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The Relationship between Fundamental Baseball Batting Ability and Fastball Hitting Accuracy

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Abstract

The purpose of this study is to discern the relationship between spatial accuracy, timing accuracy, and bat control and hitting accuracy for elite collegiate baseball batters. Nine college baseball batters performed three tasks. The first task was hitting a fastball thrown by a pitching machine (HPT). The second task was observing a pitching machine's fastball and indicating the location (OPT). The third task was hitting a ball on a baseball tee (TBT). The subjects' performance in hitting accuracy was defined by their success rate in the HPT. The distribution of the point of ball-bat impact in the TBT represented the subjects' ability in the bat control. The fluctuations in the location in pitcher-to-catcher direction between the HPT and the TBT represented the subjects' temporal accuracy. The subjects' spatial accuracy was defined by their performance in the OPT. Although they were able to control their bat swings to hit a ball within the effective impact area most of the time in the *Tee Ball Task*, timing and spatial components of their performance indicated larger errors and lower precision. Our results suggest that the perceptual skills involved in baseball hitting are the main reason why batters fail to hit a ball accurately.

Keywords : batter, ball-bat contact, motor control

1. INTRODUCTION

Successful hitting is an outcome involving the correct prediction of pitched ball trajectory and accurate execution of the bat swing so that the bat is at the right location at the right time. To put it the other way around, unsuccessful hitting can be the result of errors in prediction of ball trajectory, timing of ball-bat contact, or swinging the bat to its intended location [1,2]. It seems likely that these errors all occur because these components of accurate hitting all require fine-tuned perceptual and motor skills. Batters have to predict the trajectory of pitches with various speeds, spins, and launch angles. To hit a fair ball, the allowable length of timing error for ball-bat contact is less than 10 ms [3]. Moreover, the size of the bat's barrel surface area that allows batters to hit a ball far and fast is small; approximately 100 mm wide and 25 mm high [4].

One index generally used to describe a batter's overall accuracy of ball-bat contact is the "batting average". Having a batting average above 0.3 qualifies one as an excellent batter in Major League Baseball [4]. No batter has ever finished an entire season with a batting average above 0.4 (with enough at-bats to be qualified for a batting championship) since Ted Williams of the Boston Red Sox achieved 0.406 in 1941. Although the batting average describes how often a batter reaches at least first base, it does not exactly indicate the batter's ability to hit accurately. For example, a ground ball or pop fly often results in a base hit because the batted ball goes to a location where field players have a hard time covering. Similarly, batters often make an out even when they hit a line drive if the ball is caught by a field player. In order to quantitatively evaluate a batter's ability to hit accurately, a detailed physical analysis of their ability to make proper contact between the bat and ball is required. Specifically, it is necessary to evaluate the batters' abilities to 1) predict when and where a thrown ball will arrive, 2) swing a bat to the intended location and time, and most importantly, 3) minimize the distance between the sweet spot and the contact point at the moment of contact. The purpose of our investigation was to 1) quantify batter's performance in spatial perception, timing accuracy, and bat control, and then 2) analyze the relationship between the accuracy of ball-bat contact and these three parameters.

2. METHODS

2.1 PARTICIPANTS Nine college baseball field players participated in the experiment. Mean age, height, and body mass (mean ± SD) were 20.2 ± 1.1 years, 1.76 ± 0.08 m, and 72.3 ± 10.0 kg, respectively. The mean length of their baseball experience was 12 ± 1.9 years (range, 9-16). Their team is a member of the Tokyo Big Six Baseball League and won the league championship five times and the national championship twice in the last ten seasons. Seven subjects were right-handed batters, and two were left-handed batters. The experiment consisted of three tasks which were completed by each subject within one day. The study was approved by the Human Ethical Committee of Waseda University. Written consent forms were obtained from all participants. The subjects were paid for their participation on an hourly basis and were naive to the purpose of the experiment until a post-experiment debriefing was given.

2.2 PROCEDURE FOR THE HITTING A PITCH TASK

The *Hitting a Pitch Task* involved hitting thirty fastballs thrown by a two-wheel pitching machine (Inverter IS, Toa Sports Machine Inc.) in the same way as they would hit fastballs in a game. The ball release point of the pitching machine was placed 17 m from home plate and 1.6 m above the ground, which is about the same as an ordinary pitcher's release point. Launched ball velocity and ball backspin rate were maintained at a constant setting of 38.9 m/s (140 km/h) and 35 rotations per second, respectively. Ball velocity was also measured by a radar gun (The Jugs Company Japan Ltd., Japan). For consistent ball projection, an experimenter fed balls to the machine with the same seam orientation. The location of each launched ball was manipulated randomly and scattered over the strike zone by adjusting the antero-posterior tilt angle and direction of the machine.

An aluminum bat (SC900 Victory Stage Dream King; length = 0.85 m; weight = 0.9 kg; Mizuno, Japan), and official Japan amateur league baseballs (2OH100, Mizuno, Japan) were used. The subjects were instructed to place their trailing (back) foot in their normally preferred position and to utilize the same foot position during all the trials. A ten-minute-break was given after 15 trials to minimize the influence of fatigue.

2.3 DATA COLLECTION AND ANALYSIS FOR THE HITTING A PITCHTASK

The movements of bat and ball were recorded using two synchronized high-speed video cameras (Frame rate = 1000 Hz, exposure time = 0.5 ms, resolution = 680 × 480 pixels, Trouble Shooter, Fastec Imaging Corporation, USA). Camera 1 was placed 6 m away from home plate at a right angle to the line between the center of the pitching rubber and the center of home plate, and camera 2 was placed 6 m behind home plate to provide a rear view of the hitting movement. To establish the actual spin rate of the ball just after ejection from the pitching machine, the spin rate was determined from images taken by camera 3 (Frame rate = 1000 Hz, exposure time = 0.5 ms, resolution = 680 × 480 pixels, Trouble Shooter, Fastec Imaging Corporation, USA) for 150 ms after the ball's ejection. Camera 3 was located 2 m behind the pitching machine. Linear velocity of a launched ball was obtained from digitized data taken from 5 ms to 1 ms before the moment of ball-bat contact. Reflective tape was attached to the barrel end of the bat and 450 mm down from the barrel end of the bat to aid data analysis.

Data involving the location of the bat top, the bat grip, and the launched ball were obtained from images, digitized, and analyzed using a motion analysis system, Frame Dias IV (DKH, Japan). One frame (1 ms) before the frame which captured contact of the ball and bat was selected as the frame to be utilized for analysis of ball-bat location. Three-dimensional coordinates were obtained using the Direct Linear Transformation method (DLT) with an approximately 2 m × 2m ×2m size radial calibration structure with 68 reference points and 5 reference markers set vertical and horizontal relative to the ground. The right-hand orthogonal reference frame was defined by X_{global}, Y_{global}, and Z_{global}-axes with the origin at the rear point of home plate (Fig 1.).

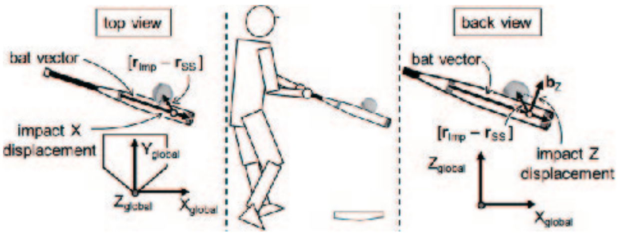

Fig1. Top view (left) and back view (right) at the moment of ball bat impact by a batter (middle). Impact Z displacement is the distance between the ball center (**r_{Imp}**) and the sweet spot of the bat (white circle) (**r_{SS}**) in the direction of **b_Z**.

The Y_{global}-axis was directed from home plate to the pitcher's plate; and the Z_{global}-axis indicated a vertically upward direction. The X_{global}-axis was defined as the cross product of the Y_{global} and Z_{global}-axes. For analysis of left-handed batters, a left-hand coordinate system with the same Y_{global} and Z_{global}-axes as the right-hand coordinate system was utilized. For calibration, poles with three reference markers (0 m, 0.75 m, and 1.5 m from the bottom) were vertically set at nine different locations within a 1.5 m × 1.5 m square on the ground. A recording of the calibration points with cameras 1 and 2 was conducted both before and after the batting tasks. To test the accuracy and reliability of this measurement method, one investigator digitized two reference markers on a swung bat for five frames on two separate occasions. The difference between the actual value (0.450 m) and calculated value (mean ± standard deviation = 0.453 ± 0.0004) was less than 2 %. For the test-retest reliability of the distance, *r* was = 0.953.

To clarify the spatial relationship between the bat's sweet spot and the ball at the point of impact, the impact Z displacement and the impact X displacement were calculated (Fig 1.). First, the bat vector was defined as lying on the long axis of the bat and as being oriented from the bat grip to the top. Then, the impact X displacement can be computed as

$$impact\ X\ displacement = \boldsymbol{b}_x \cdot (\boldsymbol{r}_{Imp} - \boldsymbol{r}_{SS}),$$

.... (1)

where the $\boldsymbol{b}_x$= unit vector that is parallel to the bat vector directed away from the sweet spot = position of the ball center at impact, and $\boldsymbol{r}_{SS}$ = position of the sweet spot at impact. The impact X displacement provides a measure of hitting accuracy in the direction parallel to the bat. The bat coordinate system was adopted to show the ball location on bat barrel at the moment of contact. The impact Z displacement can be computed as

$$impact\ Z\ displacement = \boldsymbol{b}_z \cdot (\boldsymbol{r}_{Imp} - \boldsymbol{r}_{SS}),$$

.... (2)

where the $\boldsymbol{b}_z$ = unit vector that is perpendicular to the bat vector directed upward in the vertical plane, $\boldsymbol{r}_{Imp}$= position of the ball center at impact, and $\boldsymbol{r}_{SS}$ = position of the sweet spot at impact. The impact Z displacement provides a measure of hitting accuracy in the direction perpendicular to the bat.

2.4 PROCEDURE FOR THE OBSERVING A PITCH TASK

The second task, *Observing a Pitch Task*, was designed to indicate the location of a pitch right after it passed home plate. Location and settings of the pitching machine and cameras were identical to those in the *Hitting a Pitch Task*. Twenty fastballs which arrived at different locations were thrown for each subject. Subjects were instructed to observe pitches thrown by the pitching machine and then indicate the location of the ball with a bat based on their judgment right after the ball passed home plate. This procedure was designed in order to eliminate the timing accuracy and bat control components of batting accuracy. It was also necessary to eliminate visual information about the ball's trajectory after it passed the plate. This information would not normally be available to a batter, but could be potentially be utilized by the subjects to locate the ball's position. For this reason, the subjects wore a visual occlusion liquid-crystal apparatus (PLATO, Translucent Technologies Inc., USA). The timing of visual occlusion was regulated by software (ToTaLcontrol 2.0, Translucent Technologies Inc., USA) and subjects' vision was occluded 350 ms after a ball passed a photo-sensing diode (PLDM-10, Sankei Machinery, Japan). This occurred about 100 ms before the ball passed home plate. The visual occlusion lasted for 150 ms. The same bat and ball as the *Hitting a Pitch Task* were used in this observation task.

2.5 DATA COLLECTION AND ANALYSIS FOR THE OBSERVING A PITCH TASK

The same cameras and coordinate system as used in the Hitting a Pitch Task were utilized in this task. Pitch trajectory during the period between 150 ms before and 150 ms after the ball passed home plate was recorded. Next, video cameras recorded the subjects for 30 ms while they were indicating their perceived location of the passed ball. Calculation of estimated ball-bat contact location was conducted as follows:

1. The locations of markers on the bat while the subject was indicating his perceived ball location were digitized for one frame.
2. For digitization of ball center, an experimenter digitized ten continuous frames of ball images which included the period of time when a launched ball was passing the vertical plane that contains the indicated bat.
3. Displacement from the bat's sweet spot to the ball center in the direction of Y_{global} axis was calculated for each of the ten frames. If the optimal choice of the 10 frames was made, Y_{global} displacement became smaller and closer to zero during the first five frames and attained greater negative values during the last five frames.
4. The frame before the Y_{global} displacement decreased to less than 70 mm was considered to be the ball location just before ball-bat contact and was used to calculate the estimated ball-bat contact location.

2.6 PROCEDURE FOR THE TEE BALL TASK

The third task, Tee Ball Task, was to hit a ball off a baseball tee (2ZA770, MIZUNO, Japan) from five different locations (Figure 2-4), ten times at each location. Ball location was changed every trial in a randomized order. The same bat and ball as those in the Hitting a Pitch Task were used. Since the ball (target) was at rest on the tee, this task should assess the batter's skill in bat control, while largely excluding skill in timing accuracy and visual perception. There were three kinds of ball location which were on the Y_{global} axis with different heights, a) the base of the patella = "low", b) mid-height between the acromion and iliac crest = "high", c) the midpoint between the "low" and "high" = "middle". At the height of c, there were two other ball locations; d) in which the ball was located 0.2 m towards the hitter in the X_{global} direction = "inside", and e) in which the ball was located 0.2 m away from the hitter in the X_{global} direction = "outside" (Figure 1.4). Ball locations in the Y_{global} direction were determined based on each subject's characteristics. The subjects were instructed to hit utilizing the same foot position as they did for the fastball hitting task. Three-minute-breaks were given after 10 trials to minimize the influence of fatigue.

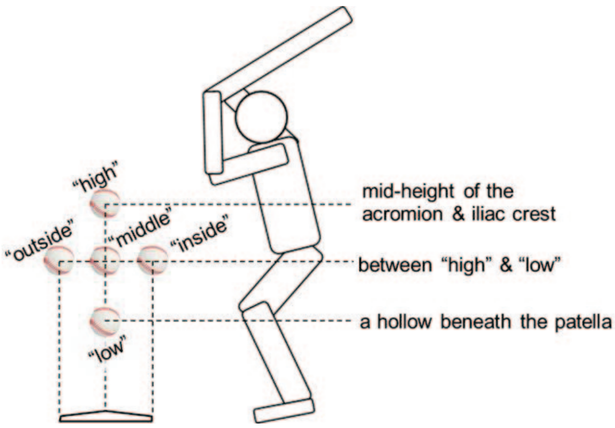

Fig 2. Five ball locations for the *Tee Ball Task*.

2.7 DATA COLLECTION AND ANALYSIS FOR THE TEE BALL TASK

The same cameras and coordinate system as utilized in the Hitting a Pitch Task were employed in this task. The movement of bat and ball 150 ms before and after ball-bat contact was recorded from the same cameras and with the same settings as for the other tasks. The frame (1 ms) before the frame capturing contact of ball and bat was selected as the frame with which to analyze ball-bat location. The coordinate systems were the same as those utilized in the Hitting a Pitch Task.

2.8 STATISTICAL ANALYSES

The subject's ability to hit a pitch accurately was determined by the mean of distance (absolute value from the sweet spot) between the ball center and the sweet spot and the standard deviation of displacement (relative value from the sweet spot) of the ball center from the sweet spot in the Hitting a Pitch Task. Shorter ball-bat distance and smaller standard deviation of the displacement at the moment of impact indicated greater hitting accuracy.

The mean of distance between the ball center and the sweet spot as well as the standard deviation of displacement of ball center from the sweet spot in the Observing a Pitch Task indicated the subject's performance for the spatial perception of ball location. The mean of distance between the ball center and the sweet spot coupled with the standard deviation of displacement of ball center from the sweet spot in the Tee Ball Task indicated the subject's performance in bat control – the batter's ability to bring the bat to its intended location. The subject's performance in timing accuracy was analyzed based on the mean distance between the ball-bat contact location and the "preferred impact location". This was established from their preferred Y_{global} ball location in the Tee Ball Task. First, an approximate equation of preferred ball locations on the XY_{global} plane in each subject's Tee Ball Task was calculated (Figure 1.5). Then, the difference between the Y_{global} value of ball-bat contact location in each trial of the Hitting a Pitch Task trial and the Y_{global} value which was calculated by assigning X_{global} value in the trial to the appropriate equation was determined.

Statistical analyses were conducted with IBM SPSS statistical software, version 20 (Japan IBM, Japan). Correlations between hitting accuracy and various factors were calculated using the Pearson product-moment correlation coefficient. Statistical significance was set at $p < 0.05$. A two-way ANOVA with repeated measures (factor-task [Hitting a Pitch Task vs. Observing a Pitch Task vs. Tee Ball Task] and direction of the impact displacement [impact X displacement vs. impact Z displacement] was used to assess difference in the standard deviation of the impact deviations in each task. Significant results were further analyzed with a post hoc Bonferroni t test for multiple comparisons. The alpha level for significance was set at $p < 0.01$.

3. RESULTS

3.1 ACTUAL HITTING ACCURACY

The mean and standard deviation (±SD) of ball location at the moment of ball-bat contact in the Hitting a Pitch Task for each subject are shown Table 1. In the Hitting a Pitch Task, mean (±SD) of each subject's ball-bat distance at the moment of impact was 40.4 ± 8.6 mm in the X_{bat} direction and 24.0 ± 3.6 mm in the Z_{bat} direction. The mean (±SD) of the standard deviation of each subject's ball-bat displacement at the moment of impact was 41.6 ± 7.8 mm in the X_{bat} direction and 22.0 ± 4.3 mm in the Z_{bat} direction. These values were used as indicators of the subjects' actual performance in hitting accuracy.

Table 1.1 Mean (±SD) of ball-bat distance for three tasks.

TaskImpact X displacement (mm)Impact Z displacement (mm)

Task	Impact X (mm)	Impact Z (mm)
Hitting a Pitch Task	40.4 ± 8.6	24.0 ± 3.6
Observing a Pitch Task	42.5 ± 17.7	53.5 ± 46.2
Tee Ball Task	27.4 ± 4.9	16.6 ± 1.6

3.2 SPATIAL PERCEPTION OF BASEBALL LOCATION

The mean (±SD) values for ball location at the moment of ball-bat contact in the Observing a Pitch Task for each subject are shown in Table 1. In the Observing a Pitch Task, mean and standard deviation of each subject's ball-bat distance at the moment of virtual ball-bat contact was 42.5 ± 17.7 mm in the X_{bat} direction and 53.5 ± 46.2 mm in the Z_{bat} direction. The mean (±SD) of the standard deviation of each subject's ball-bat displacement at the moment of impact was 36.8 ± 6.0 mm in the X_{bat} direction and 39.6 ± 12.1 mm in the Z_{bat} direction. These values were used assess the subjects' performance in spatial perception.

3.3 BAT CONTROL TO THE INTENDED LOCATION

The mean (±SD) values for ball location at the moment of ball-bat contact in the Tee Ball Task for each subject are shown in Table 1. In the Tee Ball Task, the mean (±SD) of each subject's ball-bat distance at the moment of ball-bat contact was 27.4 ± 4.9 mm in the X_{bat} direction and 16.6 ± 1.6 mm in the Z_{bat} direction. The mean (±SD) of the standard deviation of each subject's ball-bat displacement at the moment of impact was 26.1 ± 4.9 mm in the X_{bat} direction and 17.0 ± 3.6 mm in the Z_{bat} direction. These values were used as indicators of each subject's skill in controlling the bat.

3.4 TIMING ACCURACY FOR THE INTENDED IMPACT LOCATION

In the Hitting a Pitch Task, mean and standard deviation of the distance between preferred ball location and actual ball location in the Y_{global} direction, the indicator of the timing error, were 153.3 ± 33.2 mm. The mean and standard deviation of the standard deviation of displacement of the actual ball location from the ideal ball location in the Y_{global} direction were 164.6 ± 25.1 mm.

3.5 CORRELATION WITH ACTUAL HITTING ACCURACY

There was a moderate positive correlation between each subject's standard deviation of ball-bat contact location in the X_{bat} direction in the Hitting a Pitch Task and the standard deviation of virtual ball-bat contact location in the X_{bat} direction in the Observing a Pitch Task ($r = 0.64$, $p = 0.06$). The standard deviation of virtual ball-bat contact location in the X_{bat} direction in the Observing a Pitch Task also had a significantly strong positive correlation with each subject's average distance of ball-bat contact location in the Hitting a Pitch Task ($r = 0.73$, $p < 0.05$). There was no significant correlation between the actual hitting accuracy (= performance in the Hitting a Pitch Task) and timing accuracy (= fluctuation of ball-bat contact location in the Y_{global} direction) or bat control (= performance in the Tee Ball Task).

3.6 PRECISION OF BALL=BAT CONTACT IN THREE TASKS

Standard deviation of the impact X displacement and impact Z displacement are shown in Fig 3. A two-way ANOVA indicated a significant interaction of the factors ($F_{2,16} = 22.65$, $p < 0.0001$). A post hoc paired t-test showed that the standard deviation of the impact Z displacement in the Hitting a Pitch Task and the Tee Ball Task were significantly smaller than the respective standard deviation in the impact X displacement (22.0 ± 4.3 mm vs. 41.6 ± 7.8 mm for the Hitting a Pitch Task ($p < 0.001$); 17.0 ± 3.6 mm vs. 26.1 ± 4.9 mm for the Tee Ball Task ($p < 0.01$)). Another post hoc t-test showed that the impact Z displacements in the Hitting a Pitch Task and Tee Ball Task were significantly smaller than the impact Z displacements in the Observing a Pitch Task ($p < 0.05$). Also, the impact X displacement in the Tee Ball Task was significantly smaller than the impact X displacement in the Hitting a Pitch Task and Observing a Pitch Task ($p < 0.05$).

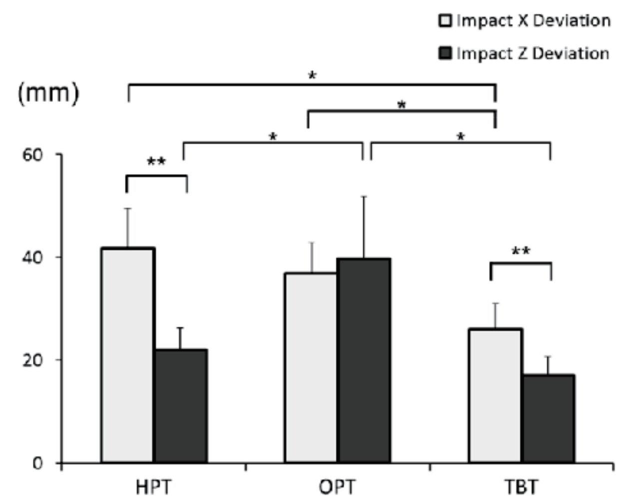

Fig 3. Standard deviation of each subject's impact displacement (mm) for three tasks: Hitting a Pitch Task (HPT), Observing a Pitch Task (OPT), and Tee Ball Task (TBT).

4. DISCUSSION

To assess hitting skill of experienced baseball batters, their performance in the three tasks was measured. The Hitting a Pitch Task was utilized to quantify their accuracy in an actual hitting situation. Timing accuracy was assessed by measuring the location of ball-bat contact in the bat-coordinate system and global-coordinate system, respectively. These parameters were utilized on the assumption that the batters' intention was to hit a ball at the sweet spot and ideal Y_{global} location in order to hit the ball far and fast. The Observing a Pitch Task was utilized to test their ability to predict the arrival location of a flying ball by pointing to the predicted location instead of swinging the bat at the intended location, which could be affected by their bat control skill. The Tee Ball Task was utilized to measure their performance to accurately hit a stationary ball. In this task, once the batters see the ball on a tee, they know exactly where to hit. Therefore, error in the location of ball-bat contact can indicate an error in their bat control. Moreover, in the Tee Ball Task, batters were asked to adjust the ball location in the Y_{global} direction because each batter's ideal impact location in the pitcher-to-catcher direction differs depending on the vertical (Z_{global}) and horizontal (X_{global}) location. The preferred ball location was utilized to measure errors in ball-bat contact location in the global-coordinate system.

4.1 PERFORMANCE IN ACTUAL HITTING ACCURACY

Eight out of nine subjects' average impact location was within the "effective impact area" — a rectangle of 25 mm height and ± 50 mm width centered around the sweet spot as defined by Adair[3]. Although the mean standard deviation of the impact X displacement and the impact Z displacement were smaller than the size of the effective impact area (41.6 mm and 22.0 mm, respectively), there were many mishits outside the effective impact area because the average impact location was skewed toward the grip end of the bat and upwards from the sweet spot. The reason for this tendency is unclear, but some possibilities will be suggested.

In this experiment, a four-seam fastball was launched from the machine. When a launched ball is spinning, in addition to the gravitational force and air drag force, the direction and rate of spin will have an influence on flight trajectory[5]. As a ball spins closer to pure backspin, and at faster rates, the lift force acting against the drop of the ball becomes greater. Although the ball backspin rate adopted in this experiment replicated a normal ball backspin rate thrown by actual pitchers [6], the spin angle might have been closer to a pure backspin than that thrown by actual pitchers. This would lead the subjects to swing under the ball.

Another possible explanation is that the fastball has the smallest amount of drop of the normally thrown pitches. If batters are trained to swing based on the average trajectory of all the various kinds of pitches, they would tend to swing under the fastball trajectory more than with other types of pitches. It is also possible that if the batters intended to hit line drives, they would need to swing 10 mm to 20 mm under the ball rather than at the center of the ball [7].

4.2 PERFORMANCE IN BAT CONTROL

Performance in the subjects' bat control was evaluated by their performance in the Tee Ball Task. Since the ball was not moving in this task, a batter with good bat control could hit the ball at the sweet spot repeatedly. The means of impact X displacement and impact Z displacement, which are indicators of the subject's performance in bat control, were 27.4 ± 4.9 mm and 16.6 ± 1.6 mm, respectively. Based on this result, when the ball was not moving, batters were able to hit the ball with less deviation from the sweet spot. Standard deviation of the impact X displacements, which indicates the precision of ball-bat contact in the X_{bat} direction, in the Tee Ball Task was significantly smaller than that in the Hitting a Pitch Task. On the other hand, there was no significant difference in the standard deviation of the impact Z displacements in the two tasks. Therefore, movement of the ball impairs the precision of ball-bat contact in the X_{bat} direction only. However, the lack of significant correlation between performance in bat control and actual hitting accuracy suggests there might be a difference in the hitting action for hitting a flying ball or tee ball. When a batter tries to hit a flying ball, their perceived affordance to hit the ball affects the execution of hitting action. Gibson defined that affordances need not to be conceived by the actor via some sort of cognitive processing, but rather can be directly perceived (8). Fajen termed "affordance-based control" as a strategy for an actor to make adjustments so that the intended action is always possible within the limits of their action capability (9). Batters swing a bat when a flying ball affords hitting. Since a pitched baseball arrives at home plate in a split second, quick decision making which utilizes affordance would be very important. The Tee Ball Task did not task any temporal constraints to the batters, and they might be using a different decision making process when they hit the ball off a tee. This would minimize the relationship between performance in the Hitting a Pitch Task and that in the Tee Ball Task.

4.3 PEFORMANCE IN SPATIAL PERCEPTION

Performance in the subjects' spatial perception was evaluated based on how accurately they could point to the location of a launched ball in the Observing a Pitch Task. As shown in Figure1.6b, average locations of each subject's virtual ball-bat contact location were dispersed widely, especially in the Z_{bat} direction. If they swung the bat to those locations, they would miss the ball in many trials. However, there was no trial where any subject swung and missed a ball in the Hitting a Pitch Task. The dispersion might be caused by the few seconds of time delay from when the ball passed the batter to when he pointed to the perceived ball location. It is also possible that there might be a gap between an individuals' perception about his predicted location of the moving ball and the location of his swung bat when he was hitting a ball. There was a significant correlation between the standard deviation of impact X displacement in the Observing a Pitch Task and the impact X displacement in the Hitting a Pitch Task. This correlation could be a reason for the significantly greater standard deviation of the subjects' impact X displacement in the Hitting a Pitch Task than that of the Tee Ball Task. Subjects with a superior performance of spatial perception in X_{bat} location had a greater precision in the actual hitting accuracy in the X_{bat} direction.

4.4 PERFORMANCE IN TIMING ACCURACY

Timing error was assessed by measuring the distance between the preferred ball-bat location and the actual ball-bat location in the Y_{global} direction. Based on the horizontal ball velocity during the 5 ms before ball-bat contact (35.8 ± 0.7 m/s) and the mean distance (15.3 mm), the average timing error from an ideal ball-bat contact location was 4.3 ms. This timing error, which was calculated based on ball speed and fluctuation of contact location in space, was close to the timing error of elite athletes in other sports such as the 2 ms to 5 ms timing error in table tennis return (10) or the 2 ms to 3 ms timing error in cricket batting (11). Interestingly, there was no correlation between timing accuracy and actual hitting accuracy. As shown in Figure 1.7, some successful ball-bat contact was made far away from the batter's preferred ball location. At the other extreme, there was also unsuccessful ball-bat contact which occurred near the preferred ball location. Therefore, whether a batter makes ball-bat contact at the batter's preferred ball location is not a good determinant of his overall hitting accuracy.

4.5 BATTER'S ABILITY IN ACCURATE HITTING

In our investigation, the performance of collegiate baseball batters with at least 9 years of experience was investigated. When they hit fastballs launched from a pitching machine, most of them were able to keep their average location of ball-bat contact within the effective impact area. Precision in the impact Z displacement when they hit launched balls was not different from when they hit balls off a baseball tee. On the other hand, precision in the impact X displacement when they hit launched balls was not different from when they observed, and then pointed to the locations of launched balls. Based on the subjects' precision in the Tee Ball Task (impact X displacement = 26.1 mm, impact Z displacement = 17.0 mm), they have sufficient skill in bat control to repeatedly hit a ball within the effective impact area. In fact, they were able to hit a ball within the bat's effective impact area (approximately 100 mm wide and 25 mm high) in about 48 % of all trials in the Tee Ball Task. However, there were larger errors in spatial perception and timing accuracy. Therefore, it was suggested that deficiencies in perceptual skill in baseball hitting might be the main reason why batters fail to hit a ball accurately. Since errors in spatial perception and timing accuracy might be interrelated, the following experiments will assume that errors in ball-bat contact with moving balls are errors in spatio-temporal perceptual skill.

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