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Article

Measures of Joint Kinematic Reliability During Repeated Softball Pitching

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Abstract: Background/Objectives: Three-dimensional motion analysis is often used to evaluate improvements or decrements in movement patterns in athletes. The purpose of this study was to evaluate the reliability of joint flexion/extension angles of the pitching elbow and bilateral knees and hips in softball pitchers. Methods: Fourteen softball pitchers (17.9 ± 2.3 years) were tested in one session consisting of four sets of five consecutive fastballs and a second session of two sets of five fastballs. The magnitude of systematic bias and within-subject variation was calculated between pitches. An iterative intraclass correlation coefficient (ICC) process was used to determine intra- and inter-session reliability, standard error of measurement and minimal detectable change. Results: Reductions in within-subject variation were observed for all variables when the number of pitches used in calculations was increased. Intra-session ICC values ranged from an average of 0.643 for pitching elbow to 0.989 for stride leg knee. Inter-session ICC values ranged from an average of 0.663 for pitching elbow to 0.996 for stride leg knee. Conclusions: Joint flexion/extension angles during the softball windmill pitch can be measured with good to high reliability using three-dimensional motion analysis. Biomechanical analysis can be confidently used to detect changes in the pitching motion over the course of a season or following an intervention.

Keywords: intra-session; inter-session; minimal detectable change; joint kinematics

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1. Introduction

Biomechanical evaluation of sport can provide a detailed analysis of movement, which can be used to both prevent and rehabilitate injury and improve performance [1,2]. With respect to softball performance, the calculation of joint positions using three-dimensional (3D) motion analysis can improve understanding of movement patterns. Reliable kinematic assessments of the softball windmill pitch can be used to categorize athletes into the most appropriate training program and pick up on subtle biomechanical changes that may lead to long-term pain [3]. However, the number of pitches used for analysis cannot be arbitrarily selected, with no rationale for the number of trials used to assess changes in biomechanics.

Phases of fast-pitch softball, windmill-style delivery have been described by the humerus's position in relation to the trunk in the sagittal plane, with these positions labeled as the positions of a clock [4]. Although the windmill pitch is a continuous motion, it can be divided into smaller phases, similar to the baseball pitch, to better understand and evaluate the movement pattern. Using motion analysis, previous work has found trunk and upper extremity flexion angles during specific phases of the windmill pitch are related to pitch type [5,6] and performance [6,7]. The reliability of kinematic assessment in the sagittal plane is essential to quantify, identify and track changes in windmill pitch movement patterns.

To correctly interpret changes in kinematics due to maturation or fatigue, researchers need to know if the change is real or the result of testing error. Equipment limitations, soft tissue artifacts [8], and subject's biological variations can cause error in biomechanical measurements even with the best methodology. Despite standardized procedures to ensure optimal reliability, some movements may be too dynamic or inherently variable to monitor small changes in performance. Therefore, multiple trials of the same activity are considered to provide a more stable representation of biomechanical variations [9]. If measurement techniques display high reliability, researchers can be more confident that a real change has occurred in a given variable [10]. Additionally, establishing good reliability allows future studies to utilize a smaller sample size to determine if a real change is present.

It is paramount that reliability is available when working with or conducting research in a specific population. The main measures of reliability are: (1) systematic bias; (2) within-subject variation and (3) test–retest reliability [10]. Systematic bias refers to variations in the group average from one trial to another, which may be caused by learning effects or fatigue [10]. The presence of systematic bias is important to determine if familiarization trails are needed to reduce learning effects [11]. Within-subject variation encompasses the degree of random variation (noise) in repeated measurements on the same subject, which can arise from biological factors or measurement error [10]. Smaller values of within-subject variation allow a more precise assessment of meaningful changes in a performance variable. Lastly, test–retest reliability measures how consistently subjects maintain their rank order within a sample [10] and is used to assess the stability and repeatability of specific variables across repeated trials [12]. Minimal detectable change can then be measured as the level in which change in score is due to real change rather than measurement error. Analyzing the magnitude of these factors in the windmill softball pitch will provide valuable information to inform future studies of softball biomechanics in terms of the necessary number of trials required to obtain accurate and stable measures of the windmill pitch and what extent of joint angle change needs to occur to be considered a true performance change.

With more studies using 3D motion analysis to evaluate changes in biomechanics due to an intervention or over the course of a season, it is necessary to understand whether kinematic differences represent a true change in movement pattern. Clinicians and researchers must seek reliable methods to quantify windmill softball pitch mechanics. The purpose of this study was to report the reliability of joint flexion/extension angles of the pitching elbow and bilateral knees and hips. Specifically, the aims of the current study are: (1) to determine the magnitude of systematic bias; (2) to establish the within-subject variation; (3) to analyze test–retest reliability and (4) to assess standard error of measurement (SEM) and minimal detectable change (MDC) of discrete kinematic variables.

2. Materials and Methods

2.1. Participants

Fourteen female softball pitchers (17.9 ± 2.3 yrs, 166.4 ± 8.7 cm, 72.2 ± 12.6 kg) completed this study. All participants were currently active on an American high school (n = 6) or collegiate (n = 8) roster as softball pitchers, participating in softball-related activity at a minimum of 3 times per week, with at least one-year varsity experience pitching with a windmill style softball pitch. Approval of the study was given by the University's Institutional Review Board. Written informed consent was obtained from all participants, with written parental consent obtained from participants under the age of 18. Participants were asked to refrain from engaging in exercise or additional physical activity other than their daily living activities for the twenty-four hours prior to each testing session.

Subject anthropometrics, marker placement and motion analysis system calibration were completed by the same researcher for each subject. Upper and lower extremity anthropometrics were taken of each participant, including height (centimeters) and weight (kilograms). These measurements were entered in the Vicon Nexus software (Vicon Motion Systems Inc., Centennial, CO, USA) to create a custom model from the 3D coordinate data. The Vicon Three-Dimensional (3D) Infrared Optical Capture System (Vicon Motion Systems Inc., Centennial, CO, USA) used 15 wall-mounted and three tripod-mounted high-speed infrared cameras and kinematics were collected at 300 Hz. Kinematics during the windmill softball pitch were calculated based on the three-dimensional coordinate data of a custom marker set created based on Vicon's full body model. A custom marker set was necessary for analyzing the windmill softball pitch due to the unique challenges presented by its 360-degree arm motion, which standard marker sets are not optimized to capture. Additionally, the specific technique used by some softball pitchers, where they swipe the lateral aspect of their thigh with their glove, prohibited the use of standard marker locations on the lateral thigh. Thirty-one 14 mm retro-reflective markers were placed on the participant's torso, upper and lower extremities. Retro-reflective markers were placed on the spinous process of the 7th cervical vertebra (C7), sternal notch, xyphoid process, 1st sacral vertebrae (S1), non-pitching lateral aspect of the upper arm and forearm and bilaterally on the following landmarks: acromioclavicular joint, lateral and medial humeral epicondyle, radial and ulnar styloid, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), medial and lateral femoral epicondyle, medial and lateral malleolus, lateral aspect of 1st and 5th metacarpophalangeal joint and posterior aspect of the heel (Figure 1). Additionally, a custom-fabricated 4 non-collinear marker cluster, using 9.5 mm markers, was placed on the posterior humerus and radius of the pitching arm, bilateral posterior thigh and shank (Figure 2). A 3 non-collinear marker cluster was placed over the spinous process of the 3rd thoracic (T3) and 3rd lumbar vertebrae (L3). The orientation and position of each rigid segment's local coordinate system were determined by the reconstructed marker positions for each segment.

Figure 1. Full body custom marker placement.

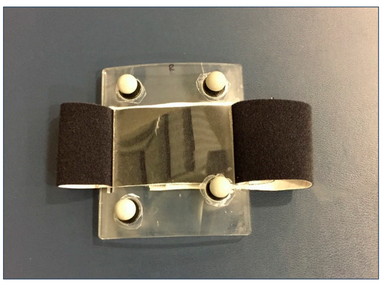

Figure 2. Non-collinear marker cluster.

2.2. Procedures

Prior to the data collection of pitches, each participant was allowed her normal pitching warm-up routine until she verbally stated that she felt warmed up and comfortable with the testing environment [3]. The average participant warm-up included a general dynamic full-body warm-up to increase the heart rate and muscle tissue temperature followed by a throwing progression of wrist flicks, isolated arm swings, one-knee drills, long toss and ending with full windmill pitching. A 2.1 m by 2.1 m (7 ft × 7 ft), a Portable Bow Net with strike zone was set up behind the home plate, and a pitching location was taped off 9.14 m from the back end of the home plate. This pitching location was on a level platform built around the force plates. Drive leg ground reaction forces (GRF) were collected using a 60 cm × 40 cm force platform (Type 9286A, Kistler Instrument Corp., Amherst, NY, USA) at a sampling frequency of 1500 Hz to determine push-off in initiating the windmill pitch. A pitching rubber was not used because it could not safely be secured to the floor. On Day 1, participants threw four sets of five consecutive fastballs. On Day 2, participants threw two sets of five fastballs. A one-minute rest was given between each set.

2.3. Data Reduction

The 3D positions of the retroreflective markers were reconstructed in the global coordinate system, with the X axis pointing toward the home plate, the Z axis being vertical and pointing upwards, and the Y axis perpendicular to both the X and Z directions. Based on the custom marker set, participant-specific models were created in Visual 3D (HAS-Motion, Kingston, ON, Canada). The estimation of hip, knee, and ankle joint centers and the definition of segmental coordinate systems used participant-specific anthropometric data. Joint angles were expressed according to the International Society of Biomechanics recommendations [13,14]. Three-dimensional joint flexion/extension angle data were calculated with Euler angle rotational decomposition using the right-hand rule in a sequence of X, Y, Z, where X values denote flexion/extension, Y values abduction/adduction and Z values axial rotation [15,16]. GRF data were recorded using the Vicon Nexus software and filtered using a low-pass, zero-lag, fourth-order Butterworth filter with a cutoff frequency of 50 Hz within MATLAB (R2015b, Mathworks Inc., Natick, MA, USA) [17]. Flexion/extension angles were calculated for the drive leg (pitching arm side) at push-off, defined by maximal anterior–posterior GRF and flexion/extension angles of the stride leg and pitching elbow at stride foot contact, defined by the first lowest position of the posterior heel marker.

2.4. Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistics 21 (IBM Corp., Armonk, NY, USA). Statistical significance was set a priori at $p < 0.05$, two-sided. The heteroscedasticity of the data was assessed by plotting the standard deviation of the trials against the mean for each participant. If heteroscedasticity was not present, raw data were used to calculate reliability. Data were log-transformed using 100× the natural logarithm of the observed value if necessary [10].

Systematic bias was determined using a repeated measure analysis of variance (RM ANOVA) for each kinematic variable to determine if values for each pitch on Day 1 were statistically significant. No statistically significant differences occurred; therefore, no pitches were removed from further calculations of reliability (WS variation and test–retest correlations).

Within-subject variation was calculated as the typical error (TE) and coefficient of variation (CV) using the mean (M_n) value and mean square error (MSE_n) value from the

RM ANOVA from n repeated cycles [10]. Variation was reported as accumulating trials with increasing 'n'. TE was calculated as

$$TE = \sqrt{MSE_n}$$

The coefficient of variation was calculated as

$$CV = 100\left(\frac{TE_n}{M_n}\right)$$

Intra- and inter-session test–retest reliability was evaluated using the intraclass correlation coefficient (ICC 1, k). The initial ICC per set was determined for two pitches. An iterative process was then conducted, whereby repated ICC values were performed, including an additional pitch with each iteration. For inter-session reliability, the iterative process included an additional pitch from each day 1 and day 2. Intra- and inter-session ICC values for pitches were calculated [18]. ICC values of <0.5, 0.5–0.75, 0.75–0.9 and >0.9 were interpreted as poor, moderate, good and excellent, respectively [12]. The SEM was estimated from standard deviation and the test–retest reliability index (SEM = sd × ($\sqrt{1}$ − intraclass correlation coefficient)) [12]. The MDC was estimated from the SEM and a 95% degree of confidence (MDC_{95} = SEM × 1.96 × $\sqrt{2}$) [12].

3. Results

Average joint flexion/extension angles can be seen in Table 1.

Table 1. Average joint flexion angles (°).

Stride Leg Hip	Stride Leg Knee	Drive Leg Hip	Drive Leg Knee	Pitching Elbow
24.11 ± 8.57	77.42 ± 12.43	25.37 ± 7.20	56.08 ± 1.95	35.04 ± 2.51

mean ± standard deviation.

When assessing for systematic bias, no statistically significant differences were seen between testing sessions for joint flexion/extension angles of stride and drive leg hip and knee and pitching elbow (Figure 3). All data were included in subsequent analyses.

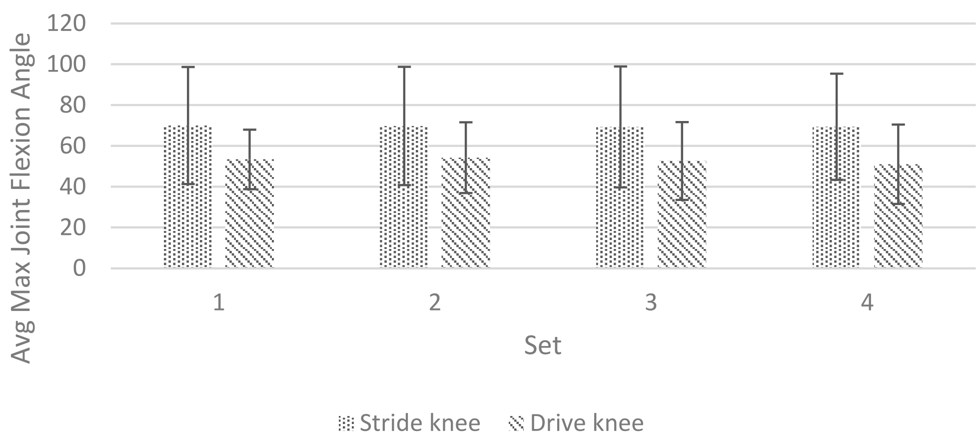

Figure 3. *Cont.*

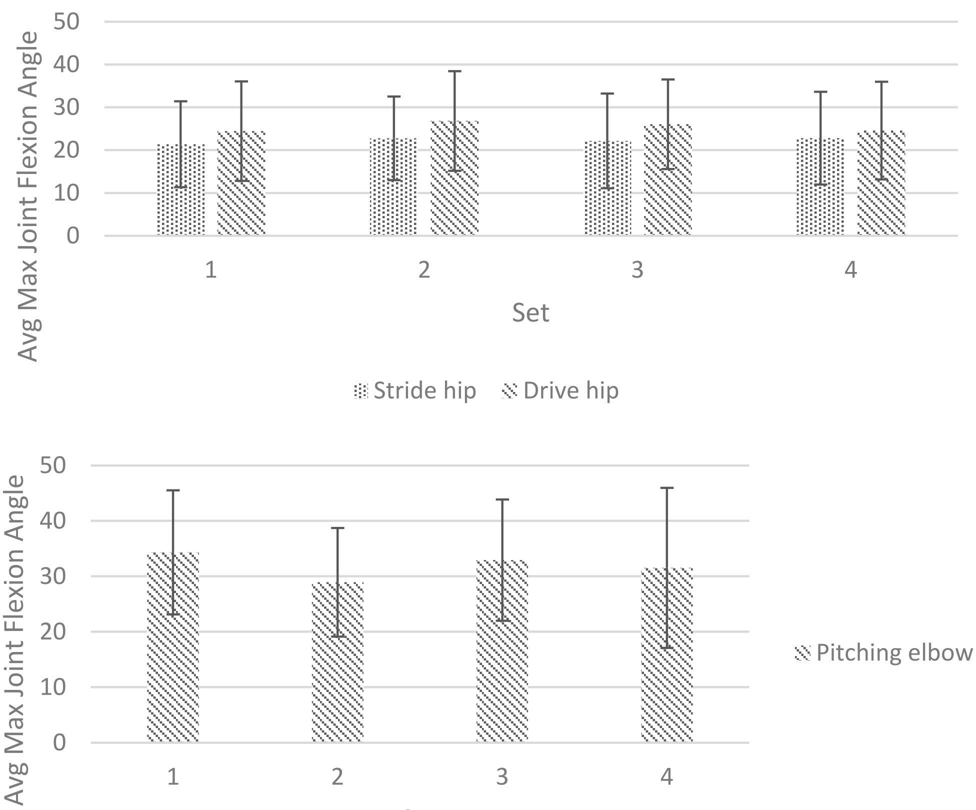

Figure 3. Systematic bias of joint flexion/extension angles. Values are set means, bars are SD.

The amount of random error within each kinematic variable was used to represent within-subject variation (Tables 2–6). Dependent on the presence of heteroscedasticity, the measures of random error are expressed in ratio form (×/÷). The CV expressed in ratio form represents the typical within-subject variability as a multiplicative factor, and values above or below 1.0 represent the proportional spread of data around the mean [19]. Additionally, the magnitude of $\%CV_{te}$ relative to each joint flexion/extension angles are shown in Tables 2–6, allowing for a direct interpretation of the percentage variation from the mean. The calculated mean $\%CV_{te}$ for stride leg hip (19.64), stride leg knee (9.83), drive leg hip (13.83), drive leg knee (7.38) and pitching elbow (26.56) demonstrate the extent of random error within each kinematic variable.

The level of performance stability for each kinematic variable was assessed for intra- and inter-session test–retest reliability, SEM and MDC (Tables 7 and 8). Intra-session ICC values ranged from an average of 0.643 for pitching elbow to 0.989 for stride leg knee. Average intra-session SEM values ranged from 4.368 for stride leg hip to 0.308 for drive leg knee. Inter-session ICC values ranged from an average of 0.663 for pitching elbow to 0.996 for stride leg knee. Average intra-session SEM and MDC values ranged from 4.37 and 12.10 for stride leg hip to 0.29 and 0.81 for drive leg knee, respectively.

Table 2. Stride leg hip joint flexion/extension angle within-subject variability.

# Pitches	TE	Lower	Upper	%CV	Lower	Upper
2	1.29	1.24	1.38	28.87	23.52	38.07
3	1.28	1.22	1.39	27.76	22.11	38.75
4	1.25	1.20	1.39	25.35	19.55	39.27
5	1.23	1.19	1.30	22.70	18.65	30.09
6	1.21	1.17	1.30	21.46	17.27	30.23
7	1.21	1.18	1.28	21.43	17.62	28.37
8	1.21	1.16	1.33	20.96	16.32	33.25
9	1.20	1.16	1.27	20.08	16.40	26.54
10	1.19	1.15	1.26	19.00	15.08	26.23
11	1.18	1.14	1.25	18.04	14.49	24.83
12	1.18	1.13	1.33	17.98	12.61	32.70
13	1.18	1.13	1.30	17.75	12.84	29.74
14	1.18	1.14	1.27	17.74	13.77	27.04
15	1.18	1.14	1.23	17.52	14.39	22.80
16	1.17	1.13	1.26	17.11	13.29	26.05
17	1.17	1.14	1.23	16.86	13.55	23.16
18	1.15	1.12	1.24	15.47	11.82	23.63
19	1.15	1.11	1.25	14.80	10.74	24.59
20	1.12	1.09	1.20	12.21	8.89	20.15

Random error expressed in ratio form (×/÷); TE, typical error for n cycles; lower, lower confidence limit; upper, upper confidence limit; %CV = coefficient of variation expressed as a percentage.

Table 3. Stride leg knee joint flexion/extension angle within-subject variability.

# Pitches	TE	Lower	Upper	%CV	Lower	Upper
2	1.19	1.16	1.26	19.27	15.93	25.75
3	1.17	1.14	1.24	17.26	13.94	24.15
4	1.15	1.11	1.26	15.44	11.19	25.70
5	1.13	1.11	1.17	13.49	11.11	17.47
6	1.13	1.10	1.18	12.89	10.39	17.59
7	1.12	1.09	1.21	12.47	9.08	20.59
8	1.12	1.10	1.19	12.30	9.60	18.53
9	1.11	1.09	1.16	10.91	8.52	16.39
10	1.10	1.08	1.14	10.21	8.25	13.87
11	1.09	1.07	1.12	8.89	7.19	12.06
12	1.09	1.07	1.11	8.62	7.13	11.10
13	1.08	1.06	1.13	7.86	5.75	12.80
14	1.07	1.06	1.11	7.22	5.66	10.76
15	1.06	1.05	1.09	6.19	4.89	9.49
16	1.06	1.04	1.10	5.75	4.16	9.63
17	1.06	1.05	1.07	5.59	4.67	7.33
18	1.04	1.03	1.07	4.50	3.48	6.70
19	1.04	1.03	1.06	4.26	3.43	5.75
20	1.04	1.03	1.06	3.68	2.63	6.39

Random error expressed in ratio form (×/÷); TE, typical error for n cycles; lower, lower confidence limit; upper, upper confidence limit; %CV = coefficient of variation expressed as a percentage.

Table 4. Drive leg hip joint flexion/extension angle within-subject variability.

# Pitches	TE	Lower	Upper	%CV	Lower	Upper
2	1.22	1.17	1.30	21.67	17.35	29.98
3	1.21	1.15	1.36	21.08	15.19	35.63
4	1.17	1.14	1.22	17.15	14.09	22.31
5	1.16	1.11	1.26	15.77	11.43	26.28
6	1.16	1.12	1.24	15.70	12.21	23.83
7	1.15	1.12	1.19	14.51	11.94	18.81
8	1.14	1.10	1.27	14.23	9.84	27.01
9	1.14	1.11	1.21	14.00	10.90	21.17
10	1.14	1.11	1.19	13.99	11.27	19.13
11	1.13	1.10	1.21	13.28	10.21	20.86
12	1.13	1.10	1.17	12.53	10.11	17.10
13	1.12	1.10	1.16	12.19	10.05	15.76
14	1.12	1.09	1.18	11.74	9.16	17.67
15	1.11	1.09	1.16	11.45	9.19	15.90
16	1.11	1.09	1.15	11.15	9.17	14.57
17	1.11	1.09	1.15	11.12	8.98	15.13
18	1.11	1.08	1.18	10.90	7.94	17.91
19	1.10	1.08	1.16	10.47	8.18	15.71
20	1.10	1.07	1.16	9.88	7.21	16.19

Random error expressed in ratio form (×/÷); TE, typical error for n cycles; lower, lower confidence limit; upper, upper confidence limit; %CV = coefficient of variation expressed as a percentage.

Table 5. Drive leg knee joint flexion/extension angle within-subject variability.

# Pitches	TE	Lower	Upper	%CV	Lower	Upper
2	1.11	1.09	1.15	11.13	9.08	14.54
3	1.10	1.08	1.17	10.47	7.63	17.18
4	1.10	1.08	1.14	9.95	8.04	13.52
5	1.10	1.07	1.14	9.53	7.46	14.27
6	1.09	1.07	1.12	9.01	7.45	11.60
7	1.09	1.07	1.13	8.61	6.59	12.89
8	1.08	1.06	1.13	8.24	6.37	12.79
9	1.08	1.07	1.11	8.22	6.83	10.79
10	1.08	1.06	1.11	7.81	6.33	10.58
11	1.08	1.06	1.11	7.73	6.30	10.79
12	1.07	1.05	1.14	7.16	4.89	14.17
13	1.07	1.06	1.09	6.98	5.80	9.06
14	1.07	1.06	1.09	6.73	5.57	8.63
15	1.07	1.05	1.11	6.54	4.79	10.62
16	1.05	1.04	1.08	5.23	4.11	7.75
17	1.05	1.04	1.07	4.75	3.73	7.04
18	1.05	1.03	1.08	4.65	3.42	7.51
19	1.05	1.04	1.06	4.54	3.69	6.12
20	1.03	1.02	1.05	3.00	2.10	5.45

Random error expressed in ratio form (×/÷); TE, typical error for n cycles; lower, lower confidence limit; upper, upper confidence limit; %CV = coefficient of variation expressed as a percentage.

Table 6. Pitching elbow joint flexion/extension angle within-subject variability.

# Pitches	TE	Lower	Upper	%CV	Lower	Upper
2	1.37	1.30	1.51	37.39	29.93	50.55
3	1.37	1.27	1.58	36.93	27.38	58.32
4	1.37	1.27	1.58	36.91	27.36	58.28
5	1.37	1.27	1.58	36.68	29.37	49.54
6	1.35	1.25	1.64	35.26	24.64	64.35
7	1.34	1.27	1.48	34.03	26.51	48.40
8	1.32	1.25	1.45	31.53	24.61	44.69
9	1.30	1.24	1.41	29.83	24.21	41.17
10	1.29	1.22	1.45	28.94	21.62	45.00
11	1.28	1.22	1.39	27.66	21.66	38.99
12	1.25	1.18	1.44	24.91	17.61	44.18
13	1.23	1.17	1.35	22.53	16.94	34.59
14	1.20	1.14	1.36	20.40	14.50	35.72
15	1.19	1.15	1.27	19.09	15.06	26.55
16	1.19	1.15	1.25	18.65	15.06	25.00
17	1.18	1.14	1.25	17.95	14.05	25.48
18	1.17	1.14	1.23	17.29	14.05	22.81
19	1.16	1.11	1.33	15.99	10.78	32.86
20	1.13	1.09	1.20	12.73	9.49	19.93

Random error expressed in ratio form (×/÷); TE, typical error for n cycles; lower, lower confidence limit; upper, upper confidence limit; %CV = coefficient of variation expressed as a percentage.

Table 7. Intra-session joint flexion/extension angle Interclass Correlation Coefficient (1,k).

	Stride Leg Hip			Stride Leg Knee			Drive Leg Hip			Drive Leg Knee			Pitching Elbow		
# Pitches	ICC	95% CI		ICC	95% CI		ICC	95% CI		ICC	95% CI		ICC	95% CI	
2	0.815	0.534	0.957	0.995	0.976	0.999	0.874	0.642	0.972	0.941	0.658	0.990	0.516	0.326	0.753
3	0.828	0.492	0.937	0.966	0.914	0.992	0.901	0.690	0.976	0.945	0.770	0.999	0.524	0.384	0.782
4	0.822	0.504	0.959	0.974	0.934	0.994	0.925	0.790	0.981	0.948	0.783	0.999	0.533	0.316	0.835
5	0.845	0.548	0.940	0.977	0.940	0.995	0.953	0.869	0.989	0.950	0.795	0.999	0.581	0.390	0.871
6	0.844	0.586	0.969	0.981	0.951	0.996	0.965	0.906	0.992	0.956	0.820	0.999	0.546	0.388	0.786
7	0.850	0.600	0.965	0.984	0.959	0.997	0.972	0.928	0.994	0.954	0.813	0.999	0.614	0.138	0.886
8	0.873	0.667	0.974	0.986	0.965	0.997	0.975	0.936	0.994	0.960	0.851	0.993	0.626	0.088	0.862
9	0.896	0.730	0.979	0.988	0.970	0.998	0.980	0.950	0.995	0.976	0.923	0.995	0.651	0.217	0.898
10	0.897	0.545	0.977	0.990	0.972	0.998	0.985	0.960	0.997	0.982	0.942	0.997	0.658	0.228	0.900
11	0.898	0.656	0.993	0.991	0.973	0.998	0.987	0.967	0.997	0.985	0.952	0.998	0.662	0.249	0.900
12	0.911	0.702	0.994	0.992	0.979	0.998	0.989	0.972	0.998	0.987	0.960	0.998	0.679	0.292	0.905
13	0.913	0.774	0.982	0.994	0.983	0.999	0.989	0.956	1.000	0.986	0.960	0.998	0.678	0.470	0.792
14	0.919	0.791	0.984	0.995	0.987	0.999	0.989	0.956	1.000	0.988	0.966	0.998	0.688	0.086	0.916
15	0.919	0.727	0.994	0.996	0.990	0.999	0.987	0.946	1.000	0.989	0.966	0.999	0.689	0.311	0.908
16	0.926	0.797	0.988	0.995	0.982	1.000	0.990	0.958	1.000	0.989	0.966	0.999	0.697	0.083	0.882
17	0.936	0.782	0.995	0.996	0.988	1.000	0.990	0.961	1.000	0.987	0.960	0.998	0.703	0.347	0.912
18	0.922	0.758	0.981	0.996	0.987	1.000	0.991	0.976	0.998	0.988	0.963	0.999	0.712	0.369	0.915
19	0.942	0.840	0.985	0.997	0.990	1.000	0.992	0.979	0.998	0.990	0.969	0.999	0.718	0.377	0.917
20	0.951	0.832	0.996	0.997	0.991	1.000	0.992	0.978	0.999	0.992	0.972	0.999	0.745	0.442	0.924

Table 8. Inter-session Maximum Joint Flexion Angle Interclass Correlation Coefficient (1,k), SEM and MDC.

	Stride Leg Hip			Stride Leg Knee			Drive Leg Hip			Drive Leg Knee			Pitching Elbow		
# Pitches Each Day	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC
2	0.753	6.08	16.84	0.992	1.10	3.04	0.748	2.59	7.19	0.932	0.60	1.67	0.501	1.31	3.62
3	0.760	5.94	16.47	0.994	0.92	2.56	0.783	2.45	6.80	0.961	0.42	1.16	0.526	1.34	3.70
4	0.812	5.30	14.68	0.996	0.77	2.14	0.826	2.23	6.17	0.977	0.33	0.92	0.593	1.22	3.37
5	0.851	4.76	13.18	0.997	0.69	1.92	0.896	2.06	5.72	0.979	0.32	0.88	0.640	1.16	3.21
6	0.880	4.28	11.85	0.997	0.64	1.77	0.925	1.71	4.74	0.986	0.24	0.66	0.685	1.23	3.41
7	0.906	3.83	10.61	0.998	0.62	1.72	0.934	2.01	5.56	0.988	0.18	0.51	0.715	1.66	4.61
8	0.922	3.55	9.83	0.998	0.58	1.59	0.949	2.10	5.82	0.989	0.18	0.50	0.760	1.57	4.34
9	0.952	2.80	7.76	0.998	0.56	1.55	0.960	1.97	5.47	0.990	0.17	0.47	0.767	1.54	4.26
10	0.953	2.76	7.66	0.998	0.55	1.53	0.967	1.72	4.77	0.988	0.19	0.51	0.793	1.50	4.16

ICC = intraclass correlation. SEM = standard error of measurement. MDC = minimal detectable change.

4. Discussion

The increasing use of 3D motion analysis combined with the growth of softball research necessitates that kinematic components of the windmill softball pitch be evaluated in terms of their reliability. It is crucial to understand if the number of pitches analyzed represents a participant's overall pitching performance and whether data are consistent over time when making clinical decisions. The present study is the first to report reliability measures of kinematic variables of the windmill softball pitch. Results of this study showed lower extremity joint flexion/extension angles were more reliable than the pitching arm (Tables 7 and 8). There was consistent improvement in reliability and a decrease in SEM and MDC with an increasing number of trials.

The first aim of this study was to determine if there was an increase or decrease in measurements from trial to trial, indicating systematic bias potentially due to learning effect or fatigue [20]. Our results showed no evidence of systematic bias throughout a simulated game (Figure 3). This was expected because the windmill pitch was not a novel task to participants, as all were experienced softball pitchers. Although data collection was in an environment unique to the participants, they were allowed unlimited time to warm up to feel ready for maximum effort pitches and to be comfortable pitching in the laboratory setting. The previous literature has noted that participants who have more experience with a specific movement display less variation in execution of that movement [21]. Data from this study also suggest that four sets of five fastballs with one-minute of recovery did not fatigue participants enough to significantly alter kinematic variables measured. Future studies measuring kinematic variables during the windmill softball pitch may not need to include familiarization trials in experienced participants who are allowed an adequate warm-up.

The study's secondary objective was to assess the extent of variation within subjects for each measured kinematic parameter. Hopkins [10] defines within-subject variability as most important measure because it affects the precision of estimates of change in the variable. Since there are no published studies providing reliability data for the softball windmill pitch, direct comparisons cannot be drawn with the data generated from the protocol used in the current study. The average $\%CV_{te}$ for each kinematic variable of the windmill pitch (7.38–26.56%; calculated from Tables 2–6) are similar in magnitude to kinetic variables in drop landing performance (6.6–27.6%) [22], velocity (22.9%) and the center of mass displacement (24.0%) of a countermovement jump [23]. This is slightly higher than what has previously been reported for kinematic measures of sprint running (0.6–19.9%) [24] and swimming (1.21–12.85%) [25].

In general, stride leg $\%CV_{te}$ tended to decrease as more pitches were included in the analysis, while drive leg $\%CV_{te}$ remained relatively stable within sets of pitches. Little variation in drive leg $\%CV_{te}$ was expected, as it remains in a closed kinetic chain position during the initiation of the windmill pitch, which allows for more predictable movement patterns. Compared to the drive leg, a slightly higher $\%CV_{te}$ in the stride may have been caused by the large breaking forces needed to translate energy from the lower to upper extremity. At stride foot contact during the fastball pitch, breaking forces have been recorded as a mean magnitude of 115%BW $\pm$ 46%BW [26]. The greatest $\%CV_{te}$ was seen in the pitching elbow likely due to the large arm velocities reached during the windmill pitch. In softball pitchers, forward flexion of the arm reached a maximum velocity greater than 5000°/s with a maximum elbow flexion velocity of 880°/s [27]. Skilled pitchers likely develop variability in movement needed for optimal performance in a dynamic environment [28], therefore increasing within-subject variability.

The third aim of this study was to determine the intra- and inter-session reliability of joint flexion/extension angles during the windmill pitch. The ICC analysis suggests that the stability of fastball pitching performance is strong when measured by the lower extremity kinematic variables of the current study. Most of the literature cites the arbitrary value of ICC > 0.75 as the cut-off point at which test–retest reliability is deemed to be good [12]. However, it is up to the researcher to determine when a measurement is reliable enough for its intended use [20]. More recently it has been suggested that ICC values are more of an objective means to determine the number of trials necessary to reach stability of performance and that they should be used as a methodological consideration [29].

The ICC analyses demonstrate good test–retest reliability for most kinematic variables measured. The initial lower extremity intra-session ICC values, calculated with the first two pitches, were high, ranging from 0.815 to 0.995 (Table 7). Moderate intra-session reliability was seen in the pitching elbow until good reliability was reached on the 20th consecutive pitch (Table 8). Similarly, good lower extremity inter-session reliability was seen with only the first two pitches captured on each day, and it increased with the inclusion of more pitches. Pitching elbow demonstrated good inter-session reliability at the eighth consecutive pitch. Greater stability in lower extremity kinematics is likely also due to predictability of movement patterns in a closed kinetic chain. In the closed kinetic chain, the terminal joint is stationary, thus preventing free motion and promoting increased joint stability [30]. The open kinetic chain, such as the pitching arm during the windmill softball pitch, is not subject to these same constraints.

The final aim of the study was to calculate SEM and MDC for each kinematic variable. While the ICC statistic provides a measure of reliability, it does not help researchers and clinicians interpret meaningful changes between repeat tests [31]. The MDC is the minimal amount of change in data that must occur in order to confirm that the change in value is not attributable to measurement error. This is the first study to provide ICC parameters and establish MDC for the softball windmill pitch.

Little research has investigated the number of trials needed for optimal reliability in overhead movements. Future research can use the present data to determine the magnitude of change required for a real effect of joint flexion/extension angle to have occurred. It has been suggested that <10% for $\%CV_{te}$ is the acceptable threshold for a test measure to be deemed reliable [32]. However, the arbitrary 10% cut-off point has faced criticism because it lacks a basis in analytical goals [20]. Similar to previous research on sprint running [24] and swimming [25], there was a trend for reliability to improve with the addition of multiple trials. ICC values in the current study suggest good intra- and inter-session reliability of kinematic variables. It is recommended that ICC and within-subject variability data should be considered together to judge if a variable is reliable enough for intended use and when creating a data collection protocol. When comparing between day data, the MCD is thought to represent the minimal threshold beyond which is considered a true change in performance [33]. The values presented can help researchers and clinicians determine when a meaningful change in performance has occurred.

These results are limited by the homogeneous nature of participants and the use of only windmill pitch fastballs. Results of this study suggest a minimum number of pitches is needed to achieve stability of lower extremity joint flexion/extension angles; this should be utilized in context of the study population and pitch style. Future studies can calculate the reliability of different age and/or skill ranges. Additionally, joint calculations were conducted in the sagittal plane and may not necessarily translate to reliability of movement in the frontal or transverse planes.

Findings of the current study indicate no need for familiarization in a laboratory setting when participants are allowed a warm-up period of their choosing. Joint flexion/extension angles of the knees, hips and pitching elbow demonstrate small within-subject variation and good test–retest correlation coefficients during the windmill softball pitch. There was a consistent trend of increasing reliability and decreasing $\%CV_{te}$ and MDC with the inclusion of more pitches. Researchers can use the data in the current study to estimate the magnitude of change in joint flexion/extension angles required to say a real change has occurred.

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