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Differences in trunk rotation during baseball batting between skilled players and unskilled novices

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Abstract

We investigated differences in trunk rotation patterns during baseball batting in eight skilled (collegiate level) players and nine unskilled novices using high-speed video cameras. The maximum angle during the backswing, angle at bat-ball impact, and angular displacement during the forward swing were analyzed for data on upper torso, pelvis, and torso-pelvis interaction (trunk twist) angles. We also noted movement variability in these angles over 10 trials, which was calculated as the standard deviation. The timing of the maximum angle during the backswing and variability was also analyzed. Statistical analysis revealed that angular displacements in the upper torso, pelvis, and torso-pelvis interaction were significantly larger in skilled players than in unskilled novices (p < 0.001, p < 0.001, and p < 0.05, respectively). The timing of the maximum pelvis angle during the backswing was significantly later in skilled players than in unskilled novices (p < 0.05). Movement variability in angular displacement during the forward swing and timing during the backswing were significantly greater in unskilled novices than skilled players. Although many previous studies reported the importance of angular velocity in trunk rotation during baseball batting, our results indicate that angular displacement and movement variability during trunk rotation are also key components for understanding the proficiency of skilled baseball players and unskilled novices.

Keywords: hitting, swing, shoulder, hip, kinematics, biomechanics

Introduction

Before bat-ball impact, baseball batters perform several preparatory movements including shifting their body weight to the trailing (back) foot, stepping, landing, shifting their weight to the front foot, rotations of the hip and shoulders, and swing. During this sequential movement, batters utilize the kinetic chain, which transfers energy from the lower limb to the trunk, upper limb, bat, and ball. This phenomenon is often called ‘mechanical energy flow’1,2), suggesting that energy and momentum are transferred from proximal to distal through body segments in order to achieve maximum magnitude in the final segment3). The flow of mechanical energy during baseball pitching has been examined in detail4,5), indicating that mechanical energy flow to the upper torso in the energy-increasing phase of the upper torso and to the throwing arm and ball in the late-cocking phase are important for increasing the velocity of ball release. Regarding energy flow in baseball batting, trunk rotation including upper torso and pelvis movements should play an important role in transferring kinetic energy from the lower to the upper extremities. Several studies have focused on these rotational mechanics using kinematics4-9) and by recording electromyographical activity10,11).

The purpose of this study was to clarify the maximum angle during the backswing, angle at bat-ball impact, and angular displacement during the forward swing in order to obtain data on upper torso, pelvis, and torso-pelvis interaction (trunk twist) angles during baseball batting. We considered that elucidating these movements may improve understanding on performance in baseball batting, especially for junior players and beginners. Previous studies have shown that the angular velocity of trunk rotation...
is directly related to batting performance. However, to the best of our knowledge, no studies have analyzed the time course, angular displacement of motion, and movement variability in trunk rotation during batting. Es-

Based on this background, the present study attempted to answer three questions. The first was ‘How were the upper torso and pelvis twisted during batting?’ The second question was ‘When is the maximum angle of upper torso and pelvis rotation during the backswing, and how many degrees do batters rotate their upper torso and pelvis during forward swing until bat-ball impact?’ The third question was ‘How did the trunk rotational patterns of baseball batting differ between skilled and unskilled individuals?’

Methods

Subjects. Subjects were eight skilled male baseball players and nine male novices. All subjects were right-handed. Mean age, height, and mass among the skilled players were 27 ± 4 years (standard deviation: SD), 171 ± 6 cm, and 68 ± 6 kg, respectively. The mean baseball experience was 13 ± 3 (range, 9-18) years. Mean age, height, and mass among the novices were 26 ± 3 years, 174 ± 6 cm, and 71 ± 7 kg, respectively. The novice group was matched for age, height, and weight. All skilled players had collegiate level experience, and played baseball at least once a week after graduating from college. Unskilled novices were recruited in the Department of Life Sciences, Graduate School of Arts and Sciences, The University of Tokyo, and had participated in other sports, such as bodybuilding, soccer, and dancing. They had previous experience swinging a bat, but had never been taught or advised by baseball players or coaches. All participants were free of injuries at the time of data collection.

Subjects in the novice group were asked not to practice baseball batting before the experiment and not to be advised on batting by baseball players or coaches. Written informed consent was obtained from all subjects. The study was approved by the Ethics Committee for Human Research of the Graduate School of Arts and Sciences of the University of Tokyo. The experiments were conducted in accordance with the Declaration of Helsinki.

Procedure. The subjects performed 45 batting swings at an indoor facility kept at a constant 25 degrees C. The subjects had to hit a ball, which was tossed by the same experimenter, with 12 years of baseball experience, from a distance of 2 m to a typical hitting point during all recordings. The experimenter stood consistently at the same position, marked on the floor, facing the batter and tossed the ball (all on the right side since all batters were right-handed). A practice session with 5 trials was performed before the recordings for the batters to warm up and become familiar with the conditions. To avoid the effect of fatigue, we set a 5-min break after the 15th and 30th trials. All subjects used the same bat (Buw League SKY WARRIOR, Mizuno Co., Osaka, Japan, length = 84 cm; weight = 580 g; maximum diameter = 69.5 mm).

Batting movement was recorded at 200 Hz using three high-speed video cameras (HAS-200R, DITECT Co., Ltd, Tokyo, Japan). Cameras 1 and 2 were set approximately 3 m diagonally right and left of the home plate, respectively, and camera 3 was placed approximately 3 m behind the home plate to provide a rear view of the hitting movement (Fig. 1A). Each subject wore tight black shorts, socks, sneakers, and a black swimming cap during recording. Reflective markers were attached to the head and body of each subject and also to the bat (a total of 24 markers). These markers were attached to the subjects using double-sided adhesive tape prior to data collection. To clarify the trunk rotational pattern, we focused on four markers in this study: those on the right and left shoulders (acromions) and right and left hips (anterior superior iliac spines). We previously analyzed the two directions of head movement as an X-axis (from the home plate to the pitcher’s plate) and Z-axis (vertical downward) by focusing on a marker placed at Cz, which was located midway between the nasion and inion, and between the bilateral preauricular points, according to the International 10-20 System for recording electroencephalography (EEG). Data provided by the other markers were not focused on in this study because of the large amount of data obtained.

Data were digitized and analyzed using Frame Dias IV (DKH Co, Tokyo, Japan). Three-dimensional coordinates were obtained by Direct Linear Transformation (DLT). The X-axis was directed from the home plate to the pitcher’s plate, and the Z-axis indicated a vertical upward direction. The Y-axis was defined as the cross product of the X and Z axes. The upper torso angle was defined based on markers of the right and left shoulders, and calculated between the X-axis and projection of the upper torso vector in the X-Y plane. The pelvis angle was defined based on a marker of the right and left hips, and calculated between the X-axis and projection of the pelvis vector in the X-Y plane (Fig. 1B). The time period for analysis was from 800 ms (milliseconds) before to 600 ms after bat-ball impact. The timing of bat-ball impact was set as 0 ms, and periods prior to impact were shown as ‘negative’ numbers (those after bat-ball impact were given positive numbers). Positive values in the upper torso and pelvis
angles indicated counterclockwise rotations (i.e. forward swing), while negative values indicated clockwise rotations (i.e. backswing) (Fig. 1B). The values of the torso-pelvis interaction (trunk twist) angle were calculated as the upper torso angle minus the pelvis angle, as described previously (67). The mean values of the upper torso, pelvis, and torso-pelvis interaction (trunk twist) angles 600-800 ms before impact were set as the origin. The final values were the average for 10 of the 45 swings chosen at random to observe the reliability of data.

**Statistical analyses.** The maximum angle during the backswing was defined as the most negative angle from the origin during the backswing. The angle at bat-ball impact was needed not only to show the value when the bat and ball contacted, but also to calculate angular displacement during the forward swing. Each value was shown for upper torso, pelvis, and torso-pelvis interaction (trunk twist) angles, and these data were separately subjected to analyses of variance (ANOVAs) to compare the differences between the groups (skilled players vs. unskilled novices). Movement variability in these angles, calculated as the standard deviation (SD), was also analyzed by ANOVA. These analyses were necessary to answer questions such as ‘How the upper torso and pelvis were twisted during batting?’, ‘How many degrees batters rotate their upper torso and pelvis during the forward swing until bat-ball impact?’, and ‘How the trunk rotational patterns of baseball batting differed between skilled and unskilled individuals?’.

The timings for the maximum upper torso, pelvis, and torso-pelvis interaction (trunk twist) angles during the backswing were separately subjected to ANOVA to compare differences between the groups. This analysis was needed to clarify when the maximum angle of the upper torso and pelvis rotation during the backswing was. Movement variability in the times obtained was also analyzed. Intraclass correlation coefficients (ICCs) were calculated to show the reliability of the maximum angle during the backswing, angle at bat-ball impact, and angular displacement during the forward swing in regard to the upper torso, pelvis, and torso-pelvis interaction (trunk twist) angles. ICCs were also calculated to demonstrate the reliability of timings for the maximum angles of the upper torso, pelvis, and torso-pelvis interaction (trunk twist) during the backswing. As supplementary data, we calculated the peak angular velocities and movement variability in the upper torso and pelvis among skilled players and unskilled novices. The timings for peak angular velocity and variability were also analyzed. The significance level was set at P < .05.

**Results**

Figs. 2, 3, and 4 show the time courses of changes in the upper torso, pelvis, and torso-pelvis interaction angles in skilled players, while Figs. 5, 6, and 7 show them in unskilled novices.

The maximum angle during the backswing was -13.0° at the upper torso, -7.4° at the pelvis, and -35.1° at the torso-pelvis interaction in skilled players, and -14.6° at the upper torso, -4.1° at the pelvis, and -33.5° at the torso-pelvis interaction in unskilled novices. ICCs for the upper torso, pelvis and torso-pelvis interaction angles were 0.944 (95% CI = 0.863-0.988), 0.878 (CI = 0.728-0.973), and 0.865 (CI = 0.717-0.965), respectively, in skilled players, and 0.878 (CI = 0.750-0.965), 0.531 (CI = 0.298-0.819), and 0.847 (CI = 0.697-0.955) respectively, in unskilled novices. No significant differences were observed in these values between the groups.
The angle at bat-ball impact was 113.0° at the upper torso, 92.2° at the pelvis, and 5.4° at the torso-pelvis interaction in skilled players, and 65.0° at the upper torso, 56.9° at the pelvis, and -2.7° at the torso-pelvis interaction in unskilled novices. ICCs for the upper torso, pelvis and torso-pelvis interaction angles were 0.664 (CI = 0.410-0.911), 0.825 (CI = 0.635-0.960), and 0.637 (CI = 0.394-0.886), respectively, in skilled players, and 0.484 (CI = 0.255-0.792), 0.686 (CI = 0.465-0.894), and 0.615 (CI = 0.384-0.863), respectively, in unskilled novices. Significant differences in the upper torso (F (1, 15) = 61.019, P < .001) and pelvis (F (1, 15) = 28.525, P < .001) were observed between groups.

Angular displacement during the forward swing was 126.1° at the upper torso, 99.6° at the pelvis, and 40.5° at the torso-pelvis interaction in skilled players. ICCs for the upper torso, pelvis and torso-pelvis interaction angles were 0.309 (CI = 0.098-0.723), 0.779 (CI = 0.562-0.947), and...
0.615 (CI = 0.370-0.876), respectively, in skilled players,
and 0.641 (CI = 0.412-0.875), 0.695 (CI = 0.477-0.898),
and 0.789 (CI = 0.604-0.935), respectively, in unskilled
novices. Significant differences were observed in the up-
per torso (F (1, 15) = 55.929, P < .001), pelvis (F (1, 15)
= 37.430, P < .001), and torso-pelvis interaction (F (1, 15)
= 4.998, P < .05) between groups.

Movement variability in the maximum angle during the
backswing was 2.1° at the upper torso, 2.0° at the pelvis,
and 3.7° at the torso-pelvis interaction in skilled players,
and 3.8° at the upper torso, 2.2° at the pelvis, and 4.5°
at the torso-pelvis interaction in unskilled novices. No
significant differences were observed in these values be-
tween groups. Movement variability in the angle at bat-
ball impact was 2.1° at the upper torso, 4.9° at the pelvis,
and 4.2° at the torso-pelvis interaction in skilled players,

Fig. 4 The time course of the trunk twist angle in skilled players.

Fig. 5 The time course of the upper torso angle in unskilled
novices.
and 10.9° at the upper torso, 9.3° at the pelvis, and 6.5° at the torso-pelvis interaction in unskilled novices. A significant difference was observed in the pelvis (F (1, 15) = 8.345, P < .05) between groups. Movement variability in angular displacement during the forward swing was 6.4° at the upper torso, 4.5° at the pelvis, and 4.9° at the torso-pelvis interaction in skilled players, and 10.3° at the upper torso, 9.5° at the pelvis, and 4.9° at the torso-pelvis interaction in unskilled novices. A significant difference was observed in the pelvis (F (1, 15) = 8.965, P < .01) between groups.

Data on values and variability at each angle are listed in
The timing of the maximum angle during the backswing was -313 ms at the upper torso, -392 ms at the pelvis, and -139 ms at the torso-pelvis interaction in skilled players, and -318 ms at the upper torso, -518 ms at the pelvis, and -168 ms at the torso-pelvis interaction in unskilled novices. ICCs for the timing of the upper torso, pelvis and torso-pelvis interaction were 0.586 (CI = 0.324-0.881), 0.493 (CI = 0.236-0.839), and 0.381 (CI = 0.160-0.746), respectively, in skilled players, and 0.400 (CI = 0.185-0.736), 0.670 (CI = 0.447-0.888), and 0.199 (CI = 0.046-0.547), respectively, in unskilled novices. The timing of the maximum angle during the backswing at the pelvis angle was significantly shorter in skilled players than in unskilled novices (F (1, 15) = 4.803, P < .05). In addition, paired t-tests were performed to compare differences in the timing of the maximum angle during the backswing between the upper torso and pelvis angles. The timing was significantly later in the upper torso angle than in the pelvis angle in both skilled players (t (7) = 3.716, P < .01) and unskilled novices (t (8) = 7.577, P < .001). Variability in the timing of the maximum angle during the backswing was 29 ms at the upper torso, 67 ms at the pelvis, and 25 ms at the torso-pelvis interaction in skilled players, and 67 ms at the upper torso, 90 ms at the pelvis, and 38 ms at the torso-pelvis interaction in unskilled novices. A significant difference was observed in the upper torso (F (1, 15) = 5.941, P < .05) between groups.

Data on values and variability for each timing are listed in Table 2.

Peak angular velocity was 984°/s at the upper torso and 608°/s at the pelvis in skilled players, and 587°/s at the upper torso and 313°/s at the pelvis in unskilled novices. Significant differences were observed in the upper torso (F (1, 15) = 91.698, P < .001) and pelvis (F (1, 15) = 92.197, P < .001) between groups. Movement variability in peak angular velocity was 51°/s at the upper torso and 36°/s at the pelvis in skilled players, and 53°/s at the upper torso and 43°/s at the pelvis in unskilled novices. No significant differences were observed in these values between groups. The timing of peak angular velocity was -71 ms at the upper torso and -90 ms at the pelvis in skilled players, and -33 ms at the upper torso and -85 ms at the pelvis in unskilled novices. No significant differences were found in these values between groups. Variability in the timing of peak angular velocity was 7 ms at the upper torso and 7 ms at the pelvis in skilled players, and 8 ms at the upper torso and 8 ms at the pelvis in unskilled novices.

### Table 1. Mean values and variabilities in angles for the upper torso, pelvis, and torso-pelvis interaction

<table>
<thead>
<tr>
<th>(°)</th>
<th>Upper Torso</th>
<th>Pelvis</th>
<th>Torso-Pelvis interaction</th>
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<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Variability</td>
<td>Value</td>
</tr>
<tr>
<td>Maximum angle during the backswing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skilled player</td>
<td>-13.0 (9.7)</td>
<td>2.1 (0.8)</td>
<td>-7.4 (5.7)</td>
</tr>
<tr>
<td>Unskilled novice</td>
<td>-14.6 (11.5)</td>
<td>3.8 (2.1)</td>
<td>-4.1 (3.1)</td>
</tr>
</tbody>
</table>

| Angle at bat-ball impact |   | | | | | |
| Skilled player | 113.0 (11.9) *** | 6.8 (4.6) | 92.2 (11.7) *** | 4.9 (1.8) * | 5.4 (6.7) | 4.2 (2.7) |
| Unskilled novice | 65.0 (13.3) | 10.9 (7.6) | 56.9 (15.1) | 9.3 (3.9) | -2.7 (9.0) | 6.5 (2.4) |

| Angular displacement during the forwardswing |   | | | | | |
| Skilled player | 126.1 (5.2) *** | 6.4 (3.9) | 99.6 (8.7) *** | 4.5 (1.4) ** | 40.5 (7.0) * | 4.9 (2.5) |
| Unskilled novice | 79.5 (16.9) | 10.3 (7.1) | 61.0 (16.0) | 9.5 (4.5) | 30.8 (10.2) | 4.9 (1.9) |

Data are expressed as means (standard deviations). Significant differences between skilled players and unskilled novices are shown as asterisks; * p < 0.05; ** p < 0.01; *** p < 0.001.

### Table 2. Mean timing of the maximum angle during the backswing and variability in the timing

<table>
<thead>
<tr>
<th>(ms)</th>
<th>Upper Torso</th>
<th>Pelvis</th>
<th>Torso-Pelvis interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Variability</td>
<td>Value</td>
</tr>
<tr>
<td>Skilled player</td>
<td>-313 (85)</td>
<td>29 (13) *</td>
<td>-392 (92) *</td>
</tr>
<tr>
<td>Unskilled novice</td>
<td>-318 (68)</td>
<td>67 (42)</td>
<td>-518 (138)</td>
</tr>
</tbody>
</table>

Data are expressed as means (standard deviations). Significant differences between skilled players and unskilled novices are shown as asterisks; * p < 0.05
16 ms at the pelvis in skilled players, and 62 ms at the upper torso and 60 ms at the pelvis in unskilled novices. A significant difference was observed in the upper torso (F(1, 15) = 9.298, P < .01) and pelvis (F(1, 15) = 7.200, P < .05) between groups.

Data on values and variability for each peak angular velocity and timing are listed in Table 3.

**Discussion**

The present study investigated the pattern of trunk rotation including the upper torso, pelvis, and torso-pelvis interaction (trunk twist) during baseball batting in skilled players and unskilled novices. Analyses of movement patterns in baseball batting are necessary to apply results to actual training, and numerical expression is important to assess these movements.

We showed that the timing for the maximum angle of the backswing was observed at -313 ms in the upper torso angle and at -392 ms in the pelvis angle among the skilled players, and -318 ms in the upper torso angle and at -518 ms in the pelvis angle among the unskilled novices (Table 2). The difference in the timing of the pelvis angle between the skilled players and unskilled novices was significant. Although it was very difficult to interpret this difference, we hypothesized an effective and optimal kinetic chain for transferring energy from the lower limbs to the upper limbs in skilled players. As described in the Introduction, the kinetic chain principle asserts that in coordinated human motion, energy and momentum are transferred through sequential body segments to achieve maximum magnitude in the terminal segment. Shimada and colleagues described mechanical energy flow during baseball pitching, and showed that energy peaked in the upper torso 100–150 ms and in the lower torso 150–200 ms before ball release. In addition, they demonstrated sequential energy peaks in the upper arm, forearm, hand, and ball within 100 ms before the ball was released. Taking these results into consideration, it is likely that an effective and optimal kinetic chain transferred energy from the pelvis to the upper torso within 100 ms.

The angular displacement during the forward swing was 126° in the upper torso, and 100° in the pelvis (Tables 1 and 2). Welch and colleagues reported the angle of upper torso rotation as 30° in a clockwise direction (backswing) at the stepping phase and as 66° in a counterclockwise direction (forward swing) at bat-ball contact. They also showed the angle of pelvis rotation as 18° in a clockwise direction at stepping phase and as 83° in a counterclockwise direction at bat-ball contact. Based on these values, it is likely that 96° in the upper torso angle and 101° in the pelvis angle rotated during batting in total. Angular displacement differed in the upper torso between the findings of Welch and colleagues and our results (i.e. 96° vs. 126°), while it was very similar in the pelvis (i.e. 101° vs. 100°). We considered two possible explanations. The first was the experimental setting of batting. Welch and colleagues used a batting tee, which was placed in the hitting area. The tee was adjusted to the subject’s preferred position and hitting height. On the other hand, in the present study, subjects had to hit a ball, that was thrown by the same experimenter from a distance of 2 m to a typical hitting point. The second was the skill level. Welch and colleagues recorded data from professional baseball players in the USA, while the skilled players in the present study had collegiate level experience in Japan. A previous study reported differences in the kinematics of the baseball swing between batters of various skill levels. Therefore, differences in the setting and/or skill level may be related to angular displacement in the upper torso, even among skilled players. Further research is needed to clarify this.

Our second objective was to clarify how the upper torso and pelvis were twisted during batting. In the skilled players, the mean timing for the maximum angle of the backswing was found at -139 ms in the torso-pelvis inter-
action (trunk twist) angle; and the angular displacement during the forward swing was 40° (Table 3). Escamilla and colleagues\(^6\) showed the torso-pelvis interaction angle as 14° in a clockwise direction (backswing) at the landing phase and as 23° in a counterclockwise direction (forward swing) at bat-ball contact in adult batters. By calculating these values, at least 37° in the torso-pelvis interaction angle rotated during the batting, which was similar to our findings. However, they did not show the timing for the maximum angle of the backswing. Therefore, this is the first study to show these results. As described, since the timing for the maximum angle of the backswing was observed at -313 ms in the upper torso angle and at -392 ms in the pelvis angle among the skilled players, the timing for the maximum angle of the backswing in the trunk twist (i.e. -139 ms) occurred after the backswing motion. The angle of the trunk twist peaked during the forward swing, indicating that the importance of trunk twist during baseball batting may be associated with the forward swing rather than the backswing.

Our third aim was to examine how trunk rotational patterns of baseball batting differed between skilled and unskilled individuals. We found four marked differences. First, the angular displacements in upper torso and pelvis rotations were significantly different between skilled players and unskilled novices (Table 1, Figs. 2, 3, 5, and 6). The skilled players rotated the trunk including the upper torso and pelvis more than unskilled novices. Previous studies have reported that trunk rotational velocity differed with the playing level\(^6\)\(^,\)\(^9\), which was consistent with our results (Table 3). These findings suggested the importance of trunk rotational velocity in improving batting performance. Our results also indicate that angular displacement and angular velocity during trunk rotation are key components in producing force for a powerful swing.

Second, angular displacement for torso-pelvis interaction was significantly larger in the skilled players (Table 1, Figs. 4 and 7). Both skilled players and unskilled novices rotated the upper torso with greater angular displacement than the pelvis during batting; however, the ratio between angular displacements of the upper torso and pelvis was different between skilled players and unskilled novices. As described above, angular displacement for the upper torso and pelvis should be increased to improve batting performance in unskilled novices. Based on the results of angular displacement for torso-pelvis interaction, unskilled novices should also try to rotate their upper torso when training.

Third, the timing for the maximum pelvis angle during the backswing was significantly earlier in unskilled novices than in skilled novices (Table 2, Figs. 3 and 6). With regard to the kinetic chain from pelvis rotation to upper torso rotation, the difference in peak timing between pelvis and upper torso angles was 79 ms in skilled players and 200 ms in unskilled players. It is difficult to explain the difference in these values; however, we assumed that unskilled players did not effectively transfer kinetic energy from the lower to the upper extremities. Our previous study may support this notion\(^3\). We showed sequential motions in the right-handed skilled players; shifting body weight to the right foot, stepping forward with their left foot, shifting their body weight to the left foot, and swing. In contrast, the unskilled novices did not sufficiently shift their weight to the right foot before stepping with their left foot, and started the swing prior to starting the landing.

Fourth, variability in peak timing at the upper torso angle was significantly greater in unskilled novices than in skilled players (Table 2). In addition, variability in angular displacement at the pelvis angle was significantly greater in unskilled novices than in skilled players (Table 1). Taking these results into consideration, baseball players reduced movement variability in the trained batting, which suggested a stable swing with temporal and spatial accuracy.

As a limitation of this study, data on the pattern of trunk rotation may have been affected by the ball being thrown by an experimenter. Therefore, the difference in the impact point among trials may have affected the results obtained. However, in order to reduce this factor in the present study, the same experimenter with 12 years of baseball experience tossed the ball to all subjects in all trials from a distance of 2 m to a typical hitting point during all recordings. The experimenter stood consistently at the same position that was marked on the floor, and then faced the batter and threw the ball. We also showed data by averaging 10 trials for each batter, matched at the time of bat-ball impact. Previous studies used a similar method, and the batters hit a ball thrown by a pitcher or a pitching machine\(^5\)\(^,\)\(^7\)\(^,\)\(^8\)\(^,\)\(^14\). We followed these methods.

In addition, basic muscle power may have affected batting performance, and could have contributed to the difference observed in the pattern of trunk rotation including the upper torso, pelvis, and torso-pelvis interaction between skilled players and unskilled novices. Basic muscle power was more likely to be smaller in unskilled novices than in skilled players. Since we did not record basic muscle power in the upper and lower limbs or trunk for any subject in this experiment, we were only able to assume this possibility. However, as described in the Methods section, the unskilled novices recruited in this study had taken part in other sports. For example, unskilled novices included a champion of a bodybuilding university contest in Japan. Therefore, we considered muscle recruitment in the whole body to be important for producing the high performance required by baseball batting. In our previous study, we compared differences in the peak amplitudes of surface electromyography (EMG) in the lower limbs between skilled players and unskilled novices. Muscle activity, which was defined as % maximum voluntary contraction (MVC), was greater in skilled players at the right rectus femoris, bilateral biceps femoris, left tibialis...
anterior, and bilateral medial gastrocnemius\textsuperscript{13}, suggesting that skilled players effectively recruited muscles during batting. Based on these findings, we hypothesized more effective muscle recruitment related to trunk rotation in skilled players than in unskilled novices. Furthermore, based on the results of peak angle velocity for the upper torso and pelvis (Table 3), the speed-accuracy trade-off may be related to the lower speed of trunk rotation and/or muscle power in unskilled novices. The speed-accuracy trade-off is a well-known phenomenon in motor behavior, meaning that when performers attempt to do something more quickly, they typically do it less accurately\textsuperscript{15,16}. In our experiment, if unskilled novices attempted to increase the speed of trunk rotation and/or muscle power during batting, movement variability for trunk rotation could increase and the accuracy of bat-ball contact could decrease. Therefore, unskilled novices may withhold swing speed to maintain the accuracy of bat-ball contact.

Our findings should help junior players, beginners, coaches, and trainers to understand the trunk rotational pattern during baseball batting, and help teach trunk rotation to junior players and novices. Junior players and novices need to develop a better swing technique so that they can attain a more optimal trunk rotational pattern and potentially become more successful hitters. As the first step, it may be important to emphasize the larger angle displacement of trunk rotational movement including the upper torso and pelvis, as well as the higher trunk rotational velocity, for junior players and novices to increase the linear and angular momentum for bat-ball impact in the kinetic chain. As the next step, since this study showed a clear difference between skilled players and unskilled novices in how the trunk twist was used, coaches should focus on rotation of the upper torso. Based on the speed-accuracy trade-off theory, it may be beneficial for junior players and novices to carry out batting practice separately to improve speed and accuracy.

In a future study, we intend to focus on the factors contributing to swinging speed and batting performance among skilled players. Comparison of the batting performance of skilled players and unskilled novices may be important for developing a better swing technique for junior players and novices. However, this is one of the methods to show the batting mechanism. We will also analyze all markers, including those on the trunk, upper and lower limbs, head, and bat, to clarify the key factors for batting performance among skilled players.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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