

# Differences in Lower Extremity Kinematics Between Collegiate and Youth Softball Pitchers

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**Background:** Softball pitching is a whole-body motion that utilizes the kinetic chain to transfer the large amounts of force generated by the lower extremity to the ball. Although the lower extremity is responsible for generating most of the force in softball pitching, limited research has investigated how lower extremity kinematics vary with age.

**Purpose/Hypothesis:** The purpose of this study was to compare lower extremity kinematics between collegiate and youth softball pitchers. It was hypothesized that there would be significant lower extremity kinematic differences between age groups.

**Study Design:** Descriptive laboratory study.

**Methods:** Overall, 83 softball pitchers participated in the study: 40 youth and 43 collegiate players. Kinematic data were collected using an electromagnetic motion capture system. All participants threw 3 fastballs to a catcher for a strike at regulation distance. Owing to nonnormally distributed data, Mann-Whitney U tests were used to determine group differences at 5 events during the pitching motion. The alpha level was set a priori at .006.

**Results:** Collegiate pitchers had significantly higher drive-knee extension angular velocity at the 3-o'clock position than youth pitchers ( $182.30 \pm 145.44$  vs  $-34.66 \pm 219.66$  rad/s;  $P < .001$ ). Collegiate pitchers also had greater peak drive-knee flexion angle than youth pitchers at the top of the arm circle ( $37.98^\circ \pm 18.09^\circ$  vs  $25.38^\circ \pm 17.58^\circ$ ;  $P = .004$ ), while youth pitchers had a significantly more anteriorly shifted center of mass than collegiate pitchers at the top of the arm circle ( $49.93\% \pm 5.09\%$  vs  $46.47\% \pm 6.44\%$ ;  $P = .003$ ).

**Conclusion:** The authors found increased drive-knee flexion angle and angular extension velocity in collegiate compared with youth pitchers, although it is unknown if these differences were due to lack of experience or strength. Athletes should work on improving drive-leg mechanics to develop optimal push-off performance.

**Clinical Relevance:** This information can be applied to develop strength and conditioning programs for softball pitchers. Player performance may be improved through performing exercises to strengthen knee and hip extension musculature and learning to eccentrically load the drive leg to activate the stretch shortening cycle.

**Keywords:** drive leg; segmental velocities; stride leg; windmill softball pitching

During the pitching windup, softball pitchers must use their drive leg to generate a large amount of force to propel their body forward toward home plate and ultimately transfer that energy up the kinetic chain and finally to the ball. As a result, any weakness within the body can be detrimental to the athlete's performance. Mechanical alterations within the kinetic chain's proximal segments (lower extremity) can decrease energy transfer, requiring altered compensatory mechanics of the more distal segments (upper extremity).<sup>2,11</sup> In such a scenario, for athletes to produce the same performance level, that is, maintain pitch

speed, they must rely on the upper extremity to make up for the decrease in energy transfer, potentially increasing injury risk.

While a significant portion of the softball literature has focused on the throwing shoulder,<sup>1,12,15,18</sup> recent softball research has provided information regarding lower extremity mechanics and their effect on the kinetic chain.<sup>6,7,14,16</sup> The kinetic chain is crucial to properly execute a mechanically efficient pitching motion with maximum energy transfer. The ground-reaction force (GRF) created within the stride and drive legs produces the proximal base of stability crucial for distal arm mobility.<sup>11</sup> In overhead arm motions, the legs and trunk create 50% of the kinetic energy and force of the throwing motion.<sup>10</sup> Softball pitching is considered an overhead motion, and lower extremity mechanics

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have been associated with pitching performance. Specifically examining the stride leg, increased vertical GRF and an increased stride length have been correlated with increased ball speed.<sup>7,16</sup> The lower extremity also has a documented relationship with injury susceptibility. In collegiate softball pitchers, a posteriorly shifted center of mass (COM) and increased stride length have been found in those with compared with those without upper extremity pain.<sup>15</sup>

In addition to the aforementioned variables, descriptive studies have reported knee flexion angles during the softball pitch, but no studies have examined knee angular velocities.<sup>21</sup> In baseball, high-velocity pitchers generate greater stride-knee angular velocity and drive-leg knee extension torque compared with low-velocity pitchers.<sup>8,19</sup> As a result of the lower extremity being responsible for force generation in baseball and softball, similar relationships with drive-leg mechanics and pitching velocity may hold true in softball pitchers. Additionally, the drive and stride legs' angular velocities may indicate weakness within the lower extremities that coaches, athletes, and clinicians can utilize as a variable to assess injury risk and design programs to improve pitching performance. Furthermore, linear velocity could be another potentially valuable surrogate measure for coaches or clinicians to understand energy generation and transfer. As previously stated, softball pitchers must use their lower extremity to develop a large amount of force to push themselves off the rubber toward home plate. Currently, no research has investigated segmental linear velocity and performance, and unlike most kinematic variables reported in the literature that require a full 3-dimensional motion analysis with force plates, linear velocity measurements require minimal equipment or resources. Thus, if a significant relationship exists between linear velocity and ball velocity and/or other kinematic variables, it could provide athletes with a useful on-field variable to assess pitching performance.

Furthermore, the limited research comparing softball mechanics of various age and skill levels has not investigated the lower extremity. The few studies<sup>6,14,21,22</sup> directly comparing various skill and age levels in softball have reported variations in upper extremity and trunk mechanics and range of motion values. Furthering our understanding of the body's demands during the windmill pitch and how lower extremity mechanics progress with age will support the development of age-appropriate injury prevention strategies and strength programs. Analyzing data within various skill and age levels is important for developing the aforementioned programs, as relationships that may be found in one level may not be important in others. Therefore, being able to determine important variables/

mechanics for respective age and skill is important for the proper development of softball athletes.

Based on the limited amount of literature and the importance of the lower extremity during the windmill pitch, this study aimed to compare lower extremity kinematics between collegiate and youth softball pitchers. It was hypothesized that there would be lower extremity kinematic differences between groups. Specifically, lower extremity kinematics of collegiate pitchers would represent increased drive-knee flexion angle, drive-knee extension angular velocity, stride-knee extension angular velocity, and stride length compared with those of the youth pitchers.

## METHODS

A total of 83 female fast-pitch softball pitchers participated in this study. Participants were divided into 2 groups: youth ( $n = 40$ ; age,  $13.7 \pm 1.4$  years; height,  $164.4 \pm 8.9$  cm; weight,  $65.7 \pm 14.7$  kg) and collegiate ( $n = 43$ ; age,  $20.3 \pm 1.7$  years; height,  $173.7 \pm 7.3$  cm; weight,  $81.2 \pm 12.0$  kg). All collegiate pitchers but 1 were National Collegiate Athletic Association Division I pitchers, while youth pitchers were from various leagues. Inclusion criteria consisted of being injury and surgery free (self-reported) for at least 6 months before participation and currently active on a competitive team's roster at the position of pitcher. All testing procedures were approved by the institutional review board of Auburn University, and procedures were thoroughly explained to the participant and parents before testing. All participants and parents provided written informed consent, assent, and parental permission as appropriate.

### Testing Protocol

Kinematic and kinetic data were collected using an electromagnetic Flock of Birds system (trakSTAR; Ascension Technologies Inc) synced with The MotionMonitor software (Innovative Sports Training). Fourteen electromagnetic, 6 degrees of freedom sensors were affixed to the skin (Figure 1) using double-sided cohesion tape and then covered and wrapped with PowerFlex self-adhesive tape (Andover HealthCare, Inc).<sup>3</sup> A linked segment model was developed using the digitized joint centers for the ankle, knee, T12-L1, and C7-T1 by the digitized medial and lateral aspect of each joint, and then the midpoint between those 2 points was calculated.<sup>23,24</sup> Shoulder and hip joint centers were estimated using previously established digitization and rotation methods.<sup>20</sup> The global coordinate system was represented with the positive Y-axis in the vertical direction;

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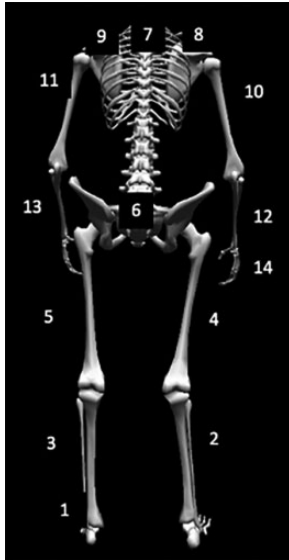
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Ethical approval for this study was obtained from Auburn University (protocol No. 18-121 EP 1803).



**Figure 1.** Sensor placement for kinematic testing.

anterior to the Y-axis in the direction of motion was the positive X-axis; and orthogonal and to the right of X- and Y-axes was the positive Z-axis. All data were originally collected at 100 Hz or 240 Hz, and trials collected at 240 Hz were interpolated to 100 Hz for analysis using a custom MATLAB script (MathWorks). Raw data regarding sensor position and orientation were independently filtered along each global axis using a fourth-order Butterworth filter with a cutoff frequency of 13.4 Hz.<sup>3,4</sup>

After sensor attachment, calibration of the system, and identification of anatomic landmarks, participants were given an unlimited amount of time to warm up. Warm-up routines were not standardized, and participants were instructed to warm up like they would before a game. Once the participant deemed herself ready, each participant pitched 3 fastballs for a strike from a simulated pitching rubber to a catcher at her age-dependent regulation distance. The average of 3 trials was used for analysis. Ball speed was collected using a calibrated radar gun (Stalker Pro II Speed Sensor Radar; Applied Concepts Inc/Stalker Radar). The pitching motion was broken down into 5 main events: (1) 3-o'clock position (90° of forward flexion), (2) top of the arm circle, (3) foot contact, (4) ball release, and (5) follow-through. All variables were analyzed at each event.

Lower extremity kinematics were defined using International Society of Biomechanics recommendations.<sup>23</sup> Knee kinematics were defined using Euler angles of rotation of the distal segment relative to the proximal segment reference frame using an ZX'Y'' decomposition sequence. Knee flexion was defined about the Z-axis of rotation. The drive leg was defined as the leg ipsilateral to the pitching arm, and the stride leg was defined as the leg contralateral to the pitching arm. The COM position was defined as a percentage of the trunk COM in relation to the base of support, with 0% representing COM directly over the drive leg and 100% representing COM directly over the stride leg. Stride

length was represented as a percentage of the participant's body height.

### Statistical Analysis

Because the data were nonnormally distributed, Mann-Whitney *U* tests were used at each of the 5 events to determine group differences for drive- and stride-knee flexion/extension angle, drive- and stride-knee flexion/extension angular velocity, drive- and stride-hip linear velocity, stride length, and COM position. In an effort to limit type 1 error, the alpha level was set a priori at .006.

Results warranted further analyses; thus, secondary analysis bivariate correlation tests were run between stride length and COM position at the 5 events. Additionally, bivariate correlation tests were run between ball speed, stride-foot GRF at ball release, and the maximum stride-foot GRF between top of the arm circle and follow-through. Correlation tests between ball speed and stride length and COM position at top of the arm circle, foot contact, and ball release were also run. Furthermore, Spearman rho correlations were run between maximum stride and drive-hip linear velocity during the entire pitching motion and ball speed. All correlations were run separately for each group and together. The alpha level was set a priori at .05. All statistical testing was performed using IBM SPSS statistical software (version 25; IBM Corp).

### RESULTS

Kinematic data for the collegiate and youth pitchers are shown in Table 1. Mann-Whitney *U* testing revealed a significantly higher drive-knee extension angular velocity at the 3-o'clock position for collegiate pitchers than for youth pitchers ( $182.30 \pm 145.44$  vs  $-34.66 \pm 219.66$  rad/s;  $P < .001$ ). At the top of the arm circle, collegiate pitchers had a greater degree of drive-knee flexion angle than youth pitchers had ( $37.98^\circ \pm 18.09^\circ$  vs  $25.38^\circ \pm 17.58^\circ$ ;  $P = .004$ ). Additionally, at the top of the arm circle the COM of the youth pitchers was positioned significantly more anteriorly than that of the collegiate pitchers ( $49.93\% \pm 5.09\%$  vs  $46.47\% \pm 6.44\%$ ;  $P = .003$ ). There were no group differences for any variable at ball release or follow-through. Lastly, collegiate pitchers had significantly faster ball speed than youth pitchers had ( $55.98 \pm 2.95$  vs  $47.03 \pm 5.83$  mph;  $P < .001$ ).

Secondary analysis correlation results revealed that across the entire sample population, stride length and COM position were significantly moderately correlated at the top of the arm circle ( $r = 0.333$ ,  $P = .002$ ), foot contact ( $r = 0.386$ ,  $P < .001$ ), and follow-through ( $r = 0.399$ ,  $P < .001$ ). When broken down into groups, collegiate and youth, collegiate pitchers only had a significantly moderate correlation between stride length and COM position at follow-through ( $r = 0.457$ ,  $P = .002$ ). Youth pitchers had a significantly moderate correlation between stride length and COM position at the top of the arm circle ( $r = 0.432$ ,  $P = .005$ ), foot contact ( $r = 0.538$ ,  $P < .001$ ), and follow-through ( $r = 0.349$ ,  $P = .027$ ). Specifically, the positive relationship between stride length and COM position indicated

TABLE 1  
Lower Extremity Kinematic Data for the Study Groups<sup>a</sup>

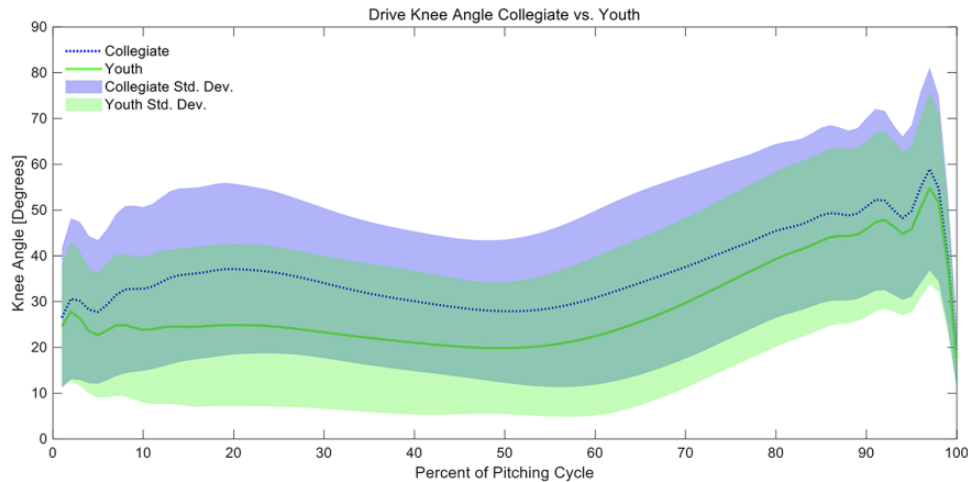
Variable	Collegiate Pitchers (n = 43)	Youth Pitchers (n = 40)	Overall (N = 83)
3-o'clock position			
Stride-knee flexion/extension angle, deg	27.08 ± 12.54	23.25 ± 13.54	25.24 ± 13.09
Drive-knee flexion/extension angle, deg	27.48 ± 15.63	24.63 ± 12.07	26.11 ± 14.02
Stride-knee flexion/extension angular velocity, rad/s	-144.57 ± 164.30	-104.19 ± 168.75	-125.11 ± 166.68
Drive-knee flexion/extension angular velocity, rad/s	<b>182.30 ± 145.44</b>	<b>-34.66 ± 219.66</b>	<b>77.74 ± 213.73</b>
Stride-hip linear velocity, m/s	3.29 ± 0.35	3.13 ± 0.70	3.21 ± 0.55
Drive-hip linear velocity, m/s	3.24 ± 0.55	2.97 ± 0.67	3.11 ± 0.63
Stride length, %	1.13 ± 0.17	1.13 ± 0.20	1.13 ± 0.18
COM position, %	44.52 ± 5.51	45.01 ± 5.06	44.76 ± 5.27
Top of arm circle			
Stride-knee flexion/extension angle, deg	21.12 ± 10.10	21.78 ± 11.36	21.44 ± 10.67
Drive-knee flexion/extension angle, deg	<b>37.98 ± 18.09</b>	<b>25.38 ± 17.58</b>	<b>31.91 ± 18.83</b>
Stride-knee flexion/extension angular velocity, rad/s	-6.90 ± 170.20	36.34 ± 189.73	13.94 ± 180.09
Drive-knee flexion/extension angular velocity, rad/s	-12.31 ± 220.60	-7.01 ± 122.01	-9.75 ± 178.92
Stride-hip linear velocity, m/s	3.08 ± 0.32	2.89 ± 0.59	2.99 ± 0.48
Drive-hip linear velocity, m/s	3.10 ± 0.49	2.82 ± 0.66	2.96 ± 0.59
Stride length, %	0.93 ± 0.14	0.98 ± 0.17	0.95 ± 0.16
COM position, %	<b>46.47 ± 6.44</b>	<b>49.93 ± 5.09</b>	<b>48.14 ± 6.05</b>
Foot contact			
Stride-knee flexion/extension angle, deg	21.58 ± 8.05	24.95 ± 10.79	23.21 ± 9.57
Drive-knee flexion/extension angle, deg	31.65 ± 15.01	22.55 ± 16.13	27.27 ± 16.13
Stride-knee flexion/extension angular velocity, rad/s	58.79 ± 130.53	86.07 ± 113.96	71.94 ± 122.85
Drive-knee flexion/extension angular velocity, rad/s	-158.13 ± 189.83	-52.87 ± 185.66	-107.40 ± 194.04
Stride-hip linear velocity, m/s	2.72 ± 0.39	2.62 ± 0.50	2.67 ± 0.45
Drive-hip linear velocity, m/s	2.80 ± 0.32	2.65 ± 0.50	2.73 ± 0.42
Stride length, %	0.89 ± 0.12	0.89 ± 0.13	0.89 ± 0.12
COM position, %	51.31 ± 5.02	53.96 ± 4.83	52.59 ± 5.08
Ball release			
Stride-knee flexion/extension angle, deg	26.51 ± 9.47	26.19 ± 10.48	26.35 ± 9.91
Drive-knee flexion/extension angle, deg	35.59 ± 20.72	32.49 ± 19.24	34.10 ± 19.96
Stride-knee flexion/extension angular velocity, rad/s	-173.07 ± 132.00	-82.15 ± 151.81	-177.44 ± 141.09
Drive-knee flexion/extension angular velocity, rad/s	212.32 ± 162.23	278.43 ± 159.85	244.18 ± 163.52
Stride-hip linear velocity, m/s	0.54 ± 0.66	0.63 ± 1.27	0.59 ± 0.99
Drive-hip linear velocity, m/s	0.79 ± 0.34	0.73 ± 0.33	0.76 ± 0.33
Stride length, %	0.73 ± 0.11	0.68 ± 0.14	0.71 ± 0.13
COM position, %	50.12 ± 8.03	51.84 ± 6.81	50.97 ± 7.52
Stride GRF, N	1213.93 ± 318.91	1006.01 ± 378.50	1113.73 ± 362.15
Normalized stride GRF, N/kg	15.05 ± 3.73	15.20 ± 4.43	15.13 ± 4.06
Follow-through			
Stride-knee flexion/extension angle, deg	8.87 ± 12.51	8.67 ± 11.12	8.77 ± 11.79
Drive-knee flexion/extension angle, deg	51.32 ± 18.54	49.83 ± 17.92	50.60 ± 18.15
Stride-knee flexion/extension angular velocity, rad/s	-106.62 ± 154.00	-88.43 ± 107.06	-97.85 ± 132.97
Drive-knee flexion/extension angular velocity, rad/s	70.10 ± 108.03	118.33 ± 130.98	93.34 ± 121.35
Stride-hip linear velocity, m/s	0.62 ± 0.32	0.54 ± 0.28	0.58 ± 0.30
Drive-hip linear velocity, m/s	0.74 ± 0.27	0.73 ± 0.29	0.73 ± 0.28
Stride length, %	0.55 ± 0.12	0.56 ± 0.14	0.56 ± 0.13
COM position, %	46.15 ± 13.62	52.30 ± 11.87	49.08 ± 13.03
Stride GRF, N	370.86 ± 215.74	320.37 ± 179.15	346.53 ± 199.37
Normalized stride GRF, N/kg	4.51 ± 2.42	4.89 ± 2.53	4.70 ± 2.47
Ball speed, mph	<b>55.98 ± 2.95</b>	<b>47.03 ± 5.83</b>	<b>51.67 ± 6.39</b>

<sup>a</sup>Data are reported as mean ± SD. Bolded text indicates statistically significant difference between groups ( $P < .006$ ). Knee flexion (+) and extension (-); knee angular velocity flexion (-) and extension (+). COM, center of mass; GRF, ground-reaction force.

that pitchers with longer stride lengths also had a more anteriorly shifted COM position.

The results also showed a significantly moderate correlation for participants as a whole and youth between ball speed and stride-foot GRF at ball release (whole:  $r = 0.406$ ,

$P < .001$ ; youth:  $r = 0.514$ ,  $P < .001$ ) and maximum stride-foot GRF between top of the arm circle and follow-through (whole:  $r = 0.500$ ,  $P < .001$ ; youth:  $r = 0.490$ ,  $P = .001$ ). Normalized maximum stride-foot GRF across the entire pitching motion did have a significantly weak correlation



**Figure 2.** Drive-knee angle kinematics for collegiate and youth pitchers over the pitching cycle. Shaded areas indicate standard deviations (Std. Dev.).

with ball speed ( $r = 0.219$ ,  $P = .046$ ) when analyzed together. Normalized stride-foot GRF at ball release for youth had a significantly moderate correlation with ball speed ( $r = 0.385$ ,  $P = .014$ ). Collegiate pitchers alone did not have any significant correlations between ball speed and stride-foot GRF.

Across all participants, ball speed had a negatively weak correlation with COM position at foot contact ( $r = -0.227$ ,  $P = .039$ ) and ball release ( $r = -0.250$ ,  $P = .023$ ) and a positively weak correlation with stride length at ball release ( $r = 0.281$ ,  $P = .010$ ). For youth pitchers, ball speed was negatively moderately correlated with COM position at ball release ( $r = -0.388$ ,  $P = .013$ ). No significant correlations were observed for collegiate pitchers between ball speed and either stride length or COM position.

The Spearman rho correlation test revealed that whole group stride-hip ( $r = 0.352$ ,  $P = .001$ ) and drive-hip ( $r = 0.531$ ,  $P < .001$ ) linear velocity were moderately positively correlated with ball speed. When analyzed separately, in youth pitchers, there was a moderately positive correlation between stride-hip ( $r = 0.486$ ,  $P = .001$ ) and drive-hip ( $r = 0.519$ ,  $P < .001$ ) linear velocity and ball speed, while significant correlations between hip linear velocity and ball speed were not seen in collegiate pitchers.

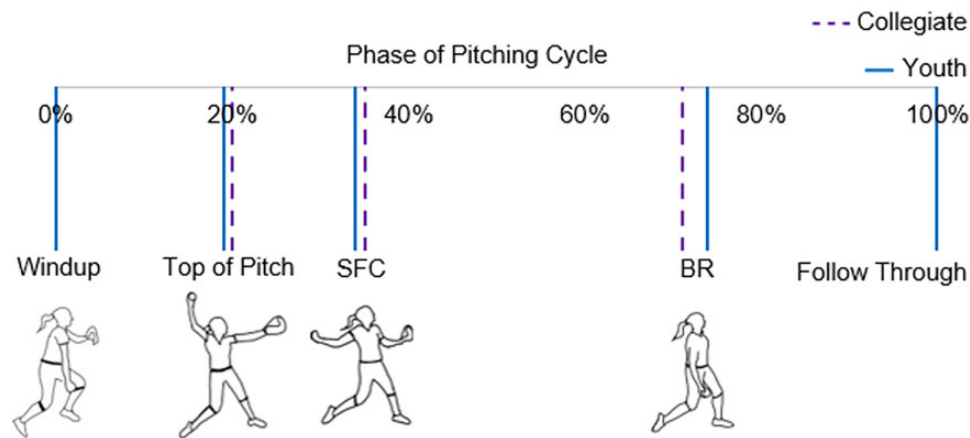
## DISCUSSION

This study is the first to compare mechanical differences within the lower extremity between youth- and collegiate-level pitchers. By analyzing the stride-knee and drive-knee flexion angle, angular velocity, and location of the COM position, this study determined significant differences between age groups. The collegiate pitchers generated a larger extension angular velocity on their drive leg at the 3-o'clock position. While no data exist for the drive-foot GRF, we speculate that this increased angular velocity on the drive leg may necessitate a larger loading force on the drive leg and therefore may be a significant factor in force

generation for increased performance. As seen in Figure 2, where the collegiate and youth drive-knee angle is shown over the pitching cycle, the drive knee is seen to be in a greater amount of flexion during the windup and top of the arm circle phases. As can be seen in Figure 3, as collegiate athletes are spending more time loading at the beginning of the pitch, they are also reaching top of the arm circle phase later than their youth counterparts.

Youth pitchers demonstrate a more anteriorly shifted COM than collegiate pitchers, allowing for a quick transition into top of the arm circle phase. This anteriorly shifted position may indicate youth pitchers transferring momentum forward too early in the pitching motion. A disruption between the arm motion and lower extremity creates a “catch-up” phenomenon, which has the potential to alter forces in distal extremities.<sup>2</sup> While there was no difference in stride length between age groups, the relationship between stride length and COM position was not investigated. However, previous research has identified a relationship between stride length and COM position with injury.<sup>15</sup> Thus, the authors decided to conduct a secondary analysis to investigate if there is a relationship between stride length and COM position in the current population. Follow-up analyses found that youth pitchers had a significantly positive correlation between stride length and COM position at top of the arm circle and foot contact. Collegiate pitchers did not have a significant correlation at those events. Youth pitchers who had increased stride length also had a more anteriorly shifted COM position. An increased stride length has been found to be correlated with increased ball speed in previous literature, and the same was found in the current population.<sup>17,22</sup> Interestingly, the current study found a negative correlation between ball speed and COM position in the population as a whole and in youth pitchers. The previous hypothesis emphasized that the anteriorly shifted COM position may not be advantageous for performance. The push-off mechanics showcased by the collegiate pitchers possibly allowed their body and COM to be in more of a power position. Youth pitchers may lack the





**Figure 3.** Timing of each event of the pitching cycle between collegiate and youth pitchers. BR, ball release; SFC, stride foot contact.

lower extremity and trunk strength to perform this motion, thus shifting their momentum anteriorly earlier in the pitching motion than collegiate pitchers.

Unlike baseball pitchers, who can use gravity to help them produce stride-foot GRF, softball pitchers must solely use their lower extremity to generate force.<sup>7</sup> Softball pitchers must be able to generate adequate force and have the ability to properly transfer the energy generated up through the kinetic chain for injury prevention.<sup>9,10,13,16</sup> This GRF decelerates the lower body and torso, creating a stable proximal base against which the pitching arm can pull as it travels through the top of the arm circle into ball release. Previous literature<sup>7,16</sup> has found a significantly positive correlation between ball speed and stride GRF. While the current study's primary aim was not to associate ball speed and stride GRF, a secondary analysis investigating this relationship was conducted. When analyzing participants as a whole, there was a significant correlation between ball speed and stride GRF at ball release and maximum stride GRF during the entire pitching motion. The same relationship was found in youth pitchers whether or not stride GRF was normalized; however, there was not a significant relationship found between ball speed and stride GRF when examining the collegiate pitchers alone. The lack of a significant relationship in collegiate pitchers was not expected, as they displayed significantly higher pitch velocities than the youth pitchers. The significant relationship between ball speed and stride GRF found in youth pitchers but not collegiate pitchers may be a result of the larger variability in skill, height, weight, and mechanics typically found in youth pitchers.<sup>5,7,16</sup> Based on prior literature and the current results, we hypothesize that the relationship between ball speed and stride GRF may only be applicable in younger populations because of the self-selection that comes with advancing age; that is, pitchers only continue to participate competitively at ages 18 to 23 years if they have elite capability.

Identifying that differences in push-off mechanics may exist between youth and collegiate pitchers can provide valuable direction to youth coaches developing strength

and conditioning programs. Exercises designed to strengthen knee and hip extension musculature and emphasize eccentric loading of the drive leg to activate the stretch shortening cycle may improve performance in the youth population. While there were no significant differences between groups for hip linear velocity, a positive relationship between ball speed and linear velocity was found. Those with increased maximum hip linear velocity across the entire pitching motion also had increased ball speed. This finding is important, as it supports using linear velocity as an on-field measure to assess pitching performance or to identify when pitchers may be getting fatigued when ball speed measurement devices are unavailable. The current study results emphasize the need to learn more about and improve push-off mechanics for improved performance in softball pitchers.

The lack of significant correlations between lower extremity mechanics and ball speed in collegiate pitchers may be the result of decreased variability in pitching mechanics at the higher level. The low variability highlights the importance of conducting further research with larger sample sizes to investigate pitching performance at the collegiate level to develop appropriate programs for collegiate pitchers looking to get an edge on their competition. Furthermore, the different results seen when separating participants into youth and collegiate groups call into question the generalizability of prior reported results in softball pitching from specific groups. More research comparing groups of softball pitchers by age and experience is needed.

The current study is not without limitations. The relationships observed were not consistent across the whole population, so caution should be taken when applying these results to other populations of softball pitchers. Strength was not measured in the current study, and therefore it is unknown if the differences found were the result of greater strength, improved mechanics from years of experience, or both. Additionally, the study did not analyze mechanics before the windup portion of the pitching motion. Windup phase push-off GRFs were not measured; therefore, this study speculates on how the knee angular velocity may

relate to forces in the drive leg. Based on the findings that the push-off portion of the pitch may have a positive effect on performance, future research should include earlier portions of the pitching motion and include a second push-off force plate when investigating lower extremity mechanics.

## CONCLUSION

This study is one of the first to compare lower extremity mechanics between age groups. The results of this study, of increased drive-knee flexion angle and angular extension velocity found in collegiate pitchers compared with youth, provide important information for pitchers looking to improve performance. The results suggest that athletes should work on improving drive-leg mechanics to develop optimal push-off mechanics. Further research should be done to investigate the relationship between mechanics and muscular strength to develop optimal training programs.

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