

A COMPARISON OF AGE LEVEL ON BASEBALL HITTING KINEMATICS

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Running Header: Baseball Hitting Kinematics

Keywords: batting, swing, biomechanics, youth, adult, mechanics

Submission Date: July 6, 2007

1st Revision Date: December 14, 2007

2nd Revision Date: February 1, 2008

3rd Revision Date: July 20, 2008

4th Revision Date: October 22, 2008

Journal of Applied Biomechanics

Manuscript ID: JAB-2007-0125-R2

Word Count: 6288

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ABSTRACT

We propose that learning proper hitting kinematics should be encouraged at a young age during youth baseball, as this may help reinforce proper hitting kinematics as a player progresses to higher levels of baseball in their adult years. To enhance our understanding between youth and adult baseball hitting, kinematic and temporal analyses of baseball hitting were evaluated with a high speed motion analysis system between 12 skilled youth and 12 skilled adult baseball players. There were only a small number of temporal differences between youth and adult hitters, with adult hitters taking significantly greater time than youth hitters during the stride phase and during the swing. Compared with youth hitters, adult hitters a) had significantly greater ($p < 0.01$) lead knee flexion when the hands started to move forward; b) flexed the lead knee over a greater range of motion during the transition phase (31° versus 13°); c) extended the lead knee over a greater range of motion during the bat acceleration phase (59° versus 32°); d) maintained a more open pelvis position at lead foot off ground; and e) maintained a more open upper torso position when the hands started to move forward and a more closed upper torso position at bat-ball contact. Moreover, adult hitters had greater peak upper torso angular velocity ($857^\circ/\text{s}$ versus $717^\circ/\text{s}$), peak left elbow extension angular velocity ($752^\circ/\text{s}$ versus $598^\circ/\text{s}$), peak left knee extension angular velocity ($386^\circ/\text{s}$ versus $303^\circ/\text{s}$), and bat linear velocity at bat-ball contact (30 m/s versus 25 m/s). The numerous differences in kinematic and temporal parameters between youth and adult hitters suggest that hitting mechanics are different between these two groups.

INTRODUCTION

Arguably, hitting a baseball is one of the most difficult skills in sport to learn (DeRenne, 2007;). Although there are numerous papers in the literature describing qualitative analyses of baseball hitting (DeRenne, 2007; Garhammer, 1983; Lefebvre, 1983), there is a paucity of papers that have quantified baseball hitting mechanics (kinematic and temporal parameters). Race (1961) was the first to examine the cinematographic and mechanical analysis in the baseball swing, quantifying in professional adult hitters both linear and angular displacements and velocities of the bat, and select upper extremity and trunk parameters. In addition, McIntyre and Pfautsch (1982) also described kinematic analyses of the baseball swing, quantifying in adult hitters both linear and angular displacements and velocities of the bat and select upper extremity variables. Messier and Owen (1985; 1986) quantified select lower extremity kinematics and ground reaction forces in batting during women's intercollegiate fast-pitch softball. More recently, Welch *et al.* (1995) provided a more thorough quantitative description of baseball hitting kinematics by quantifying linear and angular displacements and velocities of the bat, upper extremity, lower extremity, and trunk in professional baseball hitters. Although this was the first known study to analyze the kinematics of the entire body during the baseball swing, this study lacked specificity as the ball was hit off a tee rather than being pitched to the hitter.

There are currently no studies that have quantified baseball hitting kinematics in youth hitters. Learning proper hitting kinematics in youth baseball may help reinforce proper hitting kinematics as a hitter progresses to higher levels of baseball in their adult

years. Furthermore, the majority of youth baseball coaches are volunteer parent-coaches lacking coaching education on hitting (DeRenne *et al.*, 2008; DeRenne, 2007). The top five national baseball youth organizations (Little League, Pony League, Babe Ruth, Cal Ripken, and American Legion) in player participation do not require or provide these parent-coaches with formal coaching education seminars, workshops, or certification programs on hitting for their baseball coaches (DeRenne *et al.*, 2008; DeRenne, 2007). Additionally, there is a paucity of youth-specific baseball information on hitting (DeRenne *et al.*, 2008; DeRenne, 2007). Therefore, because hitting is one of the most difficult skills to perform in all of sport (DeRenne *et al.*, 2008; DeRenne, 2007); Race, 1961), and because youth parent-coaches lack coaching education on hitting and the means to obtain it, the scientific community must begin the process of quantifying hitting mechanics in youth so this information can be summarized for the layman, such as youth baseball coaches. Therefore, the purpose of this study was to quantify and compare baseball hitting mechanics between youth baseball players (12-17 years old) and adult baseball players (college and professional players 20-26 years old). We hypothesize that linear and angular velocity parameters will be significantly greater in adult hitters compared with youth hitters while angular displacement parameters will be similar between youth and adult hitters, as this pattern has been demonstrated in youth and adult baseball pitchers (Fleisig *et al.*, 1999).

METHODS

Data Collection:

Twenty-four subjects participated in this study. Twelve subjects were youth right-handed hitters playing youth league baseball, while the remaining 12 subjects were

adult right-handed hitters playing college (six subjects) and professional (six subjects) baseball. Age, body mass, body height, and bat characteristics (bats were self-selected by subjects) are shown in Table 1. Compared with youth hitters, adult hitters were older, heavier, taller, and used a heavier and longer bat. All youth hitters were all-star hitters in youth league with batting averages above 0.300, which according to youth baseball standards classified them as “good” or “skilled” hitters (DeRenne *et al.*, 2008; DeRenne, 2007; Race, 1961). All adult hitters also had batting averages above 0.300, which according to college and professional baseball standards classified them as “good” or “skilled” hitters (DeRenne *et al.*, 2008; DeRenne, 2007; Race, 1961). Institutional approval of the protocol and informed consent were obtained prior to data collection.

Two synchronized gen-locked 120 Hz video cameras (Peak Performance Technologies, Inc., Englewood, CO) were optimally positioned to view the hitter. Each camera’s optical axis formed approximately a 45° angle to the sagittal plane of the hitter. The cameras were positioned approximately 12 m apart and perpendicular to each other, with each camera approximately 8 m from the hitter. To minimize the effects of digitizing error, the cameras were positioned so the hitter was as large as possible within the viewing area of the cameras.

Each youth and adult hitter completed 10-15 hard, full effort swings with a normal grip (hands as far down as possible on the bat) as a pitching machine “pitched” balls to them during their normal batting practice. All pitches were between 32.6-33.5 m/s (73-75 mi/h) for adult hitters and 28.2-29.1 m/s (63-65 mi/h) for youth hitters, based on age appropriate velocities of normal batting practice for youth and adult hitters (DeRenne *et*

al., 2008; DeRenne, 2007; Race, 1961). In addition, the distance from the pitching machine to home plate was approximately 13.7 m (45 ft), which is a common distance for youth and adult batting practice (DeRenne *et al.*, 2008; DeRenne, 2007; Race, 1961). Ball velocity was recorded from a Jugs Tribar Sport radar gun (Jugs Pitching Machine Company, Tualatin, OR) as the ball left the pitching machine. The radar gun was calibrated prior to a testing session, and was accurate within ± 0.22 m/s.

An event synchronization device (Peak Performance Technologies, Inc., Englewood, CO) was employed to generate a time code directly onto the video signals, thereby allowing corresponding time-synchronized video frames between the two videotapes to be determined. Prior to and just after the subjects were videotaped, a 2 x 1.5 x 1 m 3-D calibration frame (Peak Performance Technologies, Inc., Englewood, CO), surveyed with a measurement tolerance of 0.5 cm, was positioned and videotaped in the same volume occupied by the hitter. The calibration frame was comprised of 24 spherical balls of known spatial coordinates.

Data Analysis:

A 3-D video system (Peak Performance Technologies, Inc., Englewood, CO) was used to manually digitize data for all subjects. A spatial model was created, comprised of the top of the head, centers of the left and right mid-toes (at approximately the head of the third metatarsal), joint centers of the ankles, knees, hips, shoulders, and elbows, mid-point of hands (at approximately the head of the third metacarpal), and proximal and distal end of bat. All points were seen in each camera view. Each of these points was digitized in every video field. Four swings were digitized for each subject.

Digitizing began 5 frames prior to when the front foot left the ground (first event) and ended 5 frames after bat-ball contact.

Pitches and swings were standardized according to the following criteria: 1) For a trial to be used the pitch had to be a strike on the inner half of the plate from waist to letter high on the subject; 2) all swings digitized and used as trials had to be a line drive hit to left-center outfield that carried in flight beyond a 68.6 m (225 feet) marker positioned in left-center field. This distance was chosen based on reports that youth and adults that can hit line drives this distance have a good mechanical swing (DeRenne *et al.*, 2008; DeRenne, 2007; Race, 1961).

The swing was defined by four events and three phases. The first event was “lead foot off ground” (first frame in which the lead foot was no longer in contact with the ground, which represented the beginning of the stride phase). The next event was “lead foot contact with ground” (first frame when the lead foot made contact with the ground, which represented the end of the stride phase). “Lead foot off ground” to “lead foot contact with ground” represented the time duration of the stride phase of the swing. The third event was “hands started to move forward” (the first frame that both hands started to move forward towards the pitcher in the positive X direction from Figure 1). “Lead foot contact with ground” to “hands started to move forward” represented the time duration of the transition phase of the swing. The last event was “bat-ball contact”, which was defined as the first frame immediately before bat-ball contact. We chose this frame to represent bat-ball contact because not all trials involved a frame that captured the exact moment of bat-ball contact. For example, one video frame might capture immediately prior to bat-ball contact, while in the subsequent frame the ball may be

preparing to leave the bat. We also used this convention because bat linear velocity would be slower after bat-ball contact compared with just before bat-ball contact. Moreover, bat linear velocity after bat-ball contact would be affected differently between youth and adult hitters due to the effects of the impulse of bat-ball impact.

“Hands started to move forward” to “bat-ball contact” represented the time duration of the bat acceleration phase of the swing. Therefore, the swing was defined as from “lead foot off ground” to “bat-ball contact”, and consisted of stride, transition, and bat acceleration phases.

A fourth-order, zero lag Butterworth digital filter was used to smooth the raw data for each of the digitized points, using cutoff frequencies between 6-12 Hz depending on the marker being smoothed and the instant in time during the swing that each data point was smoothed. To smooth data at bat-ball contact and beyond, data were cut at a frame just prior to bat-ball contact and a mathematical procedure was used to pad the data from that point on. We did not analyze kinematic data after bat-ball contact. Using the direct linear transformation method (Shapiro, 1978; Wood and Marshall, 1986), 3-D coordinate data were derived from the 2-D digitized images from each camera view. An average resultant mean square calibration error of 0.3 cm produced an average volume error of 0.1%. The origin of the global 3-D orthogonal axis system was centered at home plate with the positive X-axis pointing towards the pitching machine, which was positioned on a line from the home plate to the pitching rubber. The positive Z-axis pointed down in the vertical direction, and the positive Y-axis pointed orthogonal to the X-axis and Z-axis.

Linear and angular displacements and velocities were calculated for both the left and right sides of the body, using software from Peak Performance Technologies (Peak Performance Technologies, Inc., Englewood, CO). Stride length was determined as the distance between the right and left ankles. Knee and elbow flexion angles were defined as 0° when full extension was achieved. The pelvis was defined as a vector pointing from the right hip to the left hip, while the upper torso was defined as a vector pointing from the right shoulder to the left shoulder (Figure 1). Pelvis rotation was defined as the angle between the X-axis and the projection of the pelvis vector in the X-Y plane, while upper torso rotation was defined as the angle between the X-axis and the projection of the upper torso vector in the X-Y plane. The pelvis and upper torso rotated about a trunk axis defined from the mid-point of the left and right hips to the mid-point of the left and right shoulders. Pelvis and upper torso angles were defined as 0° when the pelvis and upper torso vectors were pointing in the direction of the X-axis (Figure 1), positive values occurred with counterclockwise rotations (as illustrated in Figure 1), and negative values occurred with clockwise rotations, as viewed from above. As pelvis and upper torso angles became less positive or more negative, the pelvis and upper torso assumed a more “closed” position, while as pelvis and upper torso angles became more positive, the pelvis and upper torso assumed a more “open” position. Both the upper torso and pelvis assumed an “open” position at ball contact, as shown in Figure 1. Angular velocity of the pelvis was calculated as the cross product of a vector joining the two hips and the derivative of this vector, while angular velocity of the upper torso was calculated as the cross product of a vector joining the two shoulders and the derivative of this vector (Feltner and Dapena, 1989).

Kinematic and temporal data were averaged for the four swings, and these averaged data were used in statistical analyses. Kinematic and temporal data between the four swings for each subject were remarkably similar, typically varying only 5-10% between swings. Multivariate analysis of variance (MANOVA) procedures were performed with dependent variables grouped as follows: 1) temporal parameters; 2) right elbow angle kinematics; 3) left elbow angle kinematics; 4) right knee angle kinematics; 5) left knee angle kinematics; 6) upper torso angle kinematics; 7) pelvis angle kinematics; and 8) linear and angular velocity kinematics. To minimize the probability of making a type I error (due to multiple comparisons) without increasing the probability of making a type II error, the level of significance was set at $p < 0.01$.

RESULTS

Temporal parameters during the swing are shown in Table 2. Compared with youth hitters, adult hitters took significantly greater time during the stride phase and during the swing. There were no other temporal differences between youth and adult hitters.

Upper and lower extremity angular displacement parameters are shown in Table 3. Compared with youth hitters, adult hitters flexed the lead (left) knee significantly more when the hands started to move forward. As a result, adult hitters flexed the lead knee over a greater range of motion during the transition phase (31° versus 13°) and extended the lead knee over a greater range of motion during the bat acceleration phase (59° versus 32°).

Upper torso and pelvis angular displacement parameters are shown in Table 4. Compared with youth hitters, adult hitters maintained a more open pelvis position at

lead foot off ground. In addition, adult hitters maintained a more open upper torso position when the hands started to move forward and a more closed upper torso position at bat-ball contact. There were no significant differences in trunk twist angle (upper torso angle minus pelvis angle) throughout the swing.

Peak angular velocity parameters are shown in Table 5. Compared with youth hitters, peak upper torso angular velocity in adult hitters was significantly greater and occurred significantly later in the bat acceleration phase. Moreover, compared with youth hitters, peak left elbow extension angular velocity and peak left knee extension angular velocity was significantly greater in adult hitters during the bat acceleration phase.

Linear displacement and velocity parameters are shown in Table 6. Compared with youth hitters, bat linear velocity at bat-ball contact was significantly greater in adult hitters. There was no significant difference in stride length between youth and adult hitters.

DISCUSSION

It is not surprising that significant differences were found between adult and youth hitters, considering that adult hitters were on the average 7.5 years older, 35-40% heavier, 5% taller, and used bats that were 15% heavier and 5% longer. It is likely that maturation from youth to adulthood may have resulted in some of these significant differences as bigger and stronger adult hitters were able to generate greater angular velocities and bat speed compared with youth hitters. It is interesting that both the adult and youth hitters spent approximately the same amount of time in the transition and bat acceleration phases, but the adult hitters spent approximately 40% greater time in the

stride phase (Table 2). Welch *et al.* (1995) reported nearly identical stride phase times for adult hitters as the current study (approximately 0.40 s), but slightly less time in the transition and bat acceleration phases - 0.18 s reported in Welch *et al.* (1995) versus 0.21 s in the current study. It is important to emphasize that the hitters in Welch *et al.* (1995) hit the ball off a stationary tee instead of from hitting a ball moving towards them as in the current study, which may affect the timing of the swing between the two studies.

The longer stride phase time for adult hitters compared with youth hitters implies that adult hitters take more time “loading up” in preparation for the swing phase. This “loading up” phase is important in generating energy in the lower extremities and trunk that can be subsequently transferred up the kinetic chain to the upper extremities and bat (Messier and Owen, 1985; Messier and Owen, 1986; Milbum, 1982).

The relative similarity in most linear and angular displacement parameters (stride length and elbow, knee, upper torso, and pelvis angles) between skilled youth and adult hitters implies that hitting mechanics are similar in many aspects of hitting among age levels, although they are different in other aspects as observed by several significant differences in linear and angular velocities found in the current study. This observation is important because it provides the proper hitting mechanics information to youth coaches of different age groups and ability levels, as youth coaches are parent volunteers without any means to obtain coaching education information from their respective national baseball organizations (DeRenne *et al.*, 2008).

Kinematic similarities between skilled youth and adult levels have also been demonstrated in baseball pitching (Fleisig *et al.*, 1999). Fleisig *et al.* (1999)

demonstrated that most linear and angular displacement parameters in baseball pitching were not significantly different between skilled youth and skilled adult pitchers, which are similar to the findings in the current study between skilled youth and adult hitters. In contrast, Fleisig *et al.* (1999) demonstrated that most linear and angular velocity parameters in baseball pitching were significantly different between skilled youth and adult pitchers, which are also similar to the findings in the current study between skilled youth and adult hitters. From these data it can be concluded that skilled adult hitters and pitchers move body segments faster than skilled youth hitters and pitchers, but segmental and joint angular positions are similar between skilled adult and youth hitters, as well as between skilled adult and youth pitchers.

It has been previously demonstrated that hitters tend to keep their lead elbow (left elbow for right-handed hitters) straighter than their rear elbow (right elbow for right-handed hitters) (Welch *et al.*, 1995). This observation was also made in the current study, in which throughout the stride and swing phases of hitting the rear elbow flexed approximately twice as much as the lead elbow. This information may be useful when initially teaching proper elbow positions to individuals first learning the arm positions needed to effectively hit a line drive to the same field (right-handed hitters hitting to left and left-center fields) or opposite field (right-handed hitters hitting to left field). McIntyre and Pfautch (1982) reported significant differences between same and opposite field hits, with line drive swings to the same field resulting in greater lead elbow extension compared with swings to the opposite field. Therefore, in certain offensive situations (e.g. hitting to the opposite field on a hit and run play, or when moving a runner over to third base from second base), it appears that right-handed hitters adjust the amount of

extension of the lead elbow so that the bat reaches a suitable position at bat-ball contact (McIntyre and Pfautch 1982). Youth or adult hitting coaches can use this information in instructing their hitters on how to pull a pitch to the same field, or hitting a pitch to the opposite field, which are very important hitting skills to learn in baseball (DeRenne 2007; McIntyre and Pfautch, 1982).

Knee flexion between left and right knees exhibited a different pattern compared with elbow flexion. From the beginning of the stride until the end of the swing, the back side (right) knee increased in flexion while the lead (left) knee decreased in flexion and became nearly fully extended. This is similar to the pattern described by Welch *et al.* (1995). It is important to note that adult hitters went from a lead knee flexion of 70° when the hands started to move forward to 11° at bat-ball contact, which is nearly 60° of lead knee extension. This observation emphasizes the importance of lead knee extension during the swing and illustrates the importance of lower extremity strength, such as the quadriceps, because this muscle group is solely responsible for extending the lead knee. High muscle activity from the lower extremity has been reported during the swing (Shaffer *et al.*, 1993).

As the lead knee extends it helps “brace” and stabilize the body as the pelvis and trunk rotate and the upper extremities moves forward. This same “bracing” due to lead knee extension has also been shown to occur in baseball pitching, an important occurrence that allows the trunk and throwing arm to rotate appropriately over a solid base (Escamilla *et al.*, 1998; Fleisig *et al.*, 1999). In contrast to adult hitters, the lead knee flexion of youth hitters progressed from 47° flexion when the hands started to move forward to 15° flexion at bat-ball contact, resulting in only 32° of lead knee

extension. In addition, the left knee straightened significantly faster in the adult hitters compared with the youth hitters, as illustrated by the significantly greater peak left-knee extension angular velocity in adult hitters. This observation implies that youth hitters do not flex the lead knee as much or straighten out the lead knee as fast compared with adult hitters. This may result in less kinetic energy transferred up the kinetic chain from the legs to the trunk to the extremities, and finally to the bat (Messier and Owen, 1985; Messier and Owen, 1986; Milbum, 1982). This phenomenon may partly be due to a lack of lower extremity strength or muscle coordination in youth, especially prior to puberty when strength and motor programming are still developing. These findings illustrate the importance of baseball specific strengthening, conditioning, and training.

Based on the trunk twist angle, the trunk's contribution to the swing does not appear to be dependent on age level. The sequencing of pelvis and upper torso rotation was the same sequencing reported in Welch *et al.* (1995). Throughout the swing the upper torso remained in a more closed position than the pelvis (from Figure 1 the upper torso would have a smaller angle than the pelvis) and achieved a greater peak angular velocity of the upper-torso than the peak angular velocity of the pelvis. Moreover, the peak angular velocity of the upper torso occurred later in the swing compared with the peak angular velocity of the pelvis. This sequencing occurred in both youth and adult hitters, and is important because kinetic energy is transferred up the body from larger slower moving segments earlier in the swing to smaller faster moving segments later in the swing (Welch *et al.*, 1995; Milbum, 1982). Through an electromyographical analysis of hitting, Shaffer *et al.* (1993) demonstrated that batting is a sequence of coordinated muscle activity that begins with the lower extremity, followed

by the trunk, and terminates with the upper extremity. These authors reported high muscle activity in the lower extremity and trunk, but relatively low muscle activity in the upper extremity. These EMG data demonstrate the importance of hitting specific lower extremity and trunk strength and power training, because the kinetic energy generated in the lower extremity and trunk is transferred up the kinetic chain to the upper extremity (which may partially explain why high upper extremity muscle activity is not needed during hitting), contributing to the large angular velocities generated in the upper extremity (Milbum, 1982). This same pattern of kinetic energy transfer from larger slower moving segments to smaller faster movement segments has also been reported during overhead throwing (Escamilla *et al.*, 1998; Joris *et al.*, 1985; Matsuo *et al.*, 2001).

Peak angular velocities progressively increased and occurred later in the swing phase from the knee to the pelvis to the upper torso to the elbows, which is in accordance with the kinetic link principle, and contributed to the relatively high bat linear velocities that were generated. The later occurring and significantly greater peak upper torso angular velocity in adult hitters compared with youth hitters helped contribute to the significantly greater peak left elbow extension angular velocity and bat linear velocity at bat-ball contact in the adult hitters. Moreover, the longer arms and bat length in the adult hitters compared with the youth hitters implies the adult hitters had a mechanical advantage (greater moment arm) over the youth hitters, which also contributed to the significantly greater linear bat velocity in the adult hitters compared with the youth hitters. A kinetic analysis of baseball hitting is now needed to examine the linear and rotational forces that are generated during hitting between youth and adult hitters.

There were some limitations to this study. Firstly, because the ball velocities from the pitching machine were different for youth (between 28.2-29.1 m/s) compared with adult hitters (between 32.6-33.5 m/s), this may have influenced some of the kinematic results between these two groups. However, it would not be realistic for youth hitters to hit baseballs traveling at the same speeds compared with the adult hitters, so ball velocities were scaled down for the youth hitters (DeRenne *et al.*, 2008; DeRenne, 2007; Race, 1961). Secondly, there are always limitations when manually digitizing joint centers because of judgment errors in locating exact positions of joint centers. Thirdly, there may have been some distortion in the smoothing of bat velocity data with the Butterworth filter because of rapid changes that occurred at bat-ball contact. The Butterworth filter distorts the data both just before and just after the bat-ball contact. However, the adult data would logically have been more influenced by the filtering at bat-ball contact, in comparison with the youth data, thus our results of the significant difference of bat linear velocity at bat-ball contact between the two groups will be conserved. Moreover, this potential error caused by this filtering is most likely much smaller than the bat velocity differences found between adults and youth. This limitation may affect points closer to the impact (such as the bat) but have less effect further away from the impact. Because the parameters reported in this study were primarily on the body relatively far from the impact, these smoothing limitations may not have much effect on our data. Fourthly, caution should be employed when generalizing the results of this study, as these results are specific to a select set of kinematic and temporal parameters between skilled youth hitters between 12-17 years old and skilled adult hitters between 20-26 years old. Youth and adult hitters not as skilled as the subjects

used in this study may have significantly different kinematic and temporal values compared with the results found in this study.

In conclusion, for the selected parameters in the current study, both similarities and differences occurred in hitting mechanics between skilled youth and adult hitters. The linear and angular displacement parameters, such as elbow and knee angles, pelvis and upper torso angles, and stride length show more similarities than differences when the two groups are compared. In contrast, the linear and angular velocity parameters, such as pelvis, upper torso, elbow extension, and knee extension angular velocities and linear bat velocity, were more varied than similar between the two groups, with most of these parameters being significantly greater in adult hitters compared with youth hitters. Moreover, compared with youth hitters, adult hitters took greater time during the stride phase and during the overall swing. Overall, there were more similarities than differences in kinematic and temporal hitting parameters between skill youth hitters and adult youth hitters. Learning proper hitting mechanics should be encouraged at a young age. Learning proper hitting kinematics in youth baseball may help reinforce proper hitting kinematics as a hitter progresses to higher levels of baseball in their adult years.

ACKNOWLEDGMENTS

The authors would like to acknowledge Kevin Chen, Melissa Lewis, Shanaal Smothers, and Lazard ZaWaunyka for all their assistance in manually digitizing the data.

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Table 1. Age, body mass, body height, and bat characteristics.

	Age (y) [*]	Body Mass (kg) [*]	Body Height (cm) [*]	Bat Mass (kg) and Weight (oz) [*]	Bat Length (cm/in) [*]
Youth (n = 12)	14.7±2.4	61.7±10.6	172.4±7.6	0.76±0.09 kg 26.8±3.2 oz	80.5±3.3 cm 31.7±1.3 in
Adult (n = 12)	22.2±2.3	84.8±6.6	180.6±3.7	0.87±0.03 kg 30.6±1.1 oz	84.8±1.3 cm 33.4±0.5 in

^{*}Significant difference ($p < 0.01$) between youth and adult hitters

Note: The college and professional subjects that comprised the adults were statistically equivalent to each other with respect to age, body mass, body height, and bat characteristics.

Table 2. Temporal parameters during the swing.

	Youth Hitters (n = 12)	Adult Hitters (n = 12)
Stride Phase (Time from Lead Foot Off Ground to Lead Foot Contact with Ground) (s) (% of Swing)	0.29±0.06* 56.2±5.6	0.40±0.07* 63.7±9.8
Transition Phase (Time from Lead Foot Contact with Ground to Hands Started to Move Forward) (s) (% of Swing)	0.09±0.03 18.3±5.2	0.07±0.04 11.9±8.2
Bat Acceleration Phase (Time from Hands Started to Move Forward to Bat-Ball contact) (s) (% of Swing)	0.13±0.03 25.6±4.4	0.14±0.02 24.5±5.2
Swing (Time from Lead foot Off Ground to Bat-Ball Contact) (s)	0.51±0.06*	0.61±0.07*

*Significant difference ($p < 0.01$) between youth and adult hitters

Note: The college and professional subjects that comprised the adults were statistically equivalent to each other with respect to all temporal parameters.

Table 3. Upper and lower extremity angular displacement^a parameters.

	Youth Hitters (n = 12)	Adult Hitters (n = 12)
<i>Left Elbow Flexion Angle (°)</i>		
Lead foot off ground	77±10	77±14
Lead foot contact with ground	61±11	59±10
Hands started to move forward	67±10	67±14
Bat-ball contact	14±7	18±6
<i>Right Elbow Flexion Angle (°)</i>		
Lead foot off ground	140±9	124±18
Lead foot contact with ground	135±9	129±9
Hands started to move forward	138±8	129±19
Bat-ball contact	64±15	55±17
<i>Left Knee Flexion Angle (°)</i>		
Lead foot off ground	51±12	45±13
Lead foot contact with ground	34±7	39±10
Hands started to move forward	47±19*	70±15*
Bat-ball contact	15±11	11±4
<i>Right Knee Flexion Angle (°)</i>		
Lead foot off ground	52±10	49±16
Lead foot contact with ground	44±13	46±16
Hands started to move forward	43±14	47±14
Bat-ball contact	62±6	66±10

*Significant difference (p<0.01) between youth and adult hitters

^a 0° =full elbow or knee extension

Note: The college and professional subjects that comprised the adults were statistically equivalent to each other with respect to all angular displacement parameters.

Table 4. Pelvis and upper torso angular displacement parameters.

	Youth Hitters (n = 12)	Adult Hitters (n = 12)
<i>Pelvis Angle (°)</i>		
Lead foot off ground	-19±6*	-10±5*
Lead foot contact with ground	-12±6	-10±5
Hands started to move forward	-16±9	-12±5
Bat-ball contact	81±5	71±13
<i>Upper Torso Angle (°)</i>		
Lead foot off ground	-18±11	-15±9
Lead foot contact with ground	-25±5	-24±9
Hands started to move forward	-27±8*	-17±8*
Bat-ball contact	58±4*	48±6*
<i>Trunk Twist (°) (Upper torso angle minus pelvis angle)</i>		
Lead foot off ground	-0±10	-6±8
Lead foot contact with ground	-13±7	-14±9
Hands started to move forward	-11±11	-6±9
Bat-ball contact	22±5	23±11

*Significant difference ($p < 0.01$) between youth and adult hitters

Note: The college and professional subjects that comprised the adults were statistically equivalent to each other with respect to all angular displacement parameters.

Table 5. Peak angular velocity parameters.

	Youth Hitters (n = 12)	Adult Hitters (n = 12)
<i>Peak Left Knee Extension Angular Velocity (°/s)</i>	303±76*	386±60*
Timing - % of Swing	75±12	78±10
<i>Peak Pelvis Angular Velocity (°/s)</i>	632±117	678±87
Timing - % of Swing	76±11	82±13
<i>Peak Upper Torso Angular Velocity (°/s)</i>	717±86*	857±53*
Timing - % of Swing	77±10*	88±6*
<i>Peak Left Elbow Extension Angular Velocity (°/s)</i>	598±126*	752±95*
Timing - % of Swing	90±13	93±12
<i>Peak Right Elbow Extension Angular Velocity (°/s)</i>	849±151	936±190
Timing - % of Swing	95±10	96±12

*Significant difference ($p < 0.01$) between youth and adult hitters

Note: The college and professional subjects that comprised the adults were statistically equivalent to each other with respect to all angular velocity parameters.

Table 6. Linear displacement and velocity parameters.

	Youth Hitters (n = 12)	Adult Hitters (n = 12)
<i>Stride Length at Lead Foot Contact with Ground (distance between ankles)</i>		
cm	81±7	87±9
% of Body Height	47±3	48±5
<i>Bat Linear Velocity at Bat-Ball Contact (m/s)</i>	25±3*	30±2*

*Significant difference ($p < 0.01$) between youth and adult hitters

Note: The college and professional subjects that comprised the adults were statistically equivalent to each other with respect to all linear displacement and velocity parameters.

Figure Captions

Figure 1. Upper torso and pelvis angle conventions (see text for explanation).

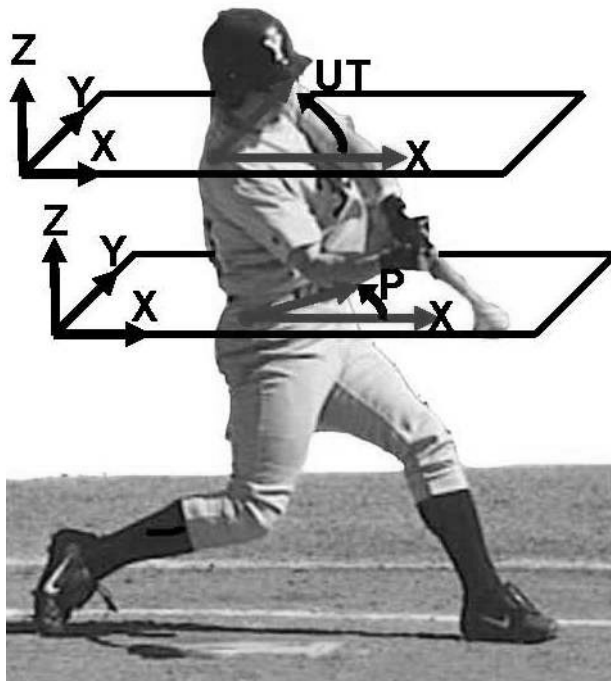


Figure 1.