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Temporal Coordination Strategies in Baseball Hitting: Insights from Stationary vs. Oncoming Ball Analysis

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ABSTRACT

Background: A baseball hit involves complex whole-body movements and coordination. Research has focused on batting against stationary balls, and insights have been gained into hitters' intended strategies. However, synchronizing the bat swing with the flying ball is crucial for an effective hit in game scenarios. **Objective:** Movement patterns in baseball hitting were analyzed by comparing two batting tasks: hitting a stationary ball on a tee stand (stationary ball hit) and hitting a ball projected by a pitching machine (oncoming ball hit). The study examined whether motor representations elicited in the stationary ball hit were applicable to the oncoming ball hit, and to identify differences in the movement patterns between the two tasks. **Methodology:** Ten male college baseball players participated in stationary and oncoming ball-hitting tasks. A three-dimensional motion analysis of ball-bat contact locations and hitting movements was conducted. **Results:** For the stationary ball hit, a high correlation was observed between the depth and course ($r_{rm}(79) = .968$) or height positions ($r_{rm}(79)=.875$) of the ball. However, for an oncoming ball hit, the impact depth did not systematically vary with course ($r_{rm}(189)=.333$) and heights ($r_{rm}(189)=.213$). Correlation analysis of the duration and timing between the stepping movement and bat swing revealed compensatory timing for starting the bat swing in response to pitch release ($r_{rm}(189) = 0.79$). **Conclusion:** The results revealed the temporal coordination of movement for initiating a bat swing at a relatively consistent timing with respect to the flight of pitches. Therefore, the ball was intercepted at a relatively consistent depth location.

Key words: Kinesiology, Task Performance and Analysis, Kinematics, Motor skill, Perceptual Motor Performance, Baseball

INTRODUCTION

In baseball hitting, the bat swing movement is produced by whole-body motion. As shown in Figure 1, a baseball hitting movement comprises multiple movement elements: (1) start of the stepping movement, (2) touchdown of the stepped foot, (3) start of the hip and upper trunk rotation, (4) start of the bat swing, and (5) the ball–bat impact (Stewart et al., 2020; Welch, Banks, Cook, & Draovitch, 1995).

To learn and improve the mechanism of bat and body movements to strike the ball harder, baseball batters practice by hitting a stationary ball on a tee stand. In this practice, for any given height and course of the ball, batters can place the tee stand forward or backward with respect to the address position. A previous study by Katsumata, Himi, Ino, Ogawa, and Matsumoto (2017) investigated how batters choose the depth locations of the ball in tee batting practice based on the following assumptions. Because the batting movement is organized with respect to the ball location, batters' location preferences reflect how they intend to swing a bat toward the ball. The batter's intention is produced by accessing the motor representation of a hitting movement that has been built and refined through practice and games. Based on this assumption, hitting the tee-ball elicits the batter's intended or planned movements with respect to the height and course of the imagined pitch. If motor representation can be elicited in tee-batting, coaches can evaluate players' intended movements, and players can notice the gap between intended and actual movements by checking those movements.

The authors of the above study analyzed the tee-batting movement by focusing the batters' preferred ball location to gain insight into the batters' motor representation. In the result, the participants chose their own preferred depth locations with respect to their address positions to hit a ball set in different courses and heights. These ball locations were distributed systematically; the depth of the ball location in the inside course shifted more forward in the direction of the pitcher, whereas the depth location of the outside ball shifted more backward in the opposite direction. The results

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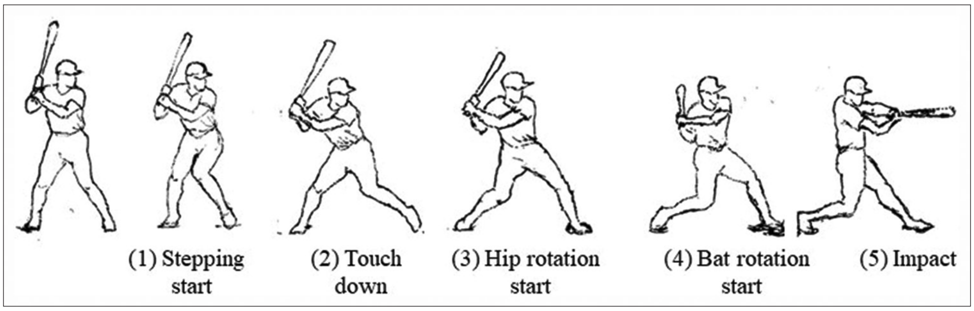

Figure 1. Hitting motion phases
The batting movement comprises a stepping motion and rotations of the hip and upper trunk. These movement components produce the rotation of the bat. The start of the bat swing for the analysis in this study refers to the bat movement initiated by the aforementioned movement components.

seemed to elucidate the motor representation of how batters intend to hit balls of different courses. An optimal depth location can be accessed based on the motor representation of the dynamics of the ball and bat movements formed during practice. This interesting and novel approach focuses on the motor representation of sports performances. However, one of the critical essences for successfully striking a ball is synchronizing the bat swing with the pitch. Therefore, the above study should be further extended to an analysis of hitting against pitching.

This study addresses the above issue by comparing the impact locations of two batting tasks: hitting a ball placed on the tee stand (the stationary ball hit) and hitting a ball projected by a pitching machine (the oncoming ball hit). In a stationary ball hit, batters choose the depth location of the impact by assuming that the pitches pass through different courses and heights in the strike zone. According to the computational theory of movement control (Wolpert & Flanagan, 2010; Zago, McIntyre, Senot, & Lacquaniti, 2009; Shadmehr, 2009), movement for achieving a given goal is produced by information processing, which is comprised of three stages (Czyż, 2021; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018): stimulus identification, response selection, and response programming. The following information processing can be assumed by applying this theory to an oncoming ball hit. In the stimulus identification stage, batters recognize the kinematic features of pitch (e.g., speed, projection angle, and type of pitch) and thereby predict when and where the ball will arrive (Wolpert & Flanagan, 2001). Based on this visual processing, batters decide whether to swing (i.e., response selection). Response selection involves determining how and when a swing should be produced for the perceived motion of the ball. Prior to swinging a bat, a batting movement is preplanned for the multiple movement elements to be controlled to strike the pitch with the sweet spot of the bat at the right time and place (i.e., response programming).

While the bat swing against the oncoming ball needs to be organized toward the upcoming ball-bat contact, the bat swing in the stationary ball task was prepared with respect to the ball location predetermined by the motor representation. Because the movement is organized to produce an impact, the location of the impact is an interesting key parameter for investigating how batters organize their movements. Therefore, by focusing on impact locations, this study examined whether an oncoming ball hit is executed in accordance with the choice of impact locations in a stationary ball hit. In terms of the above theory of movement control (Czyż, 2021; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018), the difference between the stational and oncoming ball hits is how the movement is controlled for the ball-bat contact. The bat swing for the oncoming ball must be produced by predicting when and where the ball will arrive (Wolpert & Flanagan, 2001). In contrast, a stationary ball hit does not require such a visuo-motor process because the movement is prepared for a predetermined impact location. Therefore, differences in the comparative analysis of the hitting movements between the stationary ball hit and the oncoming ball hit can reveal the features for organizing the hitting movement in response to the oncoming ball. Through these examinations, we attempted to gain insights into the movement strategy for hitting an oncoming ball.

As the first hypothesis, if a motor representation works similarly for hitting stationary and pitched balls, the pattern of depth locations across different courses and heights will be the same for both tasks. If these patterns differ between the tasks, this implies that the batters did not execute the oncoming ball hit similarly to the stationary ball hit. In addition, two complementary hypotheses are postulated. The first complementary hypothesis is that, even if the batters attempted to strike the oncoming ball as they did to hit the stationary ball, they could not swing a bat to strike it as they intended. If this is the case, the distribution of the ball–bat collision locations is expected to be similar to that of the stationary ball hit, but with a larger variability in the collision locations. The second complementary hypothesis postulates that hitting an oncoming ball is achieved by modulating the bat swing movement; thus, the collision locations differ from those of a stationary ball hit.

We tested these hypotheses by examining the distribution of collision locations using the novel approach described below. We conducted a correlation analysis with the course and height of the collision location as independent variables and the depth location as a dependent variable. When the depth locations were dependent on the course and height of the ball, a high correlation coefficient was obtained. This result supports the first hypothesis. This has been previously demonstrated for stationary ball hitting (Katsumata et al., 2017). If a low correlation is observed for an oncoming ball hit, then the first hypothesis must be rejected.

The above correlation analysis can be used to examine the distribution patterns of impact locations for various courses and heights. However, a low correlation can also be obtained, owing to the large variability in movement. Therefore, in addition to correlation analysis, a comparison of the impact locations between stationary and oncoming ball hits should be conducted. In a stationary ball hit, batters choose the depth of impact based on the course and height of the ball. For an oncoming ball hit, they intercepted the ball at a particular depth for the ball approaching in the given course and height. Therefore, the depth and location of the impact are key parameters for investigating how bat swings are prepared for various courses and heights. To this end, differences in depth locations between the two hitting tasks were examined using the analysis used for stationary ball hits in a previous study (Katsumata et al., 2017). This analysis estimates the depth location for various courses and heights of the oncoming balls based on the impact locations of stationary balls. If this estimated depth location coincides with the actual collision location in the stationary ball hit, this indicates that the batters hit the pitch in a given course and height at the same depth as they did for the same course and height in the stationary ball hit. This implies that the batters prepared and executed the bat swing in relation to the flying ball, similar to hitting a stationary ball. However, if the depth indicates that the collision locations differ between the two tasks, this supports the rejection of the first complementary hypothesis. That is, their movements are organized differently between the stationary and oncoming balls.

To support the second complementary hypothesis, the differences in movement patterns between the two hitting tasks must be identified. To this end, we analyzed the kinematics of the bat swing movement. To intercept the oncoming ball, the timing of the bat swing must be adjusted with respect to the ball's movement. Therefore, the focus of the analysis was to identify the temporal coordination for swinging the bat with respect to the various orbits of the oncoming balls. This coordinative structure has been reported in previous studies (Gray, 2020; Katsumata, 2007). In response to the delivery of fast balls and changeups, batters adjusted the timing of starting the bat swing by modulating the timing structure of the stepping movement. Therefore, the batters' relatively early or later movement timing in the early phase could be compensated by moving slower or quicker in the later phase. If such a coordinative structure is observed not in the stationary ball hit but in the oncoming ball hit, the result can be regarded as a feature of the bat swing in relation to the flying ball. This finding supports the second complementary hypothesis. We expect that the knowledge obtained from the above investigations can provide coaches and players with information about the gap between intended and actual movements. That is, while the movement pattern in the stationary ball hit elicited the batter's preferred movement for a given height and course, the movement pattern revealed in the oncoming hit indicated how they actually responded to the flying ball. This type of information can be utilized to assess batters' skill levels and performance outcomes and provide technical points to be improved or fixed.

As shown in Figure 1, baseball hitting movement is composed of multiple movement components (Stewart et al., 2020; Welch, Banks, Cook, & Draovitch, 1995). The aim of this movement structure is to produce the speed of the bat swing to smash the ball. According to the physics of impact, a mechanically effective ball-bat contact is achieved by intercepting the ball when the bat reaches its maximum speed. Therefore, the temporal organization of the bat swing in relation to the flying ball is an important factor in successfully striking a pitch. In this vein, visual information about ball movement is critical for controlling the bat swing movement in response to the ball.

This vision-based control of the hitting movement can be investigated based on theoretical frameworks for studying motor control. Computational control theory of movement control a major theoretical framework (Wolpert & Flanagan, 2010; Zago, McIntyre, Senot, & Lacquaniti, 2009; Shadmehr, 2009). According to the computational theory, information processing for the vision-based control process is comprised of three stages (Czyż, 2021; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018): processing visual information relevant to the motor performance (stimulus identification), choosing a response proper to the given situation (response selection), and programming the movement for the response to be achieved (response programming). In this computational process, the internal models of the dynamics of pitches' flights and bat movements play a central role (Wolpert & Flanagan, 2001; Wolpert & Ghahramani, 2000). Through the experience of hitting pitches of different flight orbits, an internal model can be built and refined. As the above process is improved, movement errors are reduced.

From the above perspective, when and where the oncoming ball should be hit is the central element in preplanning the bat swing movement. Because a pitch travels a specific course and height in space, bat swing planning is regarded as the process of predicting where on the ball's trajectory (i.e., the depth location) the bat should intercept the ball. In practice, batters choose the depth of the ball location for a specific course and height of the ball by hitting a stationary ball on the tee. This act of choosing the depth location can be viewed as being based on the motor representation of the dynamics of swinging a bat and striking a ball. Motor representations represent not only patterns of displacement of joints and configurations of the body, but also movement outcomes, to which a goal-oriented action is directed (Meyer, Wel, & Hunnius, 2013; Rizzolatti, Giacomo, & Sinigaglia, 2008; Rosenbaum, 2010). Motor representations, which are revealed in the early part of a bodily action, can indicate how the action will unfold to the end (Cohen & Rosenbaum, 2004). From this perspective, movement control involves representations associated with how a movement achieves its goal. In search for evidence supporting the above proposition, many studies have been conducted to identify a pattern of neural firings, a motor evoked potential or a behavioral performance (e.g., Rizzolatti, Giacomo, Fogassi, & Gallese, 2001; Hamilton & Grafton, 2008; Cattaneo, Caruana, Jezzini, & Rizzolatti, 2009; Bonini, Rozzi, Serventi, Simone, Ferrari, & Fogassi, 2010). From the above perspective of motor representation, batters' choice of depth in the stationary ball (Katsumata et al, 2017) can be interpreted as a cognitive process by accessing the motor representation (Butterfill & Sinigaglia, 2014; Mylopoulos & Pacherie, 2016). Through hitting experiences with practice and games, batters acquire a motor representation of striking a ball. Based on this representation, they chose the depth location by assuming a specific course and height of the ball in the tee batting practice.

Given the features of the pattern of impact locations for various courses and the height of the ball, exploring the bat swing movement with respect to the assumed impact location can be potentially useful for devising a way to provide instruction and/or feedback for players to improve the motor task that they are engaged in. A line of studies by Wulf et al. (Wulf, 2007 for review), which examined the influence of learners' focus of attention on their motor performances and improvements, demonstrated that an external focus of attention (i.e., the attention of a performer is directed to the movement effect) is more effective than an internal focus (i.e., attention to the movements themselves). In practical situations of learning sports skills, instruction that refers to the coordination of the performer's body movements (e.g., the order, form, and timing of various limb movements) often directs their attention to their own movements, which induces an internal focus of attention. However, Wulf's studies have demonstrated that directing performers' attention to the effect of their movements on an apparatus or implementation is more effective for better performance and retention tests after practice sessions (e.g., Wulf, Shea, & Park, 2001; Wulf & Su, 2007; and Zachry, Wulf, Mercer, & Bezodis, 2005). A type of feedback may also need to be devised for guiding performers/learners' attention to an external event that influences the performance and/or learning process (e.g., Wulf, McConnel, Gärtner, & Schwarz, 2002). From the above perspective, providing instructions or feedback associated with the ball-bat contact can induce an external focus. Therefore, this study's findings can provide information, which gives us insight into an effective practice for learning and improving the baseball batting skill.

METHOD

Participants and Study Design

The study design was quasi-experimental, and the kinematics of the hitting movements of experienced baseball players were investigated. To this end, ten healthy male college students who played for a college baseball team in the league of the Metropolitan College Baseball Conference participated in this experiment. The mean value and standard deviation of their height and weight were 172.7±5.6 cm and 71.3±6.1 kg, respectively, and their ages on average were 21.1±.3 years. The batters were right-handed and had 11.8±1.2 years of experience in playing baseball. We included them as participants based on the criteria of playing for a team at a competitive level as a regular member, practicing for four to five days on weekdays and playing games during weekends, with a skill level of consistently smashing pitches projected by a pitching machine. Sample size (n) was calculated as follows (Daniel & Cross, 2013):

$$n = [z^2 * p * (1 - p)/e^2]/[1 + (z^2 * p * (1 - p)/(e^2 * N))]$$

In the above formula z is the z-score associated with the confidence level. p is the proportion of the population. N denotes population size. e is the margin of error, expressed in decimals. When these parameter values were assumed to be $z = 1.645$, $p = 0.5$, $N = 10000$, and $e = 0.25$, the sample size was 11. When the margin of error was assumed to be 0.3, the sample size was 8. Based on these results, this study used ten as the sample size.

After the researcher explained the purpose and procedures of the experiment, each participant signed an informed consent form. The present study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the Research Ethics Committee of Daito-Bunka University (KSH14-018).

Two Batting Tasks

The first batting task involved hitting a stationary ball. The location of the ball in each trial was one of the nine locations in the strike zone, defined by the width of the home plate and the height of the batter's address posture (Figure 2). The heights of the ball were determined by following the definition of the strike zone in baseball rules, as described in Figure 2.

Prior to the hitting task, the participants chose the location of the depth for the ball-bat contact for each combination of the three courses (inside, middle, and outside) and three heights (high, middle, and low). The following procedures were used in a previous study (Katsumata et al., 2017). The participant took his batting stance, and the experimenter moved a ball attached to the edge of a mobile whiteboard at one of the nine strike locations. The participants were asked

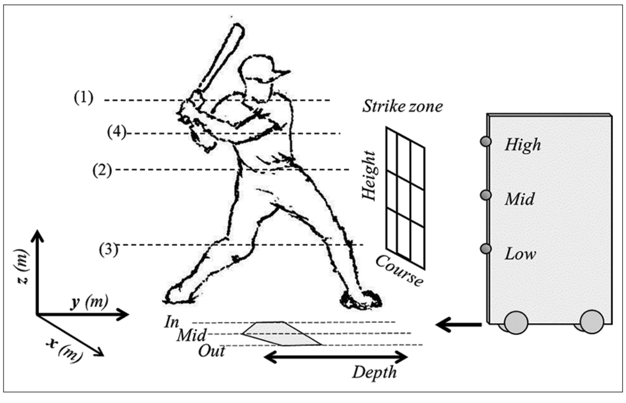

Figure 2. Definition of the strike zone and stationary ball hit
The diagram describes the method used to determine the tee location. (1) to (3) refer to the shoulder, hip, and knee heights, respectively. (4) refers to a high ball, defined as the middle height between (1) and (2). (3) correspond to a low ball. The middle ball was defined as the middle height between (3) and (4).

to look at the ball, imagine a pitch approaching the home plate, and assume a body posture at the moment of the impact by holding the bat at the position where the batter aimed to hit the ball. The researcher recorded the depth of the ball location at the assumed ball-bat contact projected onto the x-y plane at ground level. This procedure was repeated for nine combinations of ball heights and courses. The second batting task involved hitting an oncoming ball that was projected using a pitching machine (Figure 3). For these batting tasks, a baseball bat (84 cm in length and 740 g in weight; MIZUNO, Tokyo, Japan), a plastic ball (18 g in weight; 7 cm in diameter) made for indoor batting practice, and a tee stand (MIZUNO, Tokyo, Japan) were used.

Setup

Stationary ball hitting was performed in an experimental room in which eight high-speed cameras of a motion capture system based on optical marker technology (Vicon MX, Oxford Metrics, U.S.A.) were available. The batting movements were recorded at 250 Hz.

The oncoming ball-hitting task was performed in a gymnasium. The setup for the hitting task is illustrated in Figure 3. A pitching machine (Lite-Flite Machine, Jugs Company Japan, Osaka, Japan) was placed 10 m from the position of the home plate. Three high-speed cameras (Exilim, CASIO, Japan) were used: two to record the batter's movement on his frontal plane from different angles, and one on the side of the pitching machine was used to record the moment of the ball projection. The movements were recorded at a frequency of 300 Hz.

To obtain the three-dimensional coordinates of the analytical points, reflective markers were attached to vertex (head), left and right acromion (shoulder) and iliac point (hip) to capture torso movement, as well as on the fifth metatarsal bone head (toe). Markers were attached to the top and bottom of the bat, and the ball was covered with reflective tape.

Procedure

The participants were asked to address the home plate as they did in the game and practice, and the position of the right toe tip was marked on the floor. They repeated the task trials with a consistent address position by placing their foot at the marked location.

While hitting the stationary ball at each of the nine impact locations, the participants performed five trials. The order of the 45 trials for the nine impact locations was randomized. They were asked to hit the ball as they usually perform baseball batting in practice and games.

In oncoming ball hitting, the trials were repeated until 20 hits within fair territory were achieved. Twenty trials were analyzed. The ball projection angle was adjusted in each trial such that the trajectories of the pitches passed through various locations in the strike zone in the trials conducted. Participants were unaware of the pitch location. The ball was projected at approximately 80 km/h for a machine–home plate distance of 10 m. Due to the deceleration of the plastic ball caused by air resistance, the time of flight of the ball to impact was 995 ± 52 ms. To obtain the data from 20 trials, trials were repeated 33.8 times on average, corresponding to a success rate of 62.5%. In general game situations, a batting average of 30% is considered a good achievement. According to the above criteria, the task requirement level was not easy, but it was not so challenging that the data could be regarded as a successful performance.

In both batting tasks, participants could take a short break of approximately 1–3 min between trials to avoid fatigue. The oncoming ball session was conducted on the following day during the stationary ball session. Each data collection

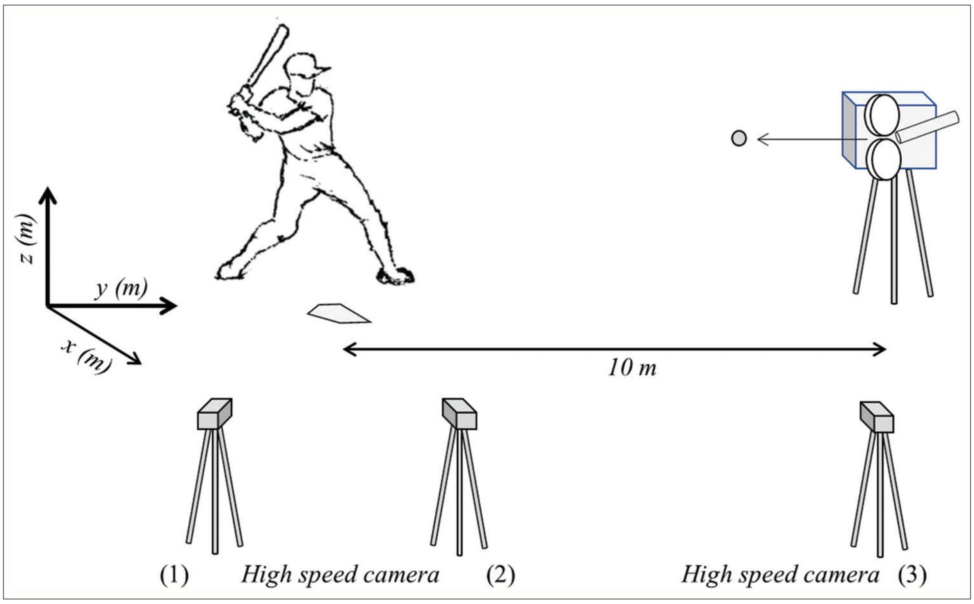

Figure 3. Setup for the oncoming ball hit
Three high-speed cameras were used to record the movements of the batter and ball: cameras (1) and (2) for recording a hitting movement and camera (3) for recording the time of ball projection.

lasted approximately 60 min. The oncoming ball task was followed by the stationary ball task to prevent the participants' choice of tee location from being affected by the performance of the oncoming ball task.

Data Reduction

A motion capture system was used to determine the three-dimensional positions of the reflective markers and the ball in a global coordinate system (Vicon Workstation, Vicon Peak, U.S.A.) for hitting a stationary ball, and by the direct linear transformation method (Hatze, 1988; Abdel-Aziz & Karara, 1971; Shapiro, 1978) using analysis software (Frame-DIAS V, DKH, Tokyo, Japan) for an oncoming ball strike. As the resolution for recording and calculating the three-dimensional position of marker, error value was 0.004±0.012 m for the high-speed camera, and 0.002±0.011 m for Vicon. This confirmed that the different recording systems for the two tasks did not affect the accuracy of the motion analysis. The definitions of the coordinate system are shown in Figures 2 and 3. These position data were smoothed using a second-order low-pass filter with a cut-off frequency of 10 Hz. The trajectory of the ball before impact in the oncoming ball hit was calculated by applying linear regression to the 20 data points of the ball immediately before the ball–bat impact.

Kinematic Parameters of the Hitting Movement for Analysis

For analyzing the kinematics of movements, the events of the hitting movement were identified to capture the changes in movement over time (Katsumata, 2007; Katsumata et al., 2017). Those events are shown in Table 1. Numerical differentiation was used to calculate the velocity of these parameters.

Analysis of the Impact Locations

Repeated measures correlation analysis of the impact locations

We tested the first hypothesis using correlation analysis, with the course and height of the collision location as independent variables and the depth location as a dependent variable. The aim of the correlation analysis was to examine whether the depth of the ball location changed with respect to the course and height of the ball across trials. To this end, repeated measures correlation was used to examine the above association within each participant, which is common across multiple participants (Bakdash & Marusich, 2017). If the depth locations changed systematically with respect to different courses and ball heights, a high correlation coefficient can be obtained. The ball locations at the time of impact were used to analyze the oncoming ball hit.

Discrepancy between the estimated impact location and the actual impacts in the oncoming ball hitting

Based on a previous study (Katsumata et al., 2017), a systematic shift in depth location is expected to occur with respect to the course and/or height of the ball. A previous study examined the regularity of the course– and height–dependence of the depth locations by multiple linear regression with the course and height as independent variables and depth as a dependent variable. Using this regression model, we examined the differences in depth locations between the two hitting tasks as described below.

By assigning the values of course and height, which were not used in the ball location of the stationary ball hit, to the regression model, we could predict the depth location with respect to those courses and heights. If we assign the courses and heights observed in the trials of the oncoming ball hit, we can estimate the depth location for those courses and heights of the ball that the participants will choose in the stationary ball hit. This depth location is referred to as the estimated impact location. The estimated impact location was calculated for each trial with the oncoming ball. Therefore, the difference between the actual depth location and the estimated impact location of the oncoming ball hit was calculated. We refer to this difference as the depth discrepancy. If the participants struck the pitch as with the stationary ball hit, the depth discrepancy would be zero or very low. We tested this assumption using a paired t-test for depth discrepancy, with the null-hypothesis of the zero–depth discrepancy.

Table 1. Kinematic parameters

	Parameter name	Definition
1	Start of the stepping movement	Time when the forward velocity of the toe of the stepping foot reached 3% of its maximum velocity
2	Touchdown of the stepped foot	Time when the forward velocity of the toe of the stepping foot became less than 3% of the maximum velocity
3	Start of the upper trunk rotation for a bat swing movement	Time when the horizontal rotation velocities of a vector composed of two reflective markers attached to the upper trunk reached 5% of the maximum rotation velocity*
4	Start of the bat swing	Time when the velocity of the bat-top reached 3% of its maximum velocity
5	Time of the impact	Time when the distance between the top of the bat and the ball was minimal
6	Duration of the bat swing	Time from the start of the bat swing to the time of impact

*After stepping began, the body exhibited a small movement. Therefore, the start of the rotational movement, defined by the 3%, occurred very early and could not provide useful information about initiating trunk rotation for swinging the bat.

Analysis of the Hitting Movement Kinematics

By focusing on the kinematic parameters (Table 1), we searched for a movement pattern for hitting an oncoming ball of various courses and heights, as described below.

Bat swing duration

The duration of a bat swing is a major component of the time structure of the bat swing movement. Bat swing duration was compared between the two hitting tasks. Furthermore, repeated measures correlation was conducted with duration as the dependent variable, and course and height as the independent variables. Therefore, the influence of the ball's course and/or height on bat swing duration was examined.

Temporal change in the batting motion toward the moment of impact

For the two hitting tasks, the hitting movement was achieved using the same movement elements such as stepping motion and trunk rotation. However, the time constraints of these tasks were different. The oncoming ball hit should be synchronized with the pitch arriving at the home plate. In contrast, batters can hit a stationary ball at their own pace. Therefore, the temporal change in batting motion toward the moment of impact can elucidate the differences in the movement patterns between the two tasks. To this end, the time of each motion event to the impact was compared between the two tasks using a paired t-test. These events included the start of the stepping movement, touchdown of the stepped foot, start of upper trunk rotation, and start of the bat swing (Table 1). In the paired t-test, the mean value of each parameter for each participant was calculated for each task condition.

Furthermore, the variabilities of these temporal changes were also focused. Timing accuracy or consistency of the motion phases is important for reliably hitting a ball. For the stationary ball hit, consistent execution of the movement prepared for each of the nine ball locations resulted in successful hits. In contrast, movement adjustments are required in an oncoming ball hit to cope with balls approaching in various trajectories. These characteristics are expected to be elucidated by comparing the variabilities of the temporal changes between the two hitting tasks. To this end, the standard errors of the mean of the above parameters were calculated and subjected to a paired t-test.

Correlation between the timing of motion phases

Another focus of the temporal structure in the hitting movement was the temporal coordination of the movement during the oncoming ball hit. To this end, we examined the compensatory timing structure using the following timing parameters. One was the time of ball release to the touchdown of the stepped foot, which indicated the timing of the stepping movement with respect to the time of ball release. The second was the time from the touchdown of the stepped foot to the start of the bat swing, which indicated the time elapsed to initiate the bat swing after the step motion. These timing parameters were subjected to repeated measures correlation analysis. If functional timing compensation exists, it is expected that the slower or faster timing of one movement component will be compensated by the faster or slower timing of the subsequent component.

Statistic Analysis

Repeated measure correlation analysis was conducted using the procedure described in a previous study (Bakdash & Marusich, 2017). The repeated measure correlation coefficient (r_{rm}) was calculated as follows:

$$r_{rm} = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y} - \overline{y})^2}{\left(\sum_{i=1}^{n}(\hat{y} - \overline{y})^2\right) + \sum_{i=1}^{n}(y_i - \hat{y})^2}}$$

y_i is an actual data of the dependent variable y in i-th trial of n samples.

$\hat{y}$ is the predicted value by fitting the common slope.

$\overline{y}$ is the mean of y.

Results of the repeated measures correlation were reported as the correlation coefficient (r_{rm}) with error degrees of freedom in parentheses, a common slope, p-value, and a 95% confidence interval for rrm. In addition to these quantitative reports, a plot of data points with repeated measures fit for the individual participants' data points was shown in the figures. The sign of the correlation corresponds to that of the common slope. This was also confirmed by the repeated measures fit shown in the figure.

For a statistical comparison of the kinematic variables between the stationary ball and oncoming ball hit, a paired t-test was conducted. To examine the differences in the kinematic parameter values with respect to the course and height of the impact locations in the stationary ball hit, a repeated measures ANOVA was conducted with the main effects of the course (inside, middle, and outside) and height (high, middle, and low) of the impact. For ANOVA, Mauchly's test of circularity was conducted, and the degrees of freedom were adjusted using Greenhouse-Geisser for violations of circularity. Significant effects of height or course were further evaluated using Sidak's multiple comparison test. For the above analyses, statistical significance was set at $p < .05$.

RESULTS

The Location of the Ball–Bat Impact

Figure 4 shows the distribution of the impact locations for both the stationary and pitched balls for one participant. The batters successfully hit pitched balls over various courses and heights. The mean and standard deviation of the pitch locations at the time of impact were 1.56 ± 0.18 m in the inside-outside direction and 0.88 ± 0.22 m in the vertical direction. The impact location shifted forward (i.e., toward the pitcher) for stationary balls that were more inside (Figure 4a) or higher (Figure 4c). In contrast, for pitched balls, the contact depth did not systematically vary with the course (Figure 4a) but were contacted closer to the pitcher

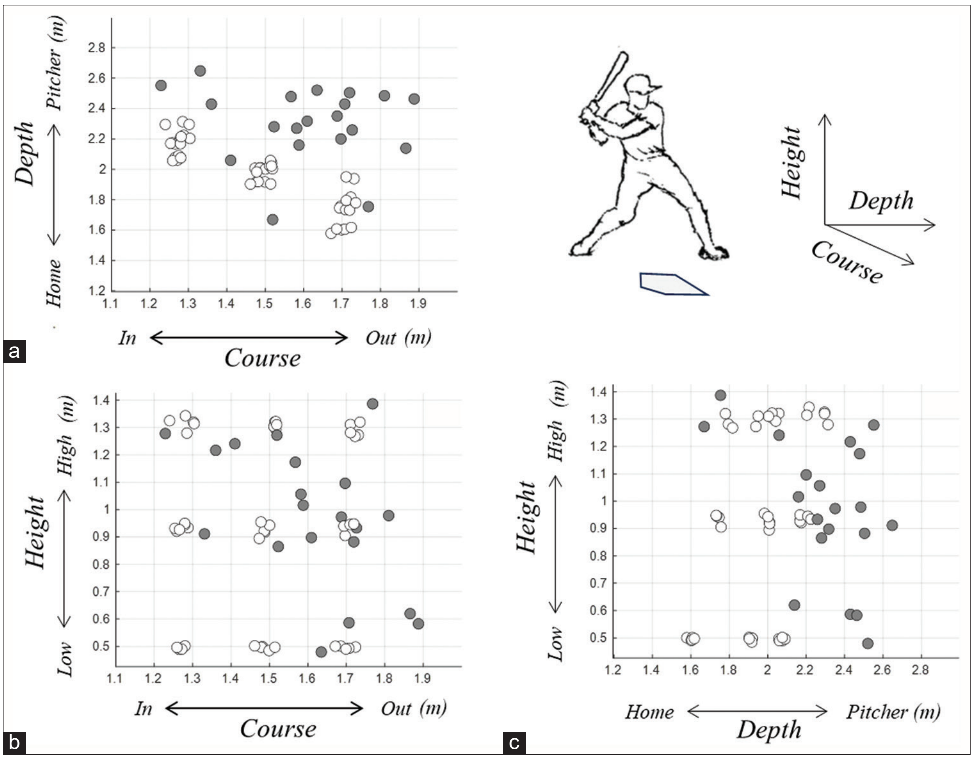

Figure 4. (a-c) Plots of the impact locations
The distributions of the impact locations in the stationary and oncoming ball strikes by one participant were superposed. Each figure was described with (A) top view, (B) frontal view from the catcher side, and (C) sagittal view from the first base side. Note the regularity of the ball positions on a stationary ball hit. ○: Stationary ball; ●: Oncoming ball

at lower pitch heights (Figure 4c). In general, pitched balls were hit more toward the pitcher than stationary balls independent of pitch height or course.

Repeated Measures Correlation Analysis on the Impact Locations

Using repeated measures correlation analysis with the course and height of the collision location as independent variables and the depth location as a dependent variable, we examined whether the depth of the ball location changed with respect to the course and height of the ball.

In the stationary ball hit, the coefficient of the correlation between the course and the depth was very high (r_{rm}(79) =.968, p <.001, 95%CI = [0.95, 0.98], the common slope = -.974). As shown in the correlation plot in Figure 5a and the sign of the common slope, the ball locations shifted more forward for the inside ball and backward for the outside ball. The correlation coefficient between height and depth was also very high (r_{rm} (79) =.875, p <.001, 95%CI = [0.81, 0.92], common slope =.251). As shown in the correlation plot (Figure 5b) and the sign of the common slope, the ball locations shifted more forward for the high ball and backward for the low ball. The high correlation coefficient in the stationary ball hit confirmed the course– and height–dependent depth locations.

As opposed to it, in the oncoming ball hit, the coefficient of the correlation between the course and the depth was low (r_{rm} (189) =.333, p <.001, 95%CI = [0.20, 0.45], the common slope = -.336). As shown in Figure 5a, the strong tendency for inside pitches to be hit more forward with stationary balls was not evident for pitched balls. However, ball bat collisions were consistently more forward toward the pitcher for the pitched ball. Likewise, the coefficient of the correlation between the height and the depth was also low (r_{rm} (189) =.213, p =.003, 95%CI = [0.07, 0.35], the common slope = -.172). Figure 5b shows that the pitched balls hit closer to the pitcher than the stationary balls at all ball heights. While there was a tendency for low balls to be contacted closer to the pitcher, the low correlations for oncoming balls indicated that the depth locations of the collision did not change with respect to the course and height of the ball.

The Discrepancy between the Impact Locations of the Oncoming Ball Hit and the Estimated Locations

In Figure 6a, the estimated impact locations by the wide range of courses and heights are plotted against the actual ball locations in the stationary ball hit. This cluster of estimated impact locations fits well with the actual ball locations. Given these results, this model was used to obtain the depth discrepancy by calculating the difference between the estimated and actual impacts. Figure 6b shows trajectories of pitches in the oncoming ball hit by the sequence of ○ symbols. The end of the symbol indicates the actual impact location. The black line represents the predicted trajectory obtained by linear regression of the ball data after the impact location. The ● symbols indicate the estimated impact locations, calculated by assigning the course and height of the actual impact to the regression model. Figure 6b shows that the depth of the ball-bat collision in the oncoming ball

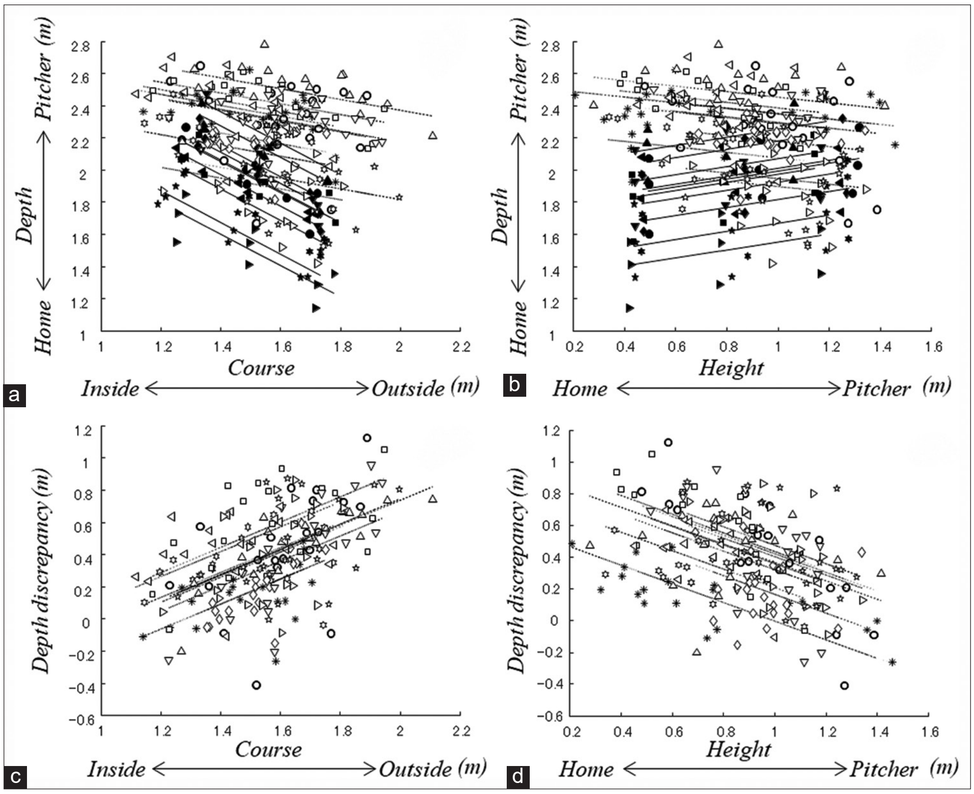

Figure 5. (a-d) Repeated measure correlation plot for the impact locations
Each figure shows a correlation plot between course and depth (A), height and depth (B), course and depth discrepancy (C), and height and depth discrepancy (D). The lines indicate the fitted line of each participant using a common slope. For (A) and (B), the black symbol indicates a stationary ball hit, and the white symbol indicates an oncoming ball hit. The solid and dotted lines show stationary and oncoming ball hits, respectively. For (C) and (D), each symbol represents each participant's repeated measures.

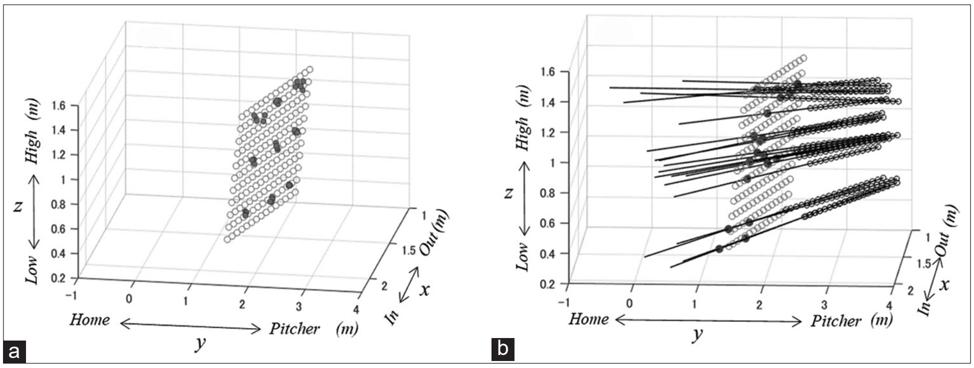

Figure 6. Actual and predicted impact locations
(A) Ball locations of the stationary ball hit predicted by the regression model using the course and height parameters. (○: Ball locations, predicted by different courses and heights; ●: Actual ball locations of the stationary ball hit) (B) Ball trajectories in the oncoming ball hit, superposed with the predicted stationary ball locations. (○: Ball trajectory; −: Ball trajectory, predicted by the linear regression; ●: Striking locations, predicted by the model for the corresponding courses and heights)

hit shifted in the direction of the pitcher compared to the estimated impact locations. This tendency became more prominent as the pitch was more outside or lower.

Within-participant means of the depth discrepancy were calculated and subjected to a t−test with the null−hypothesis of zero−depth discrepancy. The depth discrepancy was.39 ±.12 m on average and significantly different from 0 ($t(9) = 9.79$, $p < .001$, Cohen's d = 3.10). This indicates that the impact locations in the oncoming ball hit shifted forward compared with those in the stationary ball hit.

In addition, the repeated measures correlation analysis for the depth discrepancy as the dependent variable and the course and height of the pitch as independent variables showed a moderately high correlation. The more outside the pitch, the larger the depth discrepancy ($r_{rm}(189) = 0.538$, $p < .001$, 95%CI = [0.43, 0.63], common slope = 0.78). Likewise, the lower the pitch, the larger the depth discrepancy ($r_{rm}(189) = 0.503$, $p < .001$, 95%CI = [0.39, 0.60], common slope = -0.58). Therefore, the depth discrepancy changed with respect to the course and/or pitch height. As the correlation plot (Figure 5c and 5d) indicates, the more outside the pitch, the more forward the impact location. Similarly, the lower the pitch, the more forward the impact location.

The results of the correlation and depth discrepancy indicated that the depth locations at which the batter struck the pitch differed from the ones in the stationary ball hit. Based on these results, the first and first complementary hypotheses were rejected.

Kinematics of the Bat Swing Movements

Bat Swing Duration and Impact Location

The within−participant mean of the bat swing duration across all trials was calculated separately for stationary and oncoming ball hits. The average durations were 278 ± 72ms in the stationary ball hit and 281 ± 78ms in the oncoming ball hit, and the paired t-test did not show a significant difference ($t(9) = -.358$, $p = .728$, Cohen's d =.113).

Repeated measures correlation analysis between the bat swing duration of the stationary ball hit and the course and height of the ball location revealed high correlation for the course ($r_{rm}(79) = 0.92$, $p < .001$, 95%CI= [0.88, 0.95], the common slope = -.190) and for the height ($r_{rm}(79) = 0.75$, $p < .001$, 95%CI= [0.63, 0.83], the common slop =.015). These correlations indicate that, with the ball location outside farther and/or lower, the swing duration became shorter. To further examine this feature, a repeated measures ANOVA was conducted with height (high, medium, and low balls) and course (inside, medium, and outside balls) as the main factors. Course had a significant effect [$F(2, 18) = 9.067$, $p = .002$] without a significant effect of height [$F(2, 18) = .25$] or height-course interaction [$F(4, 36) = 1.76$]. Given this main effect of the course, Sidak's post-hoc multiple comparisons were also conducted, and the bat swing for the outside ball (260 ± 61ms) was significantly shorter than that for the inside ball (296 ± 45ms, $p = .029$).

In contrast, the correlation coefficient for the oncoming ball hit was very low (for the course, $r_{rm}(189) = 0.20$, $p = .007$, 95%CI= [0.055, 0.33], the common slope = -.053; and for the height, $r_{rm}(189) = 0.21$, $p = .004$, 95%CI= [0.06, 0.34], the common slope = −.044). These results suggest that the swing duration in the oncoming ball hit was not modulated, regardless of the course and height of the pitches.

Temporal change in the batting motion toward the moment of impact

Figure 7a shows the mean value of the timing of each motion event. As shown in the figure, a paired t-test revealed that the stepped foot was landed significantly earlier ($t(9) = -3.03$, $p < .01$, Cohen's d = 0.168) than those movements in the stationary ball hit. The stepping movement started also appeared to be early in the figure, even though it did not reach the level of significance ($t(9) = -2.15$, $p < .06$, Cohen's d = 0.177). In contrast, the start of the upper trunk rotation for hitting the oncoming ball started significantly later ($t(9) = 3.93$, $p < .001$, Cohen's d = 0.031). However, the start of the bat swing did not seem to differ between the two hitting tasks ($t(9) = -0.39$, $p < .71$, Cohen's d = 0.034). The figure also indicates that the upper trunk rotation and bat swing for hitting the stationary ball were initiated as soon as the touchdown of the stepped foot, whereas the trunk rotation and bat swing were initiated approximately 200 ms after touchdown.

The variability in the above timing measures was examined using the standard error of the mean (SEM). Figure 7b plots SEM for each movement event during the two hitting tasks. According to the figure, the magnitude of variability in the stationary ball hit appeared to be similar throughout the motion events. In contrast, significantly larger variabilities were observed in the timings of the start of the stepping movement ($t(9) = 4.72$, $p < .00$, Cohen's d = 0.022) and touchdown of the stepped foot ($t(9) = 3.54$, $p < .01$, Cohen's

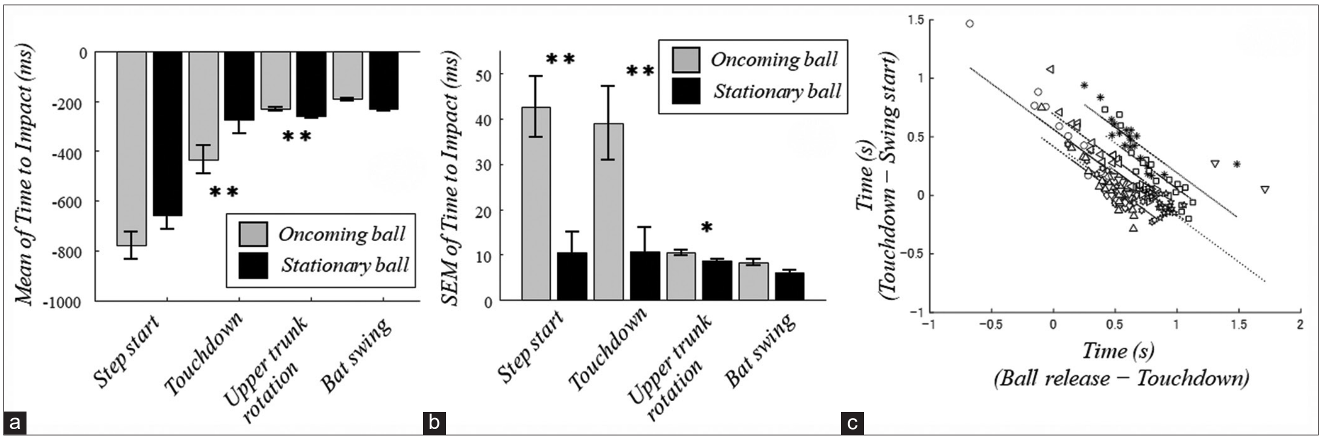

Figure 7. Temporal structure of hitting movement
(A) Mean of the time to the impact of movement events; (B) Square root of mean (SEM) of time to the impact of movement events (Step start: Start of the stepping movement; Touchdown: Touchdown of the stepped foot; Upper trunk rotation: Start of the upper trunk rotation; Bat swing: Start of bat swing; * $p < .05$, ** $p < .01$); (C) Repeated measure correlation plot for the oncoming ball hit (Time (Touchdown – Swing start): The time of Swing start subtracted by the time of Touchdown. Negative values indicate that the bat swing started before the touchdown of the stepped foot; Time (Ball release – Touchdown): The time of Touchdown subtracted by the time of ball release. A negative value indicates that the step movement started early, and the forefoot touched the ground before the ball release.) Each symbol represents the participants' repeated measures. The lines indicate the fitted line of each participant using a common slope.

d = 0.025) in the oncoming ball hit than those in the stationary ball hit. However, the variability decreased at the start of upper trunk rotation, although it was still significantly larger than that in the stationary ball hit ($t(9) = 2.91$, $p < .02$, Cohen's d = 0.002). Subsequently, the variability in the start of the bat swing in the oncoming ball decreased to its level in the stationary ball hit. Therefore, the paired t-test for the start of the bat swing showed no significant differences ($t(9) = 1.96$, $p < .08$, Cohen's d = 0.005).

Temporal coordination of motion events for hitting an oncoming ball

To examined the compensatory timing structure for the oncoming ball hit, the repeated measures correlation between the time from the ball release to the touchdown of the stepped foot and the time from the stepped foot's touchdown to the bat swing start was analyzed ($r_{rm}(189) = 0.79$, $p < .001$, 95%CI= [0.73, 0.84], the common slope = −.779). The correlation plot is shown in Figure 7c. The results show a significant negative correlation. This revealed the timing modulation of starting the bat swing. In other words, when the timing of the stepped foot touchdown was relatively early or late relative to ball release, the time taken to start the bat swing was extended or shortened.

DISCUSSION

In the stationary ball hit, the preferred impact locations for different courses and heights of the ball were distributed systematically from the inside to the outside and from the low to high locations (Figures 4, 5a, and 5 b). These results are consistent with that of the study by Katsumata et al., (2017). However, when hitting the oncoming ball, such a systematic tendency was obscured by the locations of the impact shifting further forward as the pitches travelled more outside. Hence, these results did not support the first hypothesis.

The patterns of the impact locations differed, as indicated by the depth discrepancy results. The low correlation and non-systematic distribution of the impact locations can be induced by errors in hitting the flying ball, even though the batters attempted to intercept it, as in the stationary ball hit. However, these results were not attributed to errors in the hitting performance, as the analysis was conducted for successful trials in the oncoming ball hit. Therefore, these results did not support the first complementary hypothesis.

These results indicate that the participants did not hit the oncoming ball at the preferred impact locations observed in the stationary ball hit, although the possibility that they prepared the bat swing, as in the stationary ball hit, cannot be denied. This implies that even if batters consciously assume how to swing a bat and intercept a flying ball at a particular depth for a given course and height of the ball, the results of this study cast doubt on the assumption that the bat swing movement is organized based on a conscious process.

Furthermore, the kinematic analysis of the oncoming ball hit revealed a temporal structure different from the stationary ball hit in terms of the temporal structure and compensatory relationship of batting motion phases. These results imply the modulation of movement in an oncoming ball hit. This seems to support the second complementary hypothesis, which postulated that hitting an oncoming ball is achieved by modulating the bat swing movement, and thereby, the collision locations become different from those in a stationary ball hit. Based on the results of the kinematics of the bat swing movement, a possible movement strategy for hitting an oncoming ball is discussed below.

Movement Strategies for Hitting Flying Balls

In a stationary ball hit, the duration of the bat swing differed depending on whether the ball was inside or outside. It took longer to hit the inside ball than the outside ball ($r_{rm}(79) = 0.92$), and the course-dependent time difference was 36 ms on average. This means that if the oncoming ball hit is organized by this course-dependent temporal structure, the timing adjustment of swinging the bat is required based on the batter's judgement of the course of the pitch to hit it at the predicted impact location. However, for the oncoming ball hit, the above course-swing duration correlation was not observed ($r_{rm}(189) = 0.20$). In addition, the depth location of the impact was not dependent on the pitch course ($r_{rm}(189) = .333$). Therefore, the participants did not seem to have modulated the timing and duration of swinging the bat according to the courses of the pitches. In other words, it seems to be difficult for them to achieve such a fine timing adjustment of delaying the start of the bat swing by approximately 36 ms when the ball came outside. Based on the above discussion, the authors of this study propose a movement strategy for hitting an oncoming ball as below.

As shown in Figure 7a, in the oncoming ball hit, the touchdown of the stepped foot occurred earlier, and the batters took a short pause before the start of the upper trunk rotation and bat swing. In contrast, in the stationary ball hit, upper trunk rotation and bat swing started as soon as the stepped foot landed on the ground. In a stationary ball hit, the batter's movement can be preplanned with respect to the predetermined impact location and the prepared movement can be executed without pausing. In contrast, in an oncoming ball hit, the timing of the stepping movement is either slow or fast relative to the flying ball. If batters simply execute the prepared bat swing motion immediately after completing the step movement, they will not be able to compensate for the above timing error and will not be able to hit the ball successfully. Therefore, such timing errors must be compensated by a later movement phase, that is, the timing of the upper trunk rotation and bat swing. Such timing compensation seems to be achieved by the time lag between the touchdown of the stepped foot and the start of upper trunk rotation.

This inference was supported by the correlation analysis (Figure 7c). When the timing of the touchdown of the stepped foot was relatively early or late, with respect to the time of ball release, the timing of the bat-swing start was delayed or rushed ($r_{rm}(189) = 0.79$). Therefore, the bat swing can start at a relatively consistent timing in response to the flying ball. Consequently, the inside and outside pitches could have arrived at nearly the same depth location when the bat swing started. Similarly, if the duration of the bat swing was also relatively constant, the bat could meet the pitch at a relatively consistent depth location.

Compensatory timing between the touchdown of the stepped foot and the start of the bat swing was achieved by the above temporal structure of the step motion and bat swing. Fine timing adjustments for swinging a bat against a flying ball can be avoided using this movement strategy. The result supporting the above argument has been obtained by a previous study (Katsumata, 2007), in which when fast and slow pitches were randomly delivered, batters adjusted the timing of thrusting the stepped foot on the ground. This movement phase is mechanically important for producing trunk rotation to swing a bat. Therefore, this corresponds to the timing structure in the interval from the stepped foot touchdown to the start of the bat swing observed in the present study.

Vision-based Control of the Bat Swing Movement Executed under Temporal Constraint

As discussed above, vision plays an important role in the temporal modulation of movement. Such vision-based adjustments are limited by visuomotor delay, which is the time lag of visual information used to control a movement (Brenner & Smeets, 1997; Smeets, Wijdenes, & Brenner, 2016). This time constraint has been examined in a previous study (Katsumata, Hagiwara, & Nebashi, 2019). College baseball batters hit a stationary ball on a tee stand, and the batter's vision was occluded at different times in the middle of the hitting movement using a shutter goggle. When the timing of the occlusion was less than 150 ms before the impact, the accuracy of the impact did not differ from that without visual occlusion. In other words, the accuracy deteriorated when occlusion was applied before the last 150 ms. This result indicates that information processing for vision-based control of a movement can operate until 150 ms before the ball-bat collision. Because the average bat-swing duration in the oncoming ball hit was 281 ms, vision-based modulation was still possible, even approximately 130 ms after the start of the bat swing. As shown in Figure 7a, the timing the rotations of the upper trunk started after the bat started moving. Therefore, after upper trunk rotation started, vision-based modulation of the bat swing movement seemed quite difficult. Based on the above discussion, the synchronization of the bat swing with the flight of the pitch can be achieved by adjusting the timing of the touchdown of the stepped foot and the start of trunk rotation.

Limitation of Study

As discussed below, several issues must be considered in future studies. The discussions developed above are based on statistically significant results with relevant knowledge obtained from previous studies. However, analyzing data from a larger number of participants would have been more desirable, even though the findings of the present study are in accordance with those of previous studies (Gray, 2020; Katsumata, 2007; Katsumata et al., 2017). Another concern is the design of the experiment, in which the task performance was not executed under the real situation of baseball hitting in the following points. A plastic ball for the hitting practice was used to safely execute the experiment because the ball-bat contact and kinematics of the batted ball were not the focus of the analysis. The ball was projected using a pitching machine to ensure that its speed and projection angle were relatively consistent across the participants.

To examine the kinematic features of an oncoming ball hit, this study focused on the temporal domain of the kinematics. In addition to the results of this study, the following points are desirable for further studies to obtain knowledge on the visuo-motor coordination for hitting a flying ball. We also expect that analysis in the spatial domain can reveal important knowledge about the coordination of movement in response to various courses and heights of flying balls.

This study investigated the visuo-motor control of the hitting movement from the viewpoint of computational control (Wolpert & Flanagan, 2010; Zago, McIntyre, Senot, & Lacquaniti, 2009; Shadmehr, 2009). From this perspective, it was assumed that the bat swing movement was programmed toward ball-bat collision via visual information processing for the ball movement. However, the observed features of the impact locations were not in accordance with those predicted by the batter's predetermined impact location in the stationary ball hit. According to the motor strategy proposed in the previous section, the bat meets the ball at a certain depth as long as the bat motion is synchronized with the ball motion. From this perspective, the impact location can be regarded as the result of tuning the bat to the movement of the ball, rather than as a key element in programming the motion. This feature of coordinated movement can be interpreted in terms of a theoretical framework other than the computational control theory. For instance, the theoretical frameworks of the dynamical system theory (Kugler & Turvey, 2015; Profeta & Turvey, 2018; Schöner & Kelso, 1988; Turvey, 1990; Turvey & Kugler, 1984) and the ecological approach to the perceptual-motor process (Fink, Foo, & Warren, 2009; Gibson, 2014; Ledouit, Casanova, Zaal, & Bootsma, 2013; Lee, & Young, 1985; Schöner, 1994; Rogers, 2021; Warren, 1990, 2006;) attempt to explain the coordination of movement without assuming a programming process. Further investigations from these viewpoints will provide interesting insights into the visuo-motor process for controlling the baseball hitting.

Strength and Practical Implication of Study

This study used a unique and novel approach based on the following points. According to studies on the control of multi-segment movement (Latash, 2015; Shadmehr & Wise, 2005), a goal-directed movement is organized for a working point that is directly associated with the task goal to achieve the goal. Motivated by this perspective, we assumed the ball-bat contact to be a key element in controlling the bat swing (i.e., the working point in the hitting task). To analyze the impact locations, we devised a method to predict the location of intercepting a flying ball based on the batter's assumed impact locations for various courses and heights of the stationary ball. By adopting repeated measure correlation analysis (Bakdash & Marusich, 2017), we considered each participant's tendency of the impact locations for the various courses and heights to capture the pattern of the depth of the impact with respect to the course and height of the ball. The comparison of an oncoming ball hit with a stationary ball hit is also a novel approach based on the following reason. Batters' choice of ball location was associated with their motor representation of the dynamics of the hitting movement. However, the oncoming ball hitting task involves the visuo-motor control process with respect to the ball movement. The feature of the movement in the oncoming ball, which is different from that in the stationary ball, reflects the control of the hitting movement in response to the oncoming ball. As expected, the comparison revealed the qualitatively different coordination patterns between these hitting tasks.

The results of this study have practical implications for baseball players and coaches. As revealed by the distribution of preferred impact locations in the stationary ball hit, baseball batters assume to strike the ball at different depth locations for different pitch courses. To intercept a flying ball at these locations, the timing of the bat swing must be fine-tuned depending on the course. However, they did not strike pitches at locations similar to those of the stationary ball hit. This result suggests that for executing the bat swing with respect to pitches, sticking to the preferred impact location makes it difficult to intercept pitches. This does not imply that hitting a stationary ball is not effective as a practice method. Because the ball is stationary, batters can focus on how to swing the bat without considering temporal coordination with respect to pitch flight. Therefore, this practice can be useful for learning the dynamics of the hitting movement and acquiring a proper mechanism of the bat swing movement. Utilizing this practice method by noticing the above limitations and advantages with the combination of practicing to hit pitches may help shape the coordination of movement elements to swing a bat in synchronization with a flying ball. Setting a wide range of combinations of depths, courses, and heights of the stationary ball may facilitate batters to explore the dynamics of the bat swing and shape the coordinative structure of the bat swing movement (Schöner, Zanone, & Kelso, 1992).

According to a line of studies that investigated how players' attention should be directed for their better performances and improvements (e.g., Chua, Jimenez-Diaz, Lewthwaite, Kim, & Wulf, 2021; Wulf, 2013), the focus of attention affets learning and performance of movement skills. Experimental evidence from these studies showed that an external focus of attention can facilitate the learning process and performance, while an internal focus can deteriorate them (e.g., Wulf, Shea, & Park, 2001; Wulf & Su, 2007; and Zachry, Wulf, Mercer, & Bezodis, 2005). According to their categorization of the internal or external focus, the impact location can be regarded as an external focus. However, based on the pattern of impact locations in the present study, players should be careful about how to be aware of where to intercept the flying ball because their preferred locations in the stationary ball may not be in accordance with those in the oncoming ball hit. Similarly, coaches should also be concerned with how to provide batters instructions or feedback on how to intercept the ball. Advising batters to be aware of where to intercept the ball, as in the case of a stationary ball hit, may distract the visuo-motor process that intercepts the flying ball.

Another important implication for players and coaches is that the temporal structure, comprising the stepping motion and the start of the trunk and bat rotational movements, will be a key focal point for checking and evaluating the quality or skill level of the batters' movement. By comparing the oncoming ball hit with the stationary ball hit, the temporal coordination pattern, which is composed of the stepping motion and rotations of the upper trunk and bat to synchronize the bat motion with the ball motion, was revealed. This feature is important for determining the timing of the bat swing in relation to the flying ball.

CONCLUSION

Although batters chose depth locations of impact systematically against the given courses and heights of the ball in the stationary ball hit, they did not hit the oncoming ball with various courses and heights in such course– and height–dependent collision locations. These impact locations emerged from a motor strategy for the temporal coordination of movement with respect to the flight of pitches; that is, the timing of the hitting motion phases was adjusted to initiate the bat swing at a relatively consistent timing. The pitches then reached a relatively consistent depth location. This motor strategy can be a parsimonious way of controlling the bat swing because it does not require fine timing modulation, depending on the different pitch courses. These results revealed the visuomotor control strategy for intercepting a flying ball within the given time constraints of pitch flight time and visuomotor delay.

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AUTHOR CONTRIBUTIONS

The concept of this study was developed and the experiment was designed by the corresponding author (Hiromu Katsumata). Data acquisition and data reduction for analysis were performed by the first author (Tenpei Ino). The corresponding author analyzed the data and wrote the paper for this publication.

ETHICAL APPROVAL

The present study was approved by the Research Ethics Committee of Daito-Bunka University (KSH14-018).

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