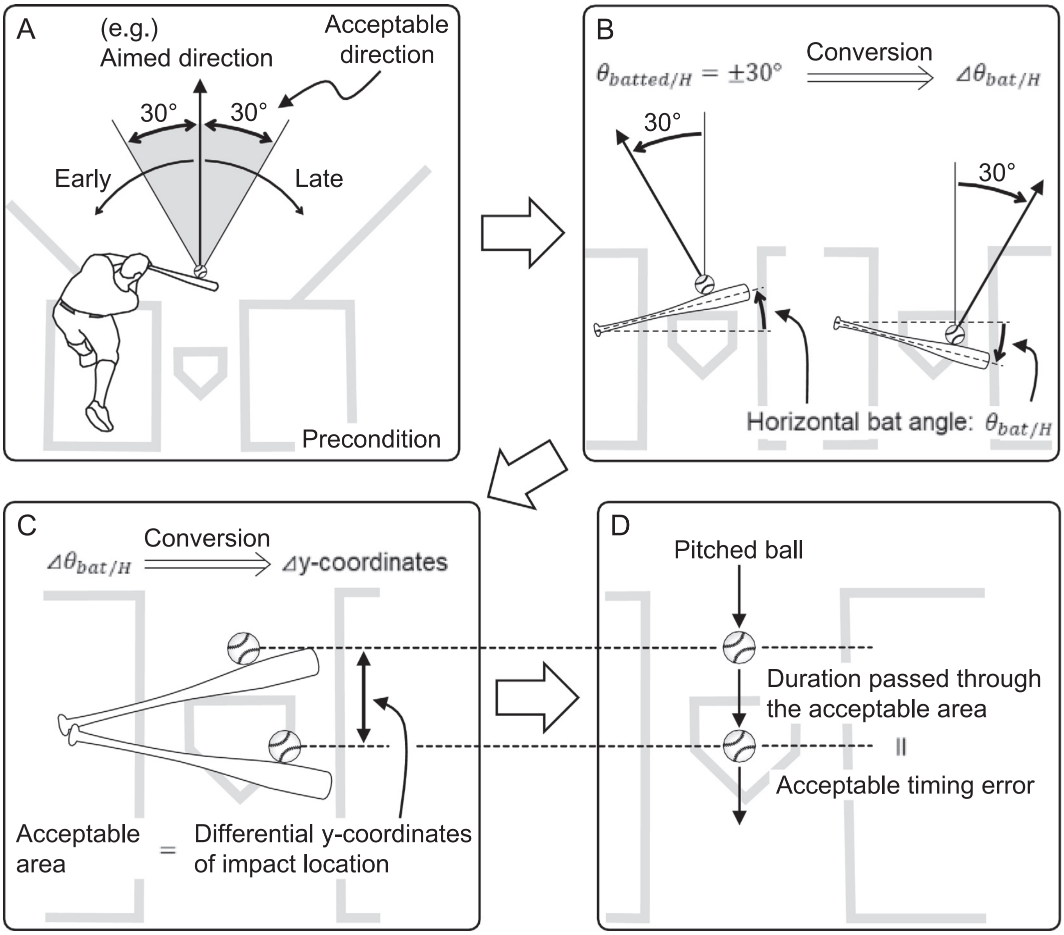

Fig. 1. The procedure for calculating the acceptable timing error.

through the bat's long axis. The projection angles of the bat on the horizontal plane (horizontal bat angle: $\theta_{bat/H}$) were determined at the instant of ball impact: 0° indicates the bat is parallel to the x-axis. The projection angles of the bat on the vertical plane (vertical bat angle: $\theta_{bat/V}$) were determined at the instant of ball impact: 0° indicates the bat is parallel to the horizontal plane. In addition, the ball's impact location along the bat's long axis was defined as the long-axis impact location (r_{imp}).

To evaluate the timing of impact for each swing, we defined the optimal impact location. Using Katsumata et al. (2017) as a reference, we hypothesize that the spatial ball location at ball-bat collision is relatively located more frequently on the catcher's side for an outside pitch than an inside pitch. We extracted the horizontal impact location (x-y coordinates) relative to the body in trials batters self-evaluated as "well-timed" and then used the x-coordinates (inside-outside pitch direction) of the impact location to calculate a linear regression formula for estimating the y-coordinates (pitcher-catcher direction). Data on the regression line were considered to represent the optimal impact location. To calculate the timing error for each trial, we used the regression equation to estimate the optimal impact location (y-coordinates) for each trial based on the x-coordinates.

We calculated the timing error as the difference between the measured and estimated y-coordinates of the impact location divided by the pitching speed for each trial. A positive error indicates that the impact timing was earlier than the optimal value, while a negative error indicates that the impact timing was later than the optimal value. The acceptable range of timing error was decided by the following assumptions based on the findings of McIntyre and Pfautsch (1982), which compare same-field and opposite-field hitting: 1) the timing error appears in the horizontal launch angle of the batted ball and the horizontal launch angle is greatly affected by the horizontal bat angle at ball-impact and 2) the impact location's y-coordinates are strongly related to the horizontal bat angle.

We determined that it was acceptable for the batted ball to be within ± 30° of the aimed horizontal direction (Fig. 1A). We then converted the ± 30° width in the horizontal direction of the batted ball into the horizontal bat angles (Fig. 1B). Furthermore, we converted the width of the horizontal bat angle into the y-coordinates of impact location and calculated their length (Fig. 1C). We then divided the lengths of these y-coordinates by the pitched ball speed to calculate the duration during which the pitched ball passed through the acceptable area (i.e., the acceptable timing error [Acceptable]; Fig. 1D). We divided the other trials that did not have acceptable timing error into two groups: 1) "Early," or those where the ball-impact was timed too early with the impact location positioned further on the pitcher's side than the acceptable range and 2) "Late," or those where the ball-impact was timed too late with the impact location positioned further on the catcher's side than the acceptable range.

2.5. Statistical analysis

For the statistical analysis, we considered all trials to be independent and assigned the value to the regression analyses. For analysis of variance, we used the mean values for each participant as representative values. In all statistical analyses, significance was set at 5%, and testing was performed using statistical analysis software (SPSS for Windows, version 24, IBM Corp., New York, USA). Descriptive data were expressed as mean ± SD.

We determined differences in mean values of timing error among the three types of pitches using a one-way repeated-measures analysis of variance (ANOVA). Bonferroni's post-hoc test was used for comparisons between the three types of pitches.

To calculate the acceptable range for timing, we used a linear regression analysis to predict the horizontal angle of the batted ball from the horizontal bat angle at ball-impact. Here, to eliminate the influence of factors other than the horizontal bat angle on the horizontal angle of the batted ball, we limited the vertical launch angle of the batted ball from −10° to 20° and the batted ball speed to 120 km/h or higher. Similarly, we conducted a regression analysis to predict the y-coordinates of impact location from the horizontal bat angle. This analysis excluded any trials involving a swing and a miss.

Finally, to verify the relationship between the timing of impact and the ball position relative to the bat at ball-impact, we performed a linear regression analysis to predict the timing error from the long-axis impact location and curvilinear regression analysis to predict the batted ball speed from the long-axis impact location.

3. Results

Of the total 1573 trials analyzed, participants self-evaluated 441 as being well-timed. The regression equation for estimating the y-coordinates from x-coordinates for the impact location relative to the hitter's body for these 441 trials was $y = -0.735 \times +1.065$ ($r = -0.443$, $P < 0.001$, Fig. 2). Comparing timing errors for the three types of pitches revealed a significant main effect ($F[2,50] = 5.532$, $P = 0.007$, $\eta_p^2 = 0.181$). Multiple comparison indicated that the absolute value of the timing error (11.5 ± 0.8 ms) for slowballs was significantly larger than that for curveballs (8.9 ± 0.5 ms) ($P = 0.003$). There was no significant difference

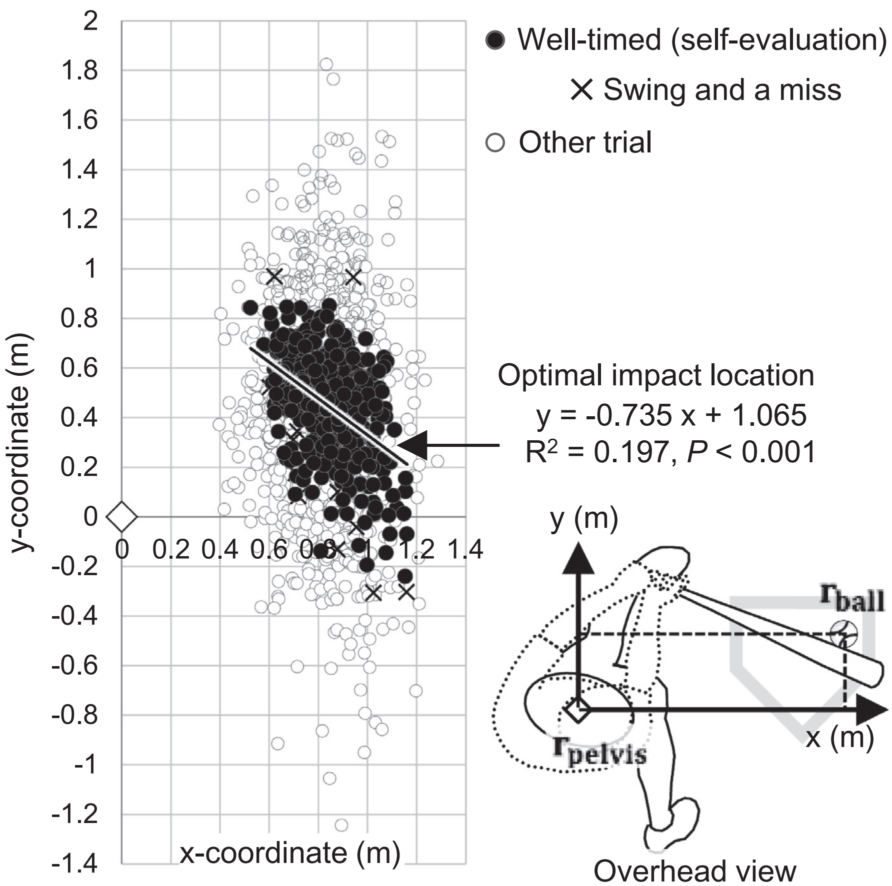

Fig. 2. Optimal horizontal-plane impact locations relative to the batter's body depending on the pitching course.

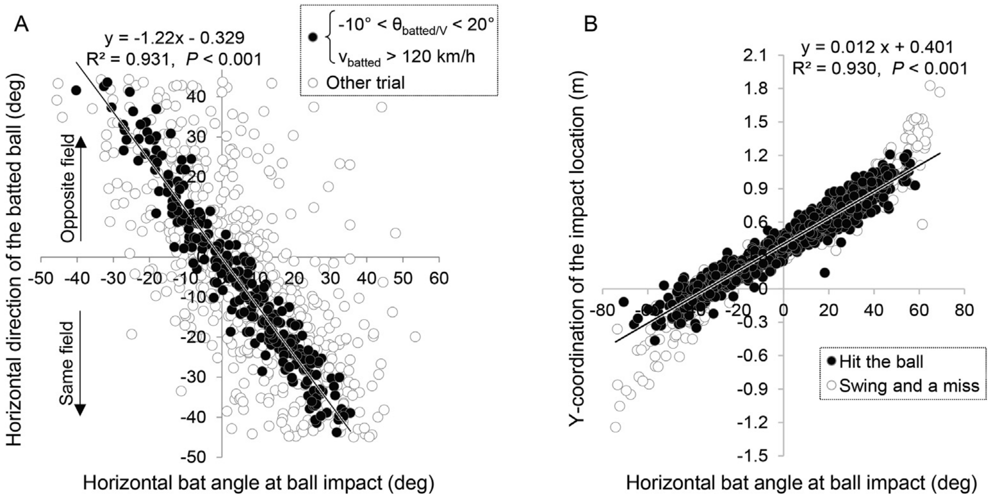

Fig. 3. (A) The relationship between the horizontal bat angle at ball impact and the horizontal angles of the batted ball, and (B) the relationship between the horizontal bat angle at ball impact and y-coordinates of impact location. The plot of the left figure (A) does not include any foul balls.

between errors for fastballs (9.4 ± 0.4 ms) and those for other conditions (vs. curveball: $P = 1.000$, vs. slowball: $P = 0.135$).

Ninety-three percent of the horizontal angles of the batted ball (x) were explained by the horizontal bat angle (y) ($R^2 = 0.931$, $P < 0.001$, $y = -1.216 \times -0.329$, Fig. 3A). The ± 30° width of the ball's horizontal angle was equivalent to the horizontal bat angle ± 23.0°. Moreover, 93% ($R^2 = 0.930$, $P < 0.001$, $y = 0.012 \times +0.401$, Fig. 3B) of the impact locations' y-coordinates (pitcher-catcher direction) were explained by the horizontal bat angle, and the width of the horizontal bat angle ± 23.0° was equivalent to ± 0.271 m of the impact location's y-coordinates. Accordingly, the acceptable range of timing error was ± 7.9 ms for fastballs, ± 10.7 ms for curveballs, and ± 10.7 ms for slowballs. The vertical bat angle at ball-impact was 23.4 ± 7.7° (−3.7–51.1°).

Based on these results, we divide the 1,573 trials into "Early" (n = 312), "Acceptable" (n = 896), and "Late" (n = 365) groups. For fastballs, the proportion of hits in each group were: Early = 4.8%, Acceptable = 48.9%, and Late = 46.3%. Fore curveballs: Early = 18.1%, Acceptable = 67.7%, and Late = 14.3%. Moreover, for slowballs: and Early = 37.1%, Acceptable = 55.0%, and

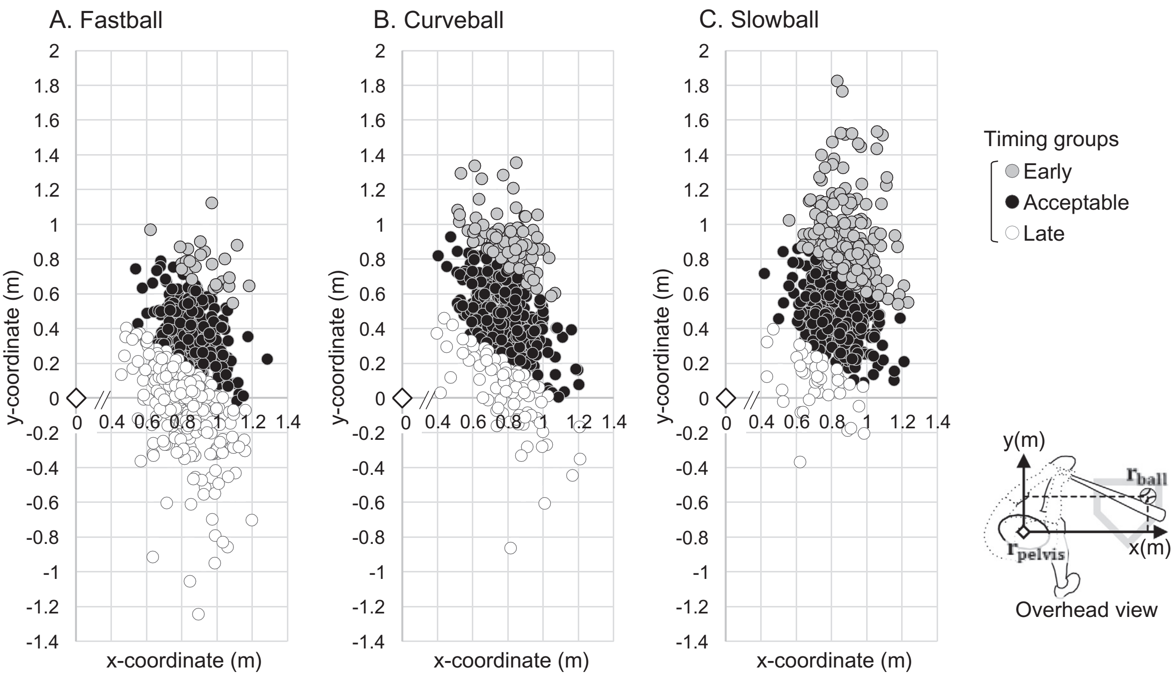

Fig. 4. Scatter plot of the impact locations relative to the batter's body for each type of pitch. The color of the circle refers to the timing of the pitch based on the acceptable range of ball-impact.

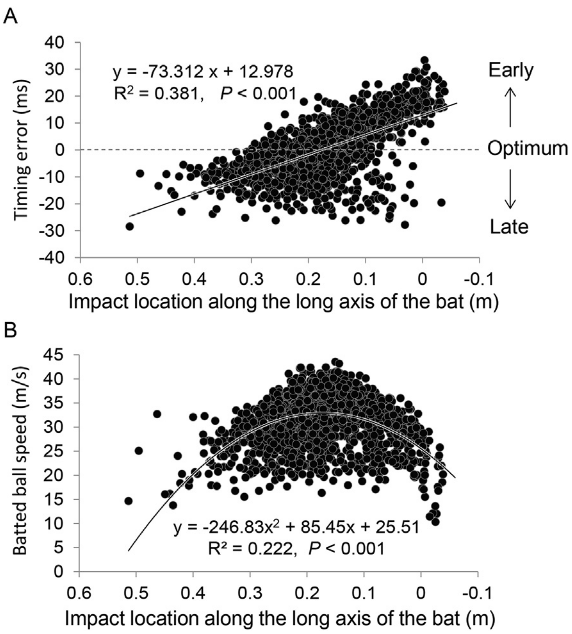

Fig. 5. The relationship between the bat's long-axis impact location and (A) the timing error and (B) the batted ball speed.

Late = 7.8%. Fig. 4 shows these impact locations relative to hitters' bodies.

We found impact location along the bat's long axis to be significantly related to timing error ($R^2 = 0.381$, $P < 0.001$, Fig. 5A) and batted ball speed ($R^2 = 0.381$, $P < 0.222$, Fig. 5B). The regression equation in Fig. 5A, B indicates that the impact location along the bat's long axis in the optimally timed trials was almost equal to that of the trials where the ball reached the maximum batted speed.

Fig. 6 shows the distribution chart of the batted balls' launch angles for each type of pitch and timing group. For all types of pitches, batted balls shifted toward right field (opposite field) as timing changed from early to late. Pitches in the Acceptable group went not only to center field but also ground balls to the same-field and fly balls to the opposite-field. Regardless of timing, curveballs resulted in more ground balls than other types of pitches.

4. Discussion

The purpose of this study was to determine the acceptable timing error range of a batter based on the ball's spatial impact location and to describe the impact characteristics of mis-hits in different types of pitch. The main findings of this study are as follows: 1) The acceptable timing error for batters to hit a ball at a reasonable impact location is ± 7.9 ms for fastballs, ± 10.7 ms for curveballs, and ± 10.7 ms for slowballs, and the more outside a pitch the further back on the bat the optimal impact location; 2) participants had a tendency to hit the ball close to the barrel end of the bat in the Early group and close to the grip of the bat in the Late group; 3) slowballs were more likely to be early than curveballs, even among balls pitched at the same speed; and 4) for all types of pitches, there were some acceptable fly balls went in the opposite-field direction and some acceptable ground balls in the same-field direction.

The novelty of the study consists in quantifying the acceptable timing error based on the participants' self-evaluation about timing and interactions between ball-bat impact. While the acceptable timing error in this study varied depending on ball speed, our findings were similar to the ± 9 ms of acceptable error reported by Bahill and Karnavas (1993) and Watts and Bahill (2000). Meanwhile, it has been reported that, in cricket, hitting balls with similar speed characteristics requires an accuracy of ± 2 ms (Regan, 1992). These differences are due to the criteria for error tolerance. According to Regan (1992), cricket batsmen must estimate with an accuracy of 15 cm cube to hit the ball with a bat's center of percussion, and the time for a 40 m/s pitched ball to pass through that space is ± 2 ms. On the other hand, Bahill and Karnavas (1993) and Watts and Bahill (2000) stated that the batter must estimate within ± 9 ms to hit a line drive in fair territory. The range of ± 9 ms is the time for the pitched ball crosses the home plate. In contrast, we present the acceptable horizontal range of the batted ball (± 30°) and converted to temporal accuracy sequentially (Fig. 1). If this were limited to ± 10°, the acceptable error for fastballs would be ± 2.6 ms and would be even smaller if the ball speed increased. The current study made sense for a functional analysis considering the batter's swing characteristics and will be helpful for future research.

Although the acceptable error is not uniquely determined, it is clear that skilled batters execute extremely accurate motor control. Most batters do not track the moving ball until the impact phase because they cannot keep coupling the moving ball and center of the eyes unless they change the head and eye angles faster as the ball approaches them (Bahill & LaRitz, 1984; Higuchi, Nagami, Nakata, & Kanosue, 2018). Instead, the accumulation of experience allows the batter to estimate accurately when and where the pitched ball will reach the bat before starting the bat swing based on the oncoming ball trajectory (Higuchi et al., 2016; Ranganathan & Carlton,

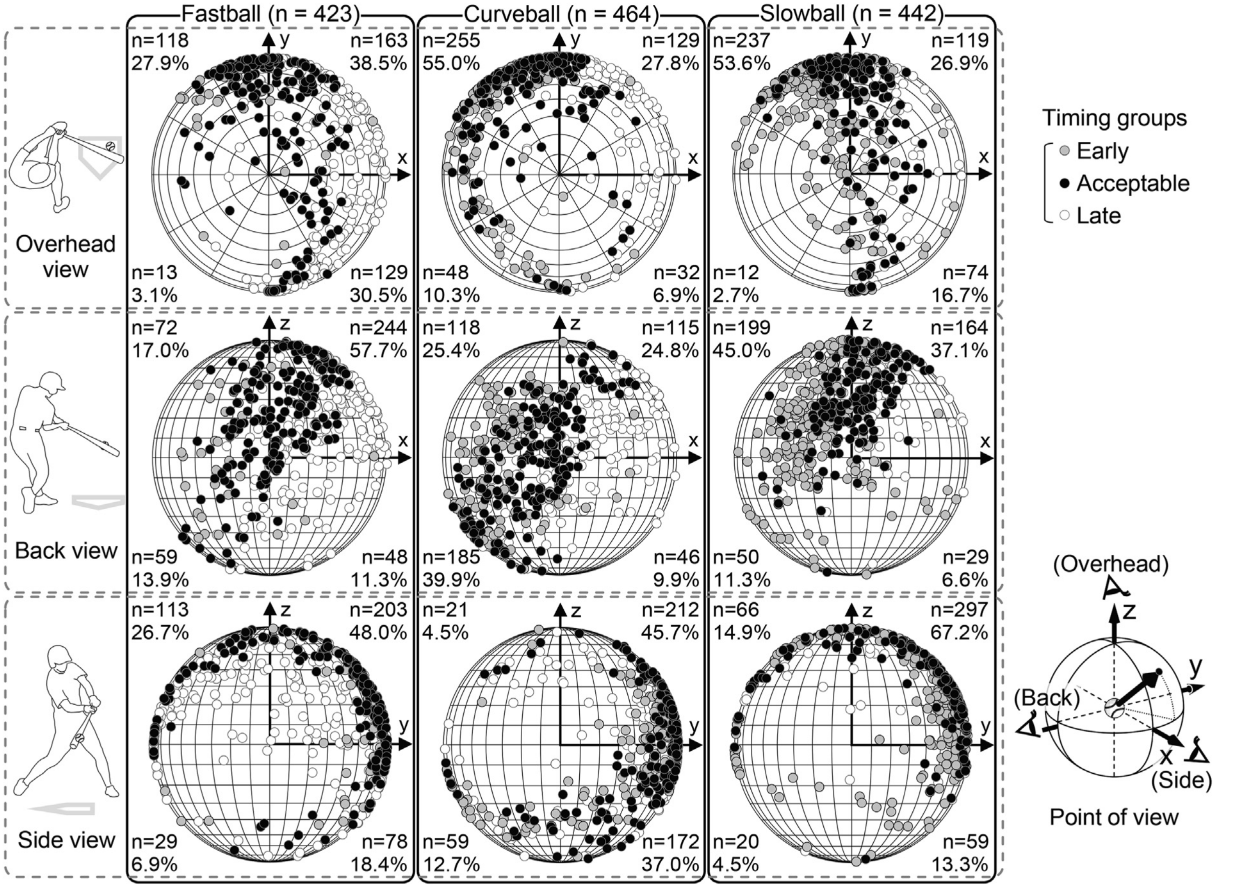

Fig. 6. Distribution chart of the launch angle (latitude and longitude) of the batted ball as seen from three different viewpoints for each type of pitch. All plots are on a spherical surface, and the frontal and back surface of the sphere are not separated. Three colors for the circles indicate the differences in timing groups. The "n" indicates the number of trials in one of four-quadrant and the percentages listed below are in the proportion of each quadrant to all trials.

2007). Therefore, the reasons why the mean absolute temporal error in previous simulation studies (e.g., Gray, 2002a; Matsuo et al., 1993; Nakamoto et al., 2012) was frequently over ± 20 ms might be that 1) the batter could not react adequately because the visibility of the incoming ball or stimulus was different from the actual ball and 2) the (optimal) impact point itself was different from the practical data. Still, it does not alter the specific findings of previous simulated studies because there was no random variation between trials in the type of pitched ball within the same condition.

The anteroposterior components (y-coordinates) of the optimal impact location differed 0.37 m between the inner edge and the outer edge in the strike zone. If, hypothetically, the pitched ball speed at ball impact was 130 km/h, this distance would be converted into 10 ms. Accordingly, when the batter swings at an outside pitch, the impact timing must be approximately 10 ms later than when swinging at an inside pitch. On the basis of the fact that the acceptable timing error was found to be ± 7.9 ms (fastballs), this difference in the time of arrival at impact location cannot be ignored. There would be a significant difference in the arrival time if the pitched ball was slower. In slower pitches, the difference in the time of arrival between pitch courses would be higher. The visuomotor delay on interceptive action is at least about 100 ms (Bootsma & van Wieringen, 1990; Brenner & Smeets, 1997; Smeets, Wijdenes, & Brenner, 2016) and the bat's moment of inertia is relatively large; thus, the batter cannot immediately correct the trajectory of the bat that has begun to accelerate. The duration of the bat movement (swing time) also depends on the impact location and hitting the inside course take longer than the outside course (Katsumata et al., 2017). Thus, the batter must control the timing of their swing start to a very high extent, depending on pitch course as well as ball speed. This is also considered to be the reason baseball hitting is regarded as one of the most sophisticated skills in sports.

The orientation of the bat's impact surface naturally shifted toward the same field for an inside pitch and toward the opposite field for an outside pitch because the y-coordinates of impact location were also strongly related to the horizontal bat angle (Fig. 3B). Thus, inside pitches were likely to result in same-field hitting and outside pitches were likely to result in opposite-field hitting. Moreover, because timing errors are also related to the impact location along the bat's long axis (Fig. 5A), if the batter tries to hit the ball in a specific direction regardless of pitching course, the batter increases the risk of missing the bat's sweet spot. For example, attempting to hit a ball toward the same field for an outside pitch will result in hitting the ball further to the pitcher's side than the optimal impact location, making the ball more likely to impact the bat near the barrel end. This appears to be the reason earlier timed hits were more likely to hit the bat's tip side (Fig. 5B). The same reasoning is valid for inside pitches. Therefore, temporal accuracy is essential to achieve the spatial accuracy required to hit the ball in the bat's sweet spot. These results supported our hypothesis that the timing error is associated with the relative impact location on the bat.

In our study, many fly balls scattered towards the opposite field and ground-balls towards the same field, even in the acceptable group (Fig. 6). The bat's long-axis was facing downward at 23.4° (vertical bat angle at ball-impact: $\theta_{bat/V}$), and the ball in the oblique impact along the bat's short-axis were scattered not only in vertical directions (i.e., ground balls or fly balls) but also in horizontal directions by the inclination of the collisional surface itself. Previous studies found that faster pitched balls (Gray, 2002a) and pitched balls with greater backspin (Higuchi, Morohoshi, Nagami, Nakata, & Kanosue, 2013) have a higher probability of being hit by the bat's higher part. Thus, fastballs were more likely to be launched as fly balls toward the opposite field two reasons that insufficient rotation of the bat at ball-bat impact and hitting the lower part of a ball (Fig. 6). For the same reason as for the fastballs, the batted balls in curveballs were likely to be scattered toward the same field with ground balls. Although the oblique impact along the bat's short axis had been analyzed in two dimensions (Bahill & Baldwin, 2008; Sawicki et al., 2003; Watts & Baroni, 1989), the data in our study indicated that the mechanical interaction between the ball-bat collisions needed to be verified along three dimensions. This is also supported by a previous study (Nakashima, Horiuchi, & Sakurai, 2018) in which the sidespin of the batted ball was larger in opposite-field hitting than in same-field hitting. Accordingly, it is necessary for the batter to judge the timing based not only on the horizontal launch angle but also the impact location, batted ball speed, the orientation of the bat, and the vertical launch angle.

Although this study did not measure the launch angle of the pitched ball from the pitching machine, curveballs pitched with topspin rotation were thrown in a more upward direction than other types of pitches in order to pass through the strike zone. This difference in projected direction may have resulted in an adjustment of swing timing and early prediction of ball trajectory. However, unlike dropped balls such as change-ups and forkballs, slowballs are less likely to be thrown in an actual game. Under severe time constraints, like in the case of baseball hitting, skilled players gain visual information not only from the ball trajectory but also from the pitching form before ball release (Müller, Abernethy, & Farrow, 2006; Moore & Müller, 2014; Takeuchi & Inomata, 2009). Therefore, the slowball is effective for the pitcher to mislead the batter about the pitch type if the pitcher can throw a ball of various pitch types in similar pitching form that the batter cannot discern. Although the use of a pitching machine is a potential weakness of our study (Pinder, Renshaw, & Davids, 2009), it is nevertheless helpful to know the rough trends of batted ball direction on each pitch type to make a strategy for defensive players. In addition, since the mean values of the absolute timing error (fastball: 9.4 ms, curveball: 8.9 ms, slowball: 11.5 ms) were smaller than the standard deviation of the flight time (fastball: 16 ms, curveball: 21 ms, slowball: 21 ms), it is considered that the skilled batters had fully utilized the visual information of the projected ball to control the timing on each trial.

Future research may investigate whether there is a relation between the combination of pitch types and timing error and what parts of the batter's body enhance timing control for different pitch types. For example, the timing of the batter might be delayed if the pitcher threw a fastball after a curveball or slowball. Future studies should provide more knowledge on this topic.

5. Study strengths and limitations

This study had some limitations. First, the batter used only the visual information of the projected ball and the rolling ball toward the release point as the timing strategy because the ball was thrown by a pitching machine. Second, since the participants were high-school players, it is unclear whether the obtained findings can be generalized to all skilled players, such as university students and baseball players. Third, two conditions are included in this experiment: the presence or lack of preliminary information about next upcoming pitch type. Therefore, the distribution of the batted ball direction may have been biased when compared to an actual game situation. Nevertheless, the strength of this study was to show the acceptable timing error according to the pitched ball speed and aimed range for the horizontal angle of the batted ball mechanically and practically.

6. Conclusions

This study examines the acceptable timing error in different types of baseball pitches, which we found to be ± 7.9 ms for fastballs (123.6 ± 4.6 km/h), ± 10.7 ms for curveballs (91.3 ± 3.5 km/h), and ± 10.7 ms for slowballs (91.9 ± 3.3 km/h). The optimal timing for outside pitches was approximately 10 ms later than for inside pitches. The timing error at the ball-impact related to the ball's impact location along the bat's long axis, timing accuracy is essential in achieving the spatial accuracy required to hit the ball with the bat's sweet spot.

Disclosures

No financial support was received for the current study, and the authors declare no conflict of interest.

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