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A Comparison of Age Level on Baseball Hitting Kinematics

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We propose that learning proper hitting kinematics should be encouraged at a young age during youth baseball because 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 ($p < .01$) 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°/s versus 717°/s), peak left elbow extension angular velocity (752°/s versus 598°/s), peak left knee extension angular velocity (386°/s versus 303°/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.

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

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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). In addition, 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 layperson, 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, whereas 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, and 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 before data collection.

Two synchronized, genlocked 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 and 33.5 m/s (73–75 mph) for adult hitters and 28.2–29.1 m/s (63–65 mph) 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 before a testing session and was accurate within ±0.22 m/s.

An event synchronization device (Peak Performance Technologies, Inc.) 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. Before and just after the subjects were videotaped, a 2- × 1.5- × 1-m three-dimensional calibration frame (Peak Performance Technologies, Inc.), surveyed with a measurement tolerance of 0.5 cm, was positioned and videotaped in the same volume occupied by the hitter. The calibration frame comprised 24 spherical balls of known spatial coordinates.

Data Analysis

A three-dimensional video system (Peak Performance Technologies, Inc.) was used to manually digitize data for all subjects. A spatial model was created that comprised the top of the head; centers of the left and right midtoes (at approximately the head of the third metatarsal); joint centers of the ankles, knees, hips, shoulders,

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

	Age (years)*	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	80.5 ± 3.3 cm
				26.8 ± 3.2 oz.	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	84.8 ± 1.3 cm
				30.6 ± 1.1 oz.	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.

and elbows; midpoint 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 five frames before when the front foot left the ground (first event) and ended five 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 foot) 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 in which both hands started to move forward toward 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 before bat-ball contact, whereas 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.

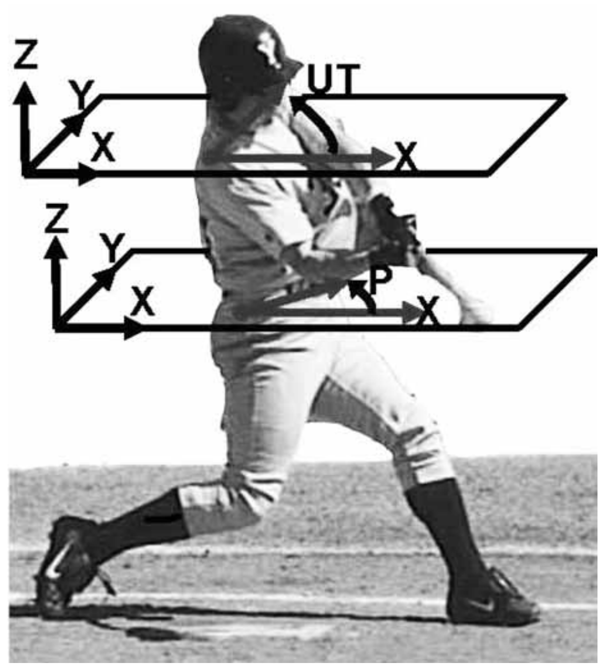

Figure 1 — Upper torso and pelvis angle conventions (see text for explanation).

Moreover, bat linear velocity after bat-ball contact would be affected differently between youth and adult hitters owing 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 and 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 before 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 & Marshall, 1986), three-dimensional 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 three-dimensional orthogonal axis system was centered at home plate with the positive *X*-axis pointing toward 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 orthogonally 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. 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, whereas 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, whereas 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 midpoint of the left and right hips to the midpoint 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, whereas 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 & 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 $p < .01$.

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, and 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

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)	0.29 ± 0.06*	0.40 ± 0.07*
Percentage of Swing	56.2 ± 5.6	63.7 ± 9.8
Transition Phase: Time from Lead Foot Contact with Ground to Hands Started to Move Forward (s)	0.09 ± 0.03	0.07 ± 0.04
Percentage of Swing	18.3 ± 5.2	11.9 ± 8.2
Bat Acceleration Phase: Time from Hands Started to Move Forward to Bat-Ball Contact (s)	0.13 ± 0.03	0.14 ± 0.02
Percentage of Swing	25.6 ± 4.4	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)
Left Elbow Flexion Angle (°)		
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
Right Elbow Flexion Angle (°)		
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
Left Knee Flexion Angle (°)		
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
Right Knee Flexion Angle (°)		
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.

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 toward them as in the current study, which may affect the timing of the swing between the two studies.

Table 4 Pelvis and upper torso angular displacement parameters

	Youth Hitters (n = 12)	Adult Hitters (n = 12)
Pelvis Angle (°)		
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
Upper Torso Angle (°)		
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*
Trunk Twist (°) (Upper torso angle minus pelvis angle)		
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)
Peak Left Knee Extension Angular Velocity (°/s)	303 ± 76*	386 ± 60*
Timing—Percentage of Swing	75 ± 12	78 ± 10
Peak Pelvis Angular Velocity (°/s)	632 ± 117	678 ± 87
Timing—Percentage of Swing	76 ± 11	82 ± 13
Peak Upper Torso Angular Velocity (°/s)	717 ± 86*	857 ± 53*
Timing—Percentage of Swing	77 ± 10*	88 ± 6*
Peak Left Elbow Extension Angular Velocity (°/s)	598 ± 126*	752 ± 95*
Timing—Percentage of Swing	90 ± 13	93 ± 12
Peak Right Elbow Extension Angular Velocity (°/s)	849 ± 151	936 ± 190
Timing—Percentage 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)
Stride Length at Lead Foot Contact with Ground (Distance between ankles, cm)	81 ± 7	87 ± 9
Percentage of Body Height	47 ± 3	48 ± 5
Bat Linear Velocity at Bat-Ball Contact (m/s)	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.

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 & Owen, 1985; Messier & 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 right field). McIntyre and Pfautsch (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 Pfautsch 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 to hit a pitch to the opposite field, which are very important skills to learn in baseball (DeRenne 2007; McIntyre & Pfautsch, 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 whereas 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 being 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 before 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 that 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 and 29.1 m/s) compared with adult hitters (between 32.6 and 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 and 17 years old and skilled adult hitters between 20 and 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.

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