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Research article

A Three-Dimensional Kinematic and Kinetic Study of the College-Level Female Softball Swing

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Abstract
This paper quantifies and discusses the three-dimensional kinematic and kinetic characteristics of the female softball swing as performed by fourteen female collegiate amateur subjects. The analyses were performed using a three-dimensional computer model. The model was driven kinematically from subject swings data that were recorded with a multi-camera motion analysis system. Each subject used two distinct bats with significantly different inertial properties. Model output included bat trajectories, subject/bat interaction forces and torques, work, and power. These data formed the basis for a detailed analysis and description of fundamental swing kinematic and kinetic quantities. The analyses revealed that the softball swing is a highly coordinated and individual three-dimensional motion and subject-to-subject variations were significant in all kinematic and kinetic quantities. In addition, the potential effects of bat properties on swing mechanics are discussed. The paths of the hands and the centre-of-curvature of the bat relative to the horizontal plane appear to be important trajectory characteristics of the swing. Descriptions of the swing mechanics and practical implications are offered based upon these findings.

Key words: Softball, Sport Biomechanics, Softball Bat, Softball Swing, Kinematics, Kinetics.

Introduction

Fastpitch softball is one the most popular competitive and recreational sports in the United States (ASA Youth Program, 2010). Females exclusively participate competitively at the high school, collegiate, and professional levels. For example, the sport is played in over 277 Division I college teams nationwide. Despite its widespread popularity, little research has been performed on the fundamental mechanics of the female softball swing especially when compared to baseball (Adiar, 2002). Messier and Owen (1984) stated, "the absence from the biomechanics literature of studies concerning female fast pitch softball batting has left the athlete and her coach with little scientific information on which to base the implantation of various techniques." Their initial biomechanical studies used direct video measurement to quantity and describe the three-dimensional velocity characteristics of eight female fast pitch softball batters. Their results included quantifying the maximum linear and angular velocity and components (fixed axis representation), presenting typical time histories of the linear and angular velocity components, and offering a qualitative description of swing mechanics based upon these data. These findings were compared to baseball batters and were found to be significantly different thus questioning the value of future biomechanical comparisons between batters of opposite genders participating in unique sports with significantly different batting requirements (Messier and Owen, 1984).

With the exception of this one study, the majority of the biomechanics research regarding the softball swing has focused on understanding the properties and performances of the bat (Bahill, 2004; Noble and Eck, 1986; Russell, 2005), and determining the relationships between bat velocity and mass properties (Fleisig et al., 2002; Koenig et al., 2004; Smith et al., 2003). Much of the motivation for this work was to provide the scientific basis for establishing standards of bat performance to balance player performance and safety (Fleisig et al., 2002).

Russell (2005; 2006) has done extensive work describing and quantifying the various relevant mass properties and associated measures of softball bats. He presents a qualitative description of softball swing mechanics from an overhead two-dimensional perspective, and discussions on the influences of the various mass properties and measure on bat performance and swing mechanics. Bahill (2004) and Noble and Eck (1986) investigated the relationships among softball bat mass properties, bat impact behavior, and resulting batted ball speed. Both studies acknowledged the complexity of batter swing mechanics, the interrelationship between bat properties and swing mechanics, and the role that individual swing characteristics have on impact behavior and batted ball speed.

Fleisig et al. (2002) experimentally investigated the relationship between bat mass properties and bat velocity (linear and angular) for 17 female collegiate softball players using bats engineered to have various mass and inertia properties. This study found that linear velocity had a significant correlation with bat moment-of-inertia (measured about the bat handle), but not bat mass. There were no correlations found relative to angular velocity. Smith et al. (2003) conducted a similar experimental study of bat mass properties and bat speed using 16 amateur slow-pitch softball players. This study isolated bat mass properties into two groups. One group varied bat mass for a constant moment of inertia, and the other varied bat moment of inertia for a constant bat mass. This study also found that linear velocity had a significant correlation with bat moment of inertia, but not bat mass. Finally, Koenig et al. (2004) investigated the relationship between bat moment-of-inertia (about the bat handle) and linear bat speed. Ten collegiate female fast-pitch softball players each swinging six different bat configurations

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were measured experimentally, and additionally analyzed with a planar one degree-of-freedom analytical model. This study found that for the majority of bat inertia values, bat speed was independent of inertia. This finding does not agree with their theoretical predictions which indicated an inverse relationship.

For these three studies bat moment-of-inertia was measured relative to a fixed location on the bat handle (ASTM F2398-04), thus these results may be misleading. Bat moment-of-inertia about this point is a function of bat mass, mass centre location, and mass centre inertia which effectively summarizes these three mass properties into one quantity, and this quantity is dominated by the location of the mass centre (Milanovich, 2010). In addition, for this measure of bat inertia to be more relevant, the location of the bat mass centre should be measured relative to the actual centre-of-rotation of the bat (Milanovich, 2010), which has been shown to be between the batter and bat handle at impact (Smith et al, 2003; Russell, 2005), dependent upon swing trajectory, and constantly moving during the swing (Milanovich, 2010). Thus the lack of consideration of subject swing characteristics may help explain the conflicting findings of these studies.

The biomechanical modeling done in support of these studies has been limited to either treating the swing as a planar rotation about a fixed axis relative to the bat (Noble and Eck, 1986), or a pure planar rotation of the body and the bat about a vertical axis through the batter (Koenig et al., 2004). Modeling complex three-dimensional sports motions as planar fixed point of rotation motions is often done to simplify the resulting computer models and equations of motion (Nesbit, 2005). Koenig et al. (2004) indicated a lack of confidence in their model, with additional development warranted based upon the conflicting conclusions between their experimental results and model predictions. It was further stated that the inclusion of additional degrees-of-freedom to their model (one DOF model) would potentially improve its accuracy in determining swing speed as a function of bat inertia. The general difficulty in modeling the swing of the bat is noted by Smith et al. (2003), Fleisig et al. (2002), and Bahill (2004). A model of the softball swing which does not restrict the motion to a plane about a fixed point of rotation may result in a more accurate and comprehensive description of the swing mechanics as has been performed in other sports motion analyses.

Thus there is an obvious and compelling need for an in-depth and comprehensive description of female softball swing mechanics. A more representative computer model of the swing would aid such a study. A detailed understanding of the mechanics of the female softball swing would be beneficial for scientifically informing various batting techniques, providing a basis for understanding the complex interrelationships among bat properties, swing characteristics, and bat performance, and providing a basis for further study of the motion. Such information would benefit the scientist, player, coach, and equipment manufacturer.

This paper presents a description of the fundamental kinematics and kinetics of a female softball swing for 14 college level participants using an unrestricted three-dimensional rigid model of the bat that was developed for this study. Specifically, the purposes of this study are the following:

- Present a more representative softball swing computer model
- Provide a detailed quantitative description of the kinetics and kinematics of the swing
- Analyze a group of subjects for basic statistical information
- Identify typical similarities and differences in swing mechanics among subjects
- Gain insight to the role of bat properties on swing mechanics
- Attempt to describe the female softball swing from a mechanics perspective

Methods

The subjects of this experiment were fourteen female college level players of various experience (12.3 ± 4.4 years), height (1.65 ± 0.06 m), and weight (62.4 ± 7.8 kg). The subjects were a combination of left-handed and right-handed, with one switch hitter. No effort was made to quantity skill level (Fleisig et al., 2002; Koenig et al., 2004; Messier and Owen, 1984; Smith et al., 2003). This number of subjects is consistent with all previous studies of female softball batting which ranged from 8 to 17 subjects (Fleisig et al., 2002; Koenig et al., 2004; Messier and Owen, 1984; Smith et al., 2003). All subjects were informed of the purposes of the study, and gave written consent for the use of their data for research purposes, in accordance with local IRB requirements.

The subjects stretched and warmed up for a minimum of 10 minutes in accordance with their normal practice habits which followed normal warm-up protocols (Fleisig et al., 2002: Smith et al., 2003). The Motion Analysis system was calibrated until the combined 3D residual for all cameras was less than 1.00 mm. (Test/retest of static marker locations varied by less than 0.20 mm for a given calibration.) The subjects were asked to execute a series of “competitive effort” swings that consisted of hitting a ball placed on a batting tee into a net (Koenig et al., 2004). Tee height and location relative to the tee were chosen by the subjects. Grip offset from the triad was measured between the hands. A marker was placed on the ball to determine the time of impact.

Two distinct bats (aluminum and composite) with significantly different inertial properties were used for the subject trials (see Table 1). These bats were measured for mass, mass centre location, and mass centre inertias using the apparatus, methods, and calibrations described in Nesbit and Serrano (2006). From these quantities, the centre-of-percussion and grip point inertia (I_{GRIP}) values were determined using the protocols specified in *ASTM F2398*. The mass properties of these two bats are consistent with bats used in other studies (Bahill, 2004; Fleisig et al., 2002; Koenig et al., 2004), yet appear to significantly differ from each other when compared to the ranges of typical bats (Russell, 2005).

Table 1. Inertial properties of trial bats.

	Material	Length (l) (m)	Mass (m) (kg)	CG (m)	$I_{X,Y}$ (kg-m^2)	CP (m)	I_{GRIP} (kg-m^2)	I_Z (kg-m^2)
Bat #1	alum	.838	.606	.480	.040	.683	.1052	3.39e-4
Bat #2	comp	.838	.671	.596	.063	.711	.1953	6.85e-4

Eight trials were recorded for each subject for each bat. Poor trials as reported by the subject (uncomfortable swing, poor flight of the ball, etc) were disregarded, and the trial repeated. At the conclusion of the trials, the subjects assessed (approved/rejected) each swing trial based upon an overall visual assessment of the motion capture data. No measure of batted ball speed was made in assessing the quality of their swing trial. In addition, the subjects were not quarried about their comfort level for each bat which is consistent with (Fleisig et al., 2002; Koenig et al., 2004; Smith et al., 2003). At the conclusion of the trials, all subjects were assessed for consistency of linear velocity for each bat type. For the majority of subjects, all their respective trials were within ± 10% of their respective mean velocity for each bat which is typical for hitting a ball off a tee (Koenig et al, 2004). All subjects presented at least three usable trials within ± 5% of their respective mean velocity. From these remaining trials, one was selected by each subject for each bat for subsequent computer analyses. This manner of filtering and subsequently selecting typical and representative trials for computer modeling analyses is practical and effective, and consistent with similar initial biomechanical modeling efforts in other sports (Nesbit, 2005).

Swing dynamic model

A three-dimensional model of the softball bat was developed to study the mechanics of the swing motion, the interactions between the subject and the bat, and the energy transfers between the two. The model contains representative mass and inertia properties and treats the bat as rigid. Figure 1 illustrates the free-body-diagram of the model.

Local and global coordinate systems were defined as shown in Figure 1. The local bat (*XYZ*) coordinate system aligned with the marker triad attached to the bat. The *Z-axis* aligned with the long axis of the bat, the Y-axis is perpendicular to the plane formed by these markers, and the *X-axis* completes the right-hand triad. The global (*XYZ*) coordinate system is fixed to the ground with the *Z-axis* in the vertical direction. Two other local coordinate systems are defined to facilitate the kinematic and kinetic component resolution and description. The grip coordinate system is attached to point *A*, and aligns with the tangential, normal, and bi-normal direction relative to the grip point path. The tangential-normal (swing-pitch-roll) coordinate system is also attached to point *A*, and aligns with the long axis of the bat, the normal direction relative to the swing plane (defined by adjacent bat positions), and the bi-normal to these two directions.

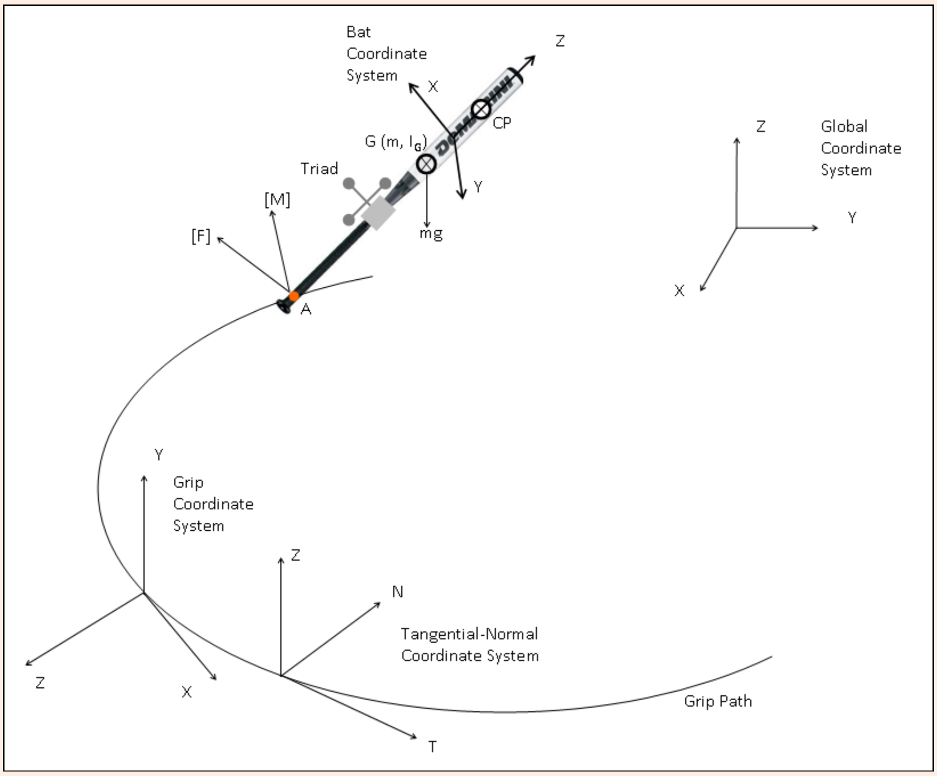


Figure 1. Free-body-diagram of softball bat. [F] and [M] represent the three components of the interaction forces and moments respectively. G is the centre of mass, COP is the centre-of-percussion, and A is the point where the subject grasps the bat (as defined by the midpoint between the hands).

The following equations of motion were developed from Figure 1:

$$F_{XG} = mA_{GX} \quad (1)$$

$$F_{YG} - mg = mA_{GY} \quad (2)$$

$$F_{ZG} = mA_{GZ} \quad (3)$$

$$M_{XB} = I_X\,\alpha_{XB} - (I_Y - I_Z)\omega_{YB}\,\omega_{ZB} - F_{YB}(R_G - R_{GRIP}) \quad (4)$$

$$M_{YB} = I_Y\,\alpha_{YB} - (I_Z - I_X)\omega_{ZB}\,\omega_{XB} + F_{XB}(R_G - R_{GRIP}) \quad (5)$$

$$M_{ZB} = I_Z\,\alpha_{ZB} - (I_X - I_Y)\omega_{XB}\,\omega_{YB} \quad (6)$$

where F_{XG}, F_{YG}, and F_{ZG} are the applied global force components, M is the mass of the bat, A_{GY}, A_{GY}, and A_{GZ} are the global linear acceleration components of the bat mass centre (G), g is the acceleration of gravity, M_{XB}, M_{YB}, and M_{ZB} are the applied moments relative to the local bat coordinate system, I_X, I_Y, and I_Z are the mass moments of inertia about the bat mass centre relative to the bat coordinate system, ω_{XB}, ω_{YB}, and ω_{ZB} are angular velocities relative to the local bat coordinate system, α_{XB}, α_{YB}, and α_{XB} are the angular accelerations relative to the local bat coordinate system, R_G is the location of the mass centre, R_{grip} is the location of the grip point. Both R_G and R_{grip} are measured relative to the end of the bat handle. F_{XB} and F_{YB} are the applied force components relative to the local bat coordinate system.

Data to kinematically drive the model are obtained from subject softball bat swings. A motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) with eight Falcon HR 240 cameras and Eva 6.02 software is used to collect and process data from the subjects' swings. The system tracks a triad of passive-reflective markers that are placed on the bat (see Figure 1). The rigid triad is attached to the bat at the top of the grip section of the bat. Two of the markers are aligned with the long axis of the bat, and the third is offset perpendicular to the long axis of the bat. The three-dimensional marker triad paths are recorded at 200 Hz then smoothed and processed to yield global body *1-2-3* angular positions of the bat ($\theta_1 X, \theta_1 Y$ [, and θ] $_1 Z$) and the three-dimensional global positions of the grip path (*X, Y, and Z*), mass centre, and centre-of-percussion using methods described in Nesbit (2005).

Numerical differentiation schemes were applied to the global linear and angular position data to yield the linear velocities and accelerations of the grip point, mass centre, and centre-of-percussion paths, and the global angular velocities and accelerations of the bat. Global kinematic information was transformed to local (bat) kinematic information (Craig, 1986). From these kinematic data, Equations (1) through (6) can be solved to yield the applied forces and moments on the bat. Subsequently, transformations were applied to resolve kinetic information to the most appropriate coordinate system (see Results Section).

From the global applied force and moment components, the total work done by the subject on the bat is determined from the following:

$$Work = \sum_{i=1}^{n} (F_{XG}\Delta X_i + F_{YG}\Delta Y_i + F_{ZG}\Delta Z_i + M_{XG}\Delta\theta_{Xi} + M_{YG}\Delta\theta_{Yi} + M_{ZG}\Delta\theta_{Zi}) \quad (7)$$

Where i indicates the value of the quantity at point i in the digitized grip point path, and the Δ function indicates a change in the associated quantity from point i to i + 1. The total power is determined by numerically differentiating the work expression of Equation (7). The total work and power quantities are comprised of the contributions from the linear force (linear work and power) and swing torque (angular work and power).

Results

The following data were determined for each subject trial: bat trajectories, bat linear and angular velocities, bat kinetic energies, subject/bat interaction forces and torques, work, and power. The portion of the swing of interest is from the initiation of the swing to impact (*time = 0 sec*). These data are presented in Table 2 for the aggregate group with basic statistical information (mean, range, and standard deviation), and Figures 2 through 11 for random subjects (based upon one trial per subject per bat). The use of four random subjects in the graphical presentation of results is intended to provide an uncluttered yet typical visual reference for identifying similarities, differences, and ranges of values among subjects. However, the following results, discussions, and conclusions are all based upon the results for the aggregate group.

Linear velocities are reported in resultant form for the grip, CG, and COP locations on the bat. Interaction forces are reported in resultant form, and as tangential, normal, and bi-normal components. Angular velocities are resolved into swing, pitch, and roll components. Interaction torques are reported in resultant form, and as swing, pitch, and roll components. The energy quantities of work, power, and kinetic energy are presented as total, and angular and linear components. In the discussions that follow references to locations in the swing (i.e., 30 degrees before impact…) are relative to an overhead perspective view of the swing (Figures 3) and should be considered general yet approximate.

The majority of the data in Table 2 and Figures 2 through 11 does not have comparable data available from the scientific literature with the following exceptions. The maximum COP/"sweet spot" linear velocity values agree well with previous studies of female collegiate softball players (Messier and Owen, 1984; Fleisig et al, 2002; Koenig et al, 2004) although the point on the bat where the measurements were made varied somewhat based upon differing interpretations of the location of the bat "sweet spot." Bat angular velocities (swing component) at impact for college-level female softball players have been reported by Messier and Owen (1984) and Fleisig et at (2002) and agree well with data presented Table 2. Messier and Owen (1984) report a mean maximum bat kinetic energy of 270 N-m which is considerably higher than the average peak value found in this study. The three-dimensional bat trajectories, interaction forces and torques, and work and power or their components, have not been previously reported.

A perspective view of one subject's swing trajectory is shown in Figure 2. Overhead two-dimensional views of four subject swings are shown in Figures 3a through 3d. Each frame represents 0.01 seconds. The red and blue paths represent of the ends of the bat, the green path is of the grip point, and the black path is of the

Table 2. Kinematic and kinetic data for all subjects.

Data	Units	Average	Std. Deviation	Time (sec)	Range
Grip Velocity (max)	m·sec^{-1}	6.16	.537	-.074	5.0-7.4
		6.08	.656	-.030	4.9-7.4
Grip Velocity (impact)	m·sec^{-1}	3.59	.663	-------	2.8-4.4
		3.55	.675		2.7-4.3
CG Velocity (max)	m·sec^{-1}	16.49	1.20	-.006	15.1-17.9
		17.33	1.33	-.008	15.8-19.0
CG Velocity (impact)	m·sec^{-1}	16.14	1.03	-------	14.9-17.3
		16.65	1.38		15.2-17.6
COP Velocity (max)	m·sec^{-1}	20.13	1.43	-.002	16.4-23.4
		20.64	1.53	-.007	16.6-23.9
COP Velocity (impact)	m·sec^{-1}	19.70	1.35	-------	15.5-23.4
		19.80	1.63		18.9-23.2
Swing Velocity	rad·sec^{-1}	29.63	2.92	-.007	23.9-34.5
		27.03	3.51	-.011	22.0-33.1
Pitch Velocity	rad·sec^{-1}	7.96	1.36	-.120	6.0-10.1
		7.04	1.88	-.110	5.3-9.9
Roll Velocity	rad·sec^{-1}	4.94	.39	-.009	3.9-5.0
		4.31	.49	-.007	3.6-4.8
Tangential Force	N	182.7	29.3	-.036	135-268
		196.5	31.1	-.033	145-286
Normal Force	N	265.1	25.8	-.005	182-312
		293.2	24.7	-.002	201-347
Bi-Normal Force	N	118.1	31.3	-.048	73-154
		134.0	28.2	-.047	98-182
Force Magnitude	N	312.0	34.5	-.004	220-396
		355.9	38.3	-.002	239-416
Swing Torque	Nm	29.5	5.5	-.035	18.7-42.2
		28.7	4.9	-.036	19.5-43.5
Pitch Torque	Nm	13.9	4.1	-.143	9.9-21.1
		15.8	4.2	-.038	11.7-23.0
Roll Torque	Nm	1.1	.29	-.033	0.7-2.2
		1.4	.21	-.041	0.9-3.0
Torque Magnitude	Nm	32.8	10.2	-.033	15.0-48.9
		34.7	10.5	-.030	17.5-50.0
Linear Work	Nm	129.9	14.6	.000	101-158
		146.2	18.4	-.001	122-184
Angular Work	Nm	44.6	6.4	-.001	22.6-61.0
		48.6	8.5	-.002	24.6-65.8
Total Work	Nm	163.6	19.7	-.001	126-199
		191.3	18.9	.000	154-227
Linear Power	Nm·sec^{-1}	1240	179	-.052	1104-1437
		1387	181	-.048	1167-1612
Angular Power	Nm·sec^{-1}	639	54	-.023	511-756
		601	69	-.021	488-733
Total Power	Nm·sec^{-1}	1917	240	-.031	1417-2431
		1980	233	-.028	1430-2535
Linear Kinetic Energy	Nm	113.3	11.5	.000	91-140
		124.3	12.1	-.001	105-163
Angular Kinetic Energy	Nm	40.6	5.5	-.001	15.8-54.7
		42.8	7.8	-.002	21.2-58.5
Total Kinetic Energy	Nm	144.3	17.3	-.001	118-177
		169.9	16.0	.000	134-201

instantaneous centre-of-rotation (COR) of the bat. In addition, Figure 4 shows the overhead perspective of the path of the grip point (red), CG (blue), and COR (black) with the bat graphics removed for one subject. In all figures, the single hollow blue circle is the pre-impact position of the ball.

The linear velocity profiles of the grip point and COP for four random subjects are given in Figures 5a and 5b (bat #1 – aluminum). When considering these data note that it has been found that maximum bat speed is slightly higher and less variable when hit off a tee compared to pitched (Koenig et al., 2004). The grip, CG, and COP linear velocity profiles for Subject 9 for bat #1 are given in Figure 6a, and for bat #2 in Figure 6b.

Figures 7 shows the angular velocity component profiles for Subject 9 using bat #1 in swing-pitch-roll component form, and the swing component profiles for random subjects (bat #1).

Figures 8 shows the interaction force and force component profiles for Subject 9 using bat #1 in tangential-normal-bi-normal component form, and the tangential force component profiles for random subjects (bat #1).

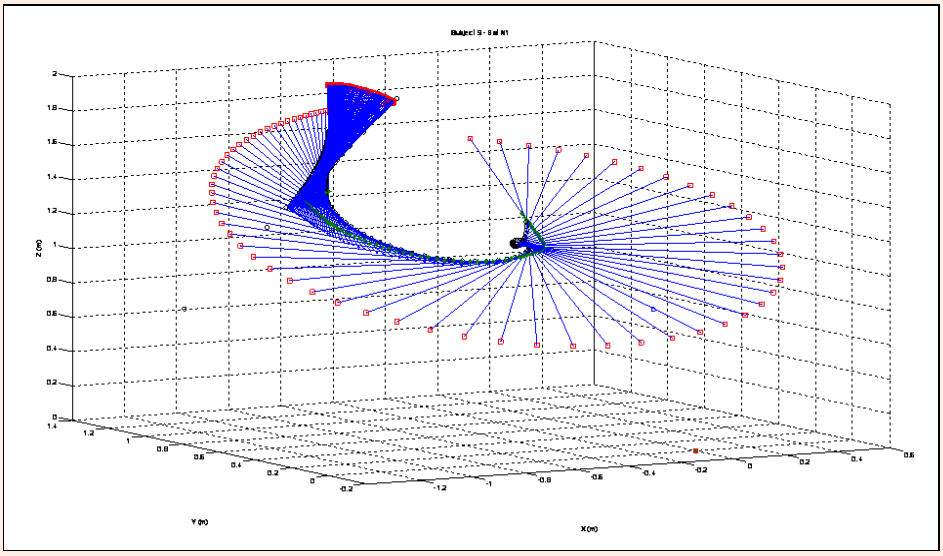


Figure 2. **Perspective view of swing trajctory.**

Figures 9 shows the interaction torque and torque component profiles for Subject 9 using bat #1 in swing-pitch-roll component form, and the swing torque component profiles for the random subjects (bat #1).

Figures 10 illustrate the total work and linear and angular work component profiles for Subject 9 using bat #1, and the total work profiles for the Random subjects (bat #1). Figures 11 illustrate the total power and linear and angular power component profiles for Subject 9 using bat #1, and the total power profiles for random subjects (bat #1).

Discussion

Bat trajectories

As evident in Figure 2, the swing is clearly a complex three-dimensional motion and the individuality swing trajectories are apparent in Figure 3. The substantial pitching motion of the bat and resulting swing plane both show considerable variability among the subjects. The path of the grip point moves in a stable plane that is established shortly after the swing is initiated. This plane ranges from 16-24 degrees below horizontal for all subjects. The trajectory of the bat also establishes a plane that becomes stable when the bat is approximately 70-95 degrees before impact (as viewed from overhead) and ranges from 5-18 degrees below horizontal.

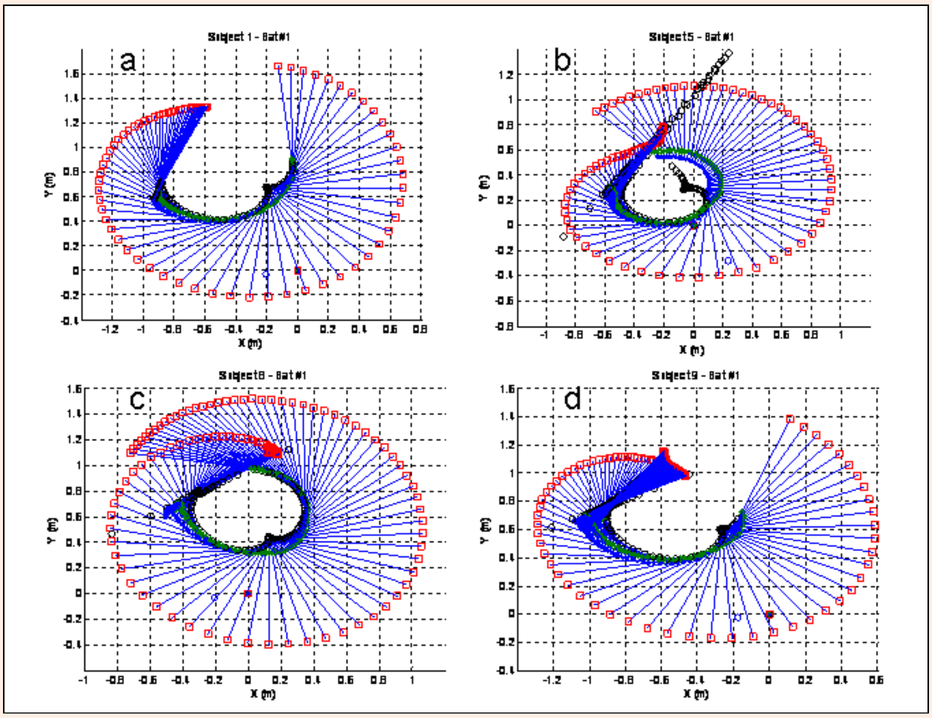
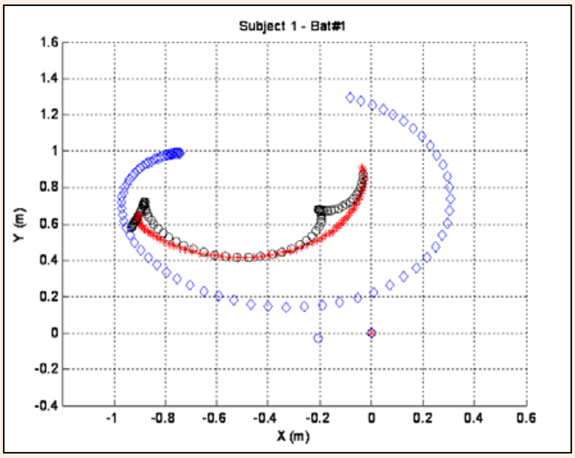


Figure 3a through 3d. **Overhead superimposed perspective view of random subject swings. (Bat #1 - Aluminum)**

From Figures 3 and 4, it can be seen that the path of the hands, bat CG, and bat COR are all of non-constant radius, and exhibit considerable variability in size, shape, and radius profile among all subjects. These universal characteristics of softball swings call into question the utilization of the simplified two-dimensional and/or fixed pivot models of the swing for analyzing and predicting bat performance. For all subjects, the path of the bat COR is inside the path of the hands at the onset of the swing, then coincides with the path of the hands from the position of the bat approximately 90 degrees before impact to 30 degrees before impact. From this point until impact, the COR remains inside the path of the hands. At impact, the point of rotation is clearly inside the bat about 2 to 10 cm for all subjects which was reported by Smith et al (2003) to be approximately 6.25 cm. This movement of the COR relative to the grip point significantly effects the inertial feel (I_{GRIP}) of the bat (Milanovich, 2010).



Figures 4. Overhead perspective of hand, CG, and COR paths.

The coordinated movement of the hands (grip point) together with the angular actions of the wrists effect the relative path of the COR of the bat. When the wrist (swing) movement dominates relative to the path of the hands, the COR is inside the grip point path which occurs at the initiation of the swing, and near impact. When the timing of the hand path is coordinated with the swing angular motion, the paths coincide. The precise mechanics resulting in this coordinated timing is unknown, however it appears to be a fundamental feature of the softball swing since all subjects exhibited this swing characteristic.

It appears that the radius profile of the path of the hands plays an important role in controlling the trajectory of the bat through control of the centripetal forces of the bat coordinated with the interaction forces and torques from the batter as has been noted in other sports (Nesbit and McGinnis, 2009). Generally the subjects follow a pattern of increasing to maximum during the first third of the swing, decreasing steadily during the second third, then decreasing slightly or not at all (and increasing for some subjects) during the last third of the swing.

Swing kinematic analyses – linear velocities

Table 2 and Figures 5 reveal that there were significant differences among the subjects in terms of magnitudes, timing, and profiles of the grip, CG, and COP linear velocities. However the profiles of Figures 5 also illustrate some common characteristics. For all subjects, from the initiation of the swing to about 135 degrees before impact, the linear velocities of the grip point and the bat COP and CG are nearly identical. Beyond 135 degrees, the linear velocities of the COP and CG increase at a greater rate than the grip velocity as the bat moves away from the body. The grip point velocity reaches its maximum at about 90 degrees from impact then begins to reduce in reaction to the rapid outward movement of the bat. At this time until about 30 degrees before impact the linear velocities of the COP and CG increase most rapidly. From 30 degrees to impact, the grip point velocity continues to reduce and reaches a local minimum at impact, and the COP and CG velocities increase (at a slower rate) to their maximum values at or very near impact. Messier and Owen (1984) reported that the peak resultant linear velocity occurs slightly before impact (32 msec average) which is consistent with the findings of this study. The large differences between the grip and COP velocities at impact illustrate the importance of the swing angular motion to the overall linear bat speed.

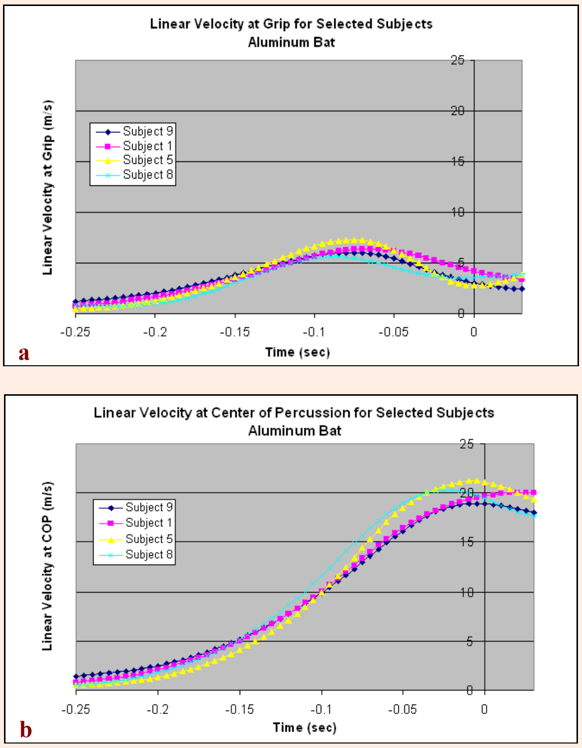


Figure 5a and 5b. Linear velocity profiles of the grip point and COP for random subjects. (Bat #1 – Aluminum).

Relative to the two trial bats, the maximum and impact grip point, CG, and COP velocities for all subjects varied little (see Figures 6). This similarity of the linear velocities is significant noting that the inertial properties of the two bats are quite different (see Table 2). This finding agrees with Koenig et al (2004) who also had subjects hit a ball off a tee using bats with wide ranging swing inertia values.

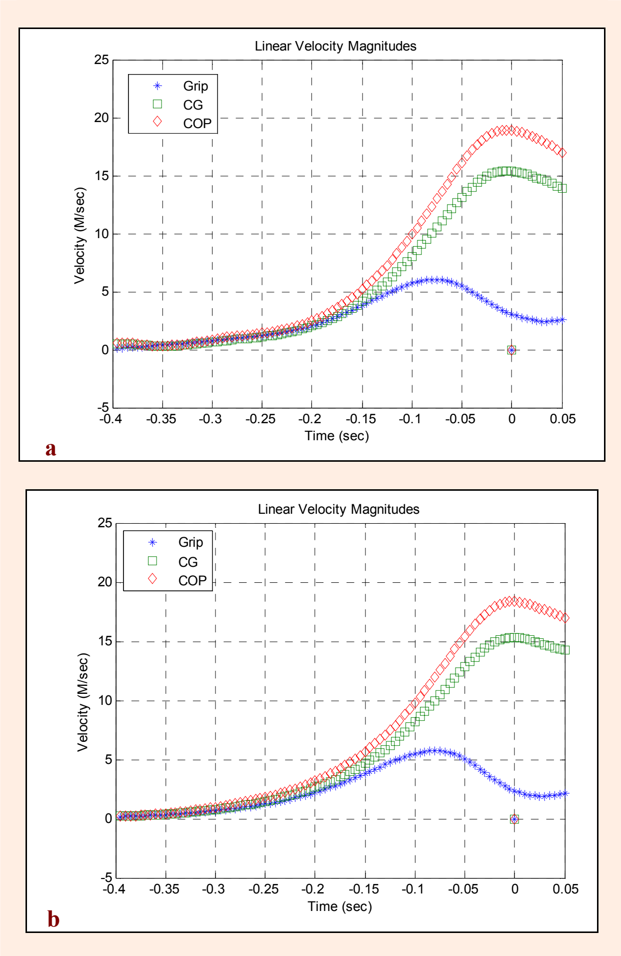
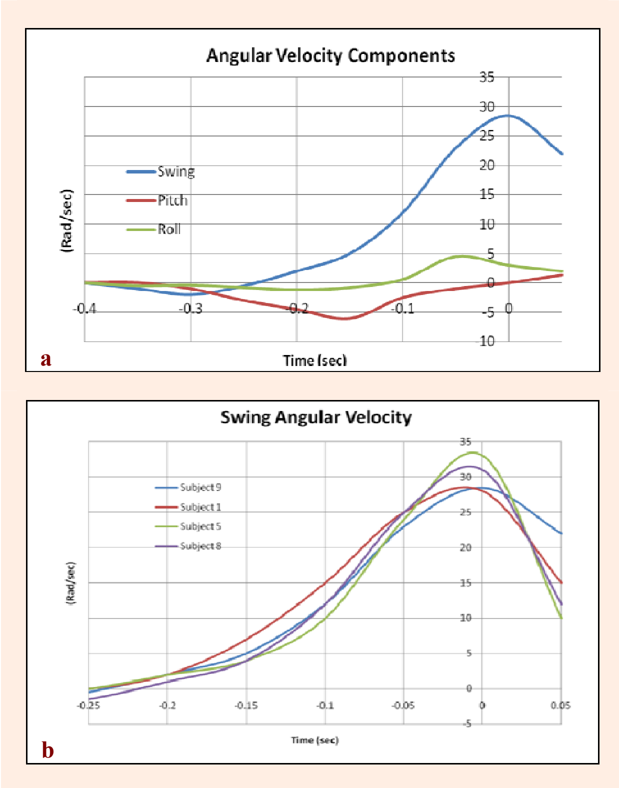


Figure 6a and 6b. Linear Velocity Profiles of Grip Point, COP, and CG for Subject 9. (Bat #1 – Aluminum (top) and Bat #2 – Composite (bottom))



Figures 7a and 7b. Angular velocity components for subject 9 and swing component for random subjects (Bat #1).

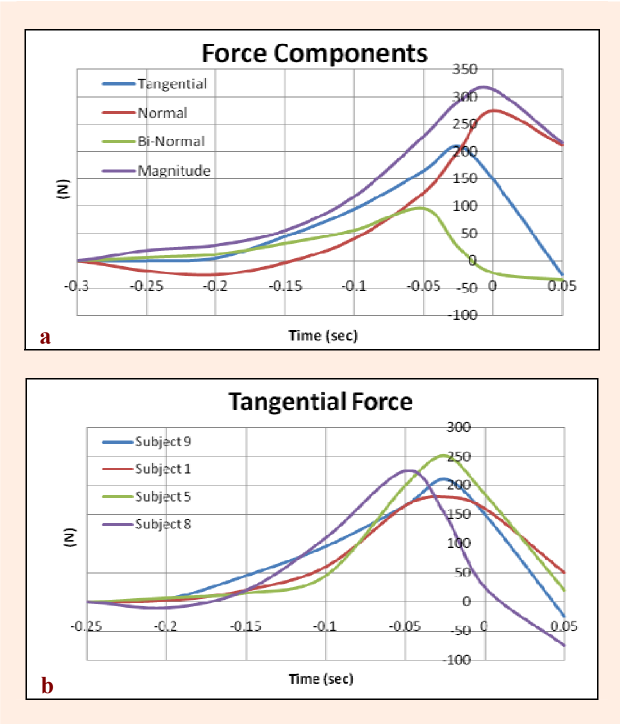
Swing kinematic analyses – angular velocities

Although the linear velocity of the bat at impact is the most important kinematic measure of the swing, it is the angular velocity components that best describe how the swing progresses from initiation to impact. The curves of Figure 7a are typical of most subjects. As expected, the swing angular velocity component is the dominant angular motion in magnitude, followed by the pitch motion, then the roll motion. The initial forward step of the batter causes some negative swing movement in reaction to the bat inertia. Following this, the batter begins to rapidly pitch the bat down while initiating the forward swing movement. The pitch velocity reaches a maximum at approximately 120 degrees before impact. This velocity component then reduces sharply to 60-75 degrees prior to impact as the swing plane becomes established and stable to impact. About 60-75 degrees prior to impact the batter begins to roll the wrists and reaches a maximum speed about 20 degrees before impact when the wrists line up. From this point to impact the roll motion reduces.

The swing motion generally presents as three phases once the forward motion has been initiated. These phases roughly correspond to the radius profile of the hand path. The first phase is from the initiation of the forward swing motion to about 135 degrees before impact. During this phase the hand path radius is increasing, the path of the COR is inside the hand path increasing the effective inertia of the bat, and centripetal loads, linear force, and swing torques (see below) are low. Here the increase in angular velocity is the lowest of the three phases. During the second phase, the hand path radius is decreasing, the path of the hands and COR coincide which results in the lowest effective inertia of the bat, and centripetal loads, linear force, and swing torque are increased. The lines-of-action of the linear force and centripetal force are nearly perpendicular. This phase proceeds until approximately 30 degrees before impact and yields the largest increase in angular velocity. From this point to impact, the hand path radius decreases slightly, the COR is again inside the path of the hands, swing torques decrease, and the increase in angular velocity is reduced. During this phase the linear forces does little to angular accelerate the bat as the lines-of-action of the force and the centripetal force become coincident. The swing angular velocity peaks just before impact for most subjects. Note that these three phases are not well delineated in all subjects. Comparison of the swing angular velocity component profiles of the Random subjects illustrates the differences with which the subjects accelerate the bat during the second phase of the swing, and the resulting peak value at impact. Generating bat speed later in the swing was noted as an advantage in yielding higher bat velocities for most subjects which supported by a hypothesis presented in Russell (2006).

Swing kinetic analyses

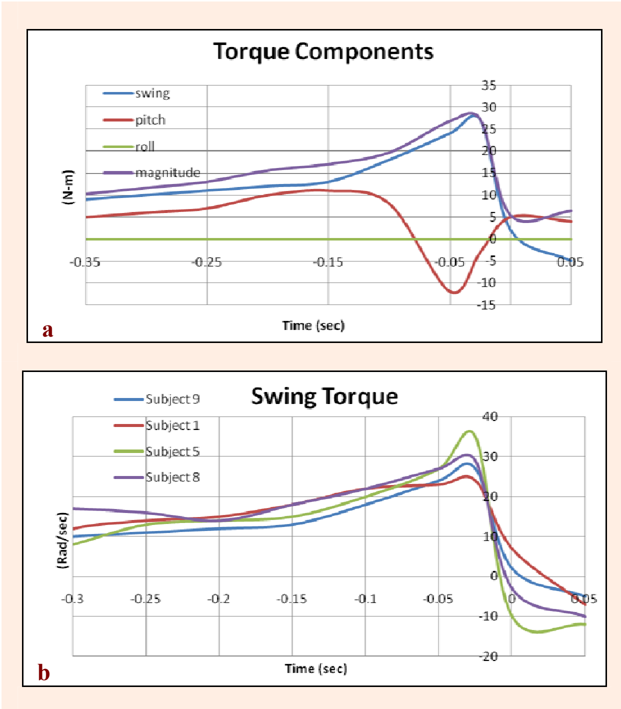
Referring to Figures 8, the tangential component is primarily responsible for changing the linear speed of the bat, while the normal and bi-normal components primarily control the level of the swing plane and the path of the grip point.



Figures 8a and 8b. Interaction force and components for subject 9 and tangential force component for random subjects (Bat #1).

Table 2 reveals a large range in values for all interaction force components for the aggregate group. This finding is not surprising noting the differences in body types, maximum bat velocities, and swing styles among the subjects. In assessing these data, one must keep in mind that the batter is only applying one force to the bat (magnitude) to both accelerate and control its path, and the direction of that force changes as the swing progresses as indicated by the components. Also, the application of the interaction force by the subject on the bat is primarily through the action and strength capacity of the arms (Nesbit and Serrano, 2005).

The force magnitude increases uniformly from zero at the initiation of the swing, to maximum at impact. Referring to Figure 8a, the initial action of the force is to pull the bat away from the body (negative normal force), and move the bat down (bi-normal). Soon after, the tangential component is engaged which acts to linearly accelerate the bat. As the swing progresses, the tangential components becomes more dominant. As the bat passes in front of the path of the hands the normal force changes direction pulling the bat handle towards the body which causes the bat to move away from the body in response. As the bat accelerates and moves away from the body, more force is required to move it down and into a stable swing plane. As the speed of the bat increases, the action of the force become more normal to the path of the hands as the batter pulls harder on the bat to maintain a circular path and reacts to the bats centripetal force. Figure 8b shows the tangential force profiles for the Random subjects. The subjects have similar force profiles until 90 degrees before impact, then the curves begin to diverge. The subjects tend to peak this force component about 30 degrees before impact, although some subjects peak much earlier. The tangential force component drops off quickly to impact.

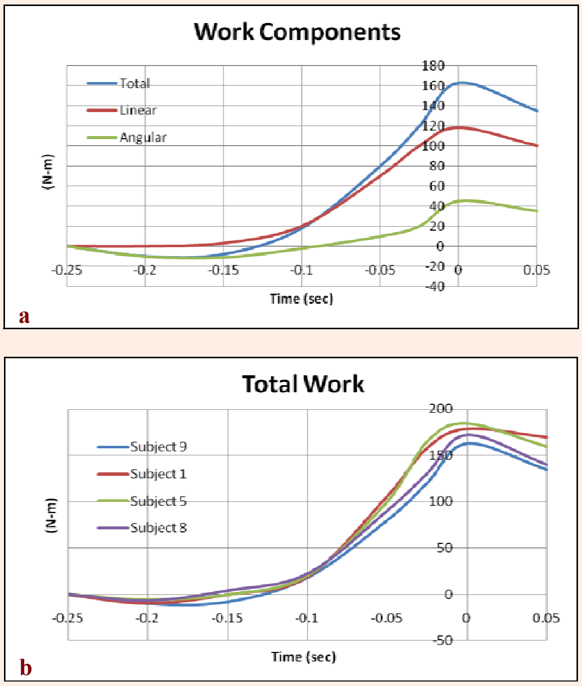


Figures 9a and 9b. Interaction torque and components for subject 9 and tangential force component for random subjects (Bat #1).

Table 2 reveals a large range in values for all interaction torque components for the aggregate group and again this finding is expected based upon the reasons given above. Unlike interaction forces, it does seem possible to independently control the swing and pitch torques. However the roll motion and swing motion appear to be "geared" together especially as the bat nears impact. The magnitude of the torque increases uniformly from the initiation of the swing to about 60 degrees before impact, then drops quickly to near zero at impact. The dominant torque is the swing torque followed by the pitch torque then the roll torque. Here, the application of the interaction torque by the subject on the bat is primarily through the action and strength capacity of the wrists (Nesbit and Serrano, 2005).

The relative profiles of the torque components reveal that the initial action of the torque is to move the bat away from the body (swing component) and simultaneously pitch the bat down. The pitch component reaches a local positive (pitching down) maximum value about 120 degrees before impact and remains fairly constant until the swing plane become well established. The pitch torque drops off quickly and becomes negative as the swing progresses in reaction to further pitching down of the bat.

The torque component then approaches zero near impact as inertial forces maintain the pitch of the swing plane. Once the swing plane becomes established, the swing torque component begins to increase rapidly to its maximum value about 30 degrees before impact, then drops rapidly to near zero at impact. Figure 9b illustrates how the Random subjects applied this torque component to bat #1. Throughout the swing, the roll torque is insignificant although there is considerable angular motion in this direction. This expected result reflects the low inertial resistance relative to the other directions.

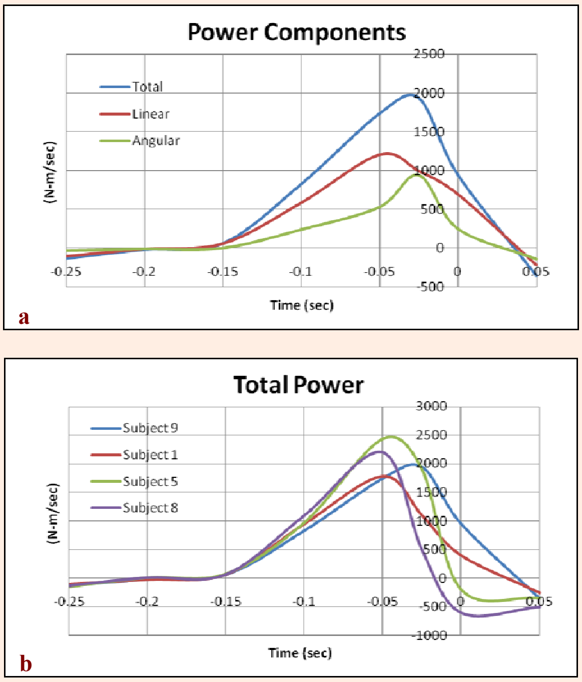


Figures 10a and 10b. Total work and components for subject 9 and total work for random subjects (Bat #1).

Swing energy analyses

An energy analysis of the softball swing was performed to determine the work and power transferred to the bat from the subject, and the resulting kinetic energy of the bat. A fundamental function of the swing is to generate mechanical energy via coordinated body movements, and transfer as much of this mechanical energy to the bat in the form of kinetic energy. An energy analysis also has the following advantages: Only the forces/torques that change the velocity of the bat are taken into account, i.e., forces/torques that does no work are ignored; the cumulative effects of forces/torques applied over a distance are determinable which introduces factors such as range of motion, timing, and sustainability of forces/torques; the collective effect of various body motions can be summarized by looking at the output (i.e., the energy transferred to the bat and the resulting bat velocity) (Nesbit and Serrano, 2005).

The total output work curves of Figures 10 indicates the subjects' ability to apply external forces and torques in the direction of motion during the swing, and reveals differences among the four subjects in magnitude, shape, and timing. It is interesting that all subjects had nearly the same total work to about 60 degrees before impact which is typical of all subjects. At this point in the swing to impact, there is a rapid increase in the rate at which the subjects apply work to the bat which is reflected in the total power (Figure 11b). It is also during this portion of the swing that the subjects separate from each other in their ability to generate bat speed. The total work and linear and angular components peak for all subjects near impact which results in the optimum transfer of energy to the bat. The total work appears to be the primary factor in generating bat velocity (and kinetic energy) and this relationship is predicted by Newton's Laws. The maximum kinetic energy of the bat was found to be about 85-90% of the work done by the subjects. This loss of efficiency is most likely due to the slight backwards movement of the bat at the initiation of the swing and the negative work done in stabilizing the swing plane.



Figures 11a and 11b. Total power and components for subject 9 and total power for random subjects (Bat #1).

The power curves reflect a subject's ability to apply external forces and torques as the swing increases in velocity. These curves also reveal significant differences among the subjects with range of 2.5/1 between subject maximum and minimum. The total power, and the linear and angular components all peak prior to impact. Total power peaks about 30 degrees before impact. The peak linear component corresponds to the point where the bat is about 45 degrees before impact, and the peak angular powers about 20 degrees from impact. The total power and components drop rapidly from their maximum values until impact as the batter is unable to maintain the interaction forces and torques at high levels as the bat rapidly increases in speed.

The internal body work is transferred to the bat by and through the arms and wrists highlighting their dual "energy generating" and "structural" functions. The data indicates that the linear contributions of work and power (action of the arms) are significantly more important than the angular contributions (action of the wrists) in transferring energy generated within the body to the bat. On average, the ratio of linear to angular work is 3/1, and linear to angular power is near 2/1. The large ranges in interaction torque and force values among subjects are tempered by each subject's ability to maintain these forces and torques over the range of motion of the swing. In other words, it is their ability to do work with these forces and torques that determines the bat velocities. Thus the differences in bat velocities among the subjects is not nearly as pronounced as their respective differences in interaction forces and torques would imply.

Effect of bat type on swing mechanics

All subjects used two distinct bats during the trials with significantly different properties (see Table 1). The objective was to reveal how the subjects may adjust/react to different bat configurations and properties. While this aspect of the study was incomplete, some interesting trends were revealed that merit reporting and possible further study. For all subjects, their individual trajectory characteristics were essentially unchanged, i.e., it was not possible to visually distinguish which bat the subjects used from figures of the type of Figures 2 through 4, nor the trajectory characteristics such as the paths of the COP, COR, or grip point. This finding is supported by the fact that the maximum grip point velocities were nearly identical for the two bats (Table 2), and the velocity profiles were often indistinguishable (Figures 6). The maximum values of the angular velocity components were all slightly lower for bat #2. This was offset by the greater distances to the CG and COP for bat #2 which ultimately resulted in slightly higher CG and COP velocities for bat #2. From a kinetic perspective, the maximum linear force components were higher for bat #2, whereas the maximum torque components were all nearly the same. In terms of energy, the subjects did more linear work and applied greater linear power to bat #2. The angular work and power were fairly consistent.

Thus in general it appears that these subjects adjusted to the different bat configurations by a variety of means which resulted in comparatively consistent kinematic trajectories. Specifically, these subjects adjusted their linear input quantities (force, linear work and power) apparently in response to different bat masses. This finding implies that batters may be sensitive to bat mass differentials, and have reserve capacity to adjust their linear kinetic and energy inputs to maintain their characteristic swing trajectories. On the other hand, these same subjects maintained consistent angular input quantities (torques, angular work and power) independent of the significant differences in bat inertias. This finding implies that batters either may not be sensitive to bat inertia differentials, or that they may be applying their maximum angular kinetic and energy capacities for both trial bats. The resulting angular kinematic response thus reflects the differences in bat inertia. Since the increased linear kinetic and energy inputs compensate for the consistent angular kinetic and energy inputs, similar kinematic trajectories and bat velocities are achieved for the two bat configurations, however differences are noted in bat kinetic energies.

Practical implications

The ability to completely describe the three-dimensional kinematics and kinetics of the female softball swing utilizing a computer model has numerous practical implications for practitioners and researchers. This information allows one to quantitatively explain a softball swing from a mechanics perspective by explicitly detailing the time history of the motions, interaction forces/torques, and energy inputs and transfers. Doing so for a group of subjects revealed a number of important characteristics of the swing, and similarities/differences among subjects. The following observations and practical implications are offered:

- The paths of the hands/grip point, bat centre-of-curvature, CG, and COP are complex for all subjects yet reveal consistent patterns among the subjects indicating that these patterns are a fundamental component of the swing. These paths were found to be relatively repeatable for a given subject and independent of the bat used.
- The ability to generate bat speed appears to depend upon a number of factors including the timing of the bat movement relative to the body, the path of the hands, the ability to do work.
- The range of values in all kinetic and energy inputs among the subjects was surprising large. However, the range in the linear velocity values does not reflect this range to the same degree.
- It appears that the most important kinetic/energy input relative to bat speed was the ability to do mechanical work on the bat. Mechanical work quantifies the effects of force/torque acting over a displacement and weighs each part equally. Thus one does not necessarily have to be strong and powerful to do much mechanical work. One must be able to apply a more consistent force/torque over a greater range of motion to do more work which is entirely possible for any size player.
- Batters may adjust some of their kinetic/energy inputs in order to maintain consistent swing trajectories. Linear input adjustments were more evident than angular input adjustments.

Conclusion

Despite the widespread popularity and large number of participants in female competitive softball, the supportive biomechanical analyses of the softball swing is limited when compared to male dominated sports such as golf and baseball. Thus the overall goal of this study was to describe the fundamental three-dimensional mechanics of the female softball swing, and reveal the underlying and important biomechanical components of the motion. The method involved developing and utilizing a computer model of the softball swing for predicting the relevant three-dimensional kinematic and kinetic quantities of the swing for college level subjects. Significant findings from these efforts included completely characterizing the 3D kinetics and kinematics of the swing, estimating the energy transfers from the batter to the bat, analyzing a group of subjects for basic statistical information, and highlighting similarities and differences in swing mechanics among subjects. This analysis revealed the true complexity and individuality of the female softball swing motion. From this information descriptions of the fundamental swing mechanics and practical implications were offered. In addition, the potential effects of bat properties on swing mechanics were discussed. An important outcome of the study was the development of the three-dimensional dynamic model of the swing which consciously avoided applying the simplifying assumptions that limited the accuracy previous modeling attempts. The findings presented in this study should form the basis for further biomechanical analyses of the female softball swing, and may have important implications for coaching, equipment design, and injury assessment.

Acknowledgements
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Key points

- The female softball swing is a highly coordinated and individual three-dimensional motion and subject-to-subject variations were significant in all kinematic and kinetic quantities.
- The paths of the grip point, bat centre-of-curvature, CG, and COP are complex yet reveal consistent patterns among subjects indicating that these patterns are fundamental components of the swing.
- The most important mechanical quantity relative to generating bat speed is the total work applied to the bat from the batter.
- Computer modeling of the softball swing is a viable means for study of the fundamental mechanics of the swing motion, the interactions between the batter and the bat, and the energy transfers between the two.

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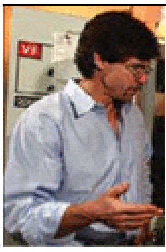

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