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Effect of stride length on overarm throwing delivery: A linear momentum response ☆,☆☆

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ABSTRACT

Changing stride length during overhand throwing delivery is thought to alter total body and throwing arm linear momentums, thereby altering the proportion of throwing arm momentum relative to the total body. Using a randomized cross-over design, nineteen pitchers (15 collegiate and 4 high school) were assigned to pitch two simulated 80-pitch games at ±25% of their desired stride length. An 8-camera motion capture system (240 Hz) integrated with two force plates (960 Hz) and radar gun tracked each throw. Segmental linear momentums in each plane of motion were summed yielding throwing arm and total body momentums, from which compensation ratio's (relative contribution between the two) were derived. Pairwise comparisons at hallmark events and phases identified significantly different linear momentum profiles, in particular, anteriorly directed total body, throwing arm, and momentum compensation ratios ($P \leqslant .05$) as a result of manipulating stride length. Pitchers with shorter strides generated lower forward (anterior) momentum before stride foot contact, whereas greater upward and lateral momentum (toward third base) were evident during the acceleration phase. The evidence suggests insufficient total body momentum in the intended throwing direction may potentially influence performance

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(velocity and accuracy) and perhaps precipitate throwing arm injuries.

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1. Introduction

Early within the pitching delivery, total body linear momentum is first generated by the drive leg (trailing or dominant) and is then arrested by the stride leg (leading or non-dominant) at stride foot contact (Seroyer et al., 2010; Stodden, Langendorfer, Fleisig, & Andrews, 2006). Thereafter, linear momentum transitions into rotation between the pelvis and trunk, through to the throwing arm, and culminates at the hand (Seroyer et al., 2010; Stodden et al., 2006). A recent study that examined the chain of body segment momentum transfers in the baseball pitching delivery suggest the greatest linear momentum progresses forward in the intended throwing direction (toward home plate), with the trunk contributing the greatest proportion of all linear and angular momentum transfers (Lin, Su, Nakamura, & Chao, 2003). In contrast, momentum approached zero near ball release with the contralateral non-throwing arm and leg, which is thought to augment forward trunk flexion momentum (Lin et al., 2003). Reducing forward total body momentum late in the pitching cycle may be attributable to improved proximal stability to augment sagittal plane trunk and throwing arm angular momentums (Lin et al., 2003). Evidence suggests that the ability to regulate forward momentum is related to throwing arm performance, with the lower body greatly influencing sequential and coordinated momentum transfers up the kinetic chain (Lin et al., 2003; Seroyer et al., 2010; Stodden et al., 2006). Pelvic and trunk linear momentums were shown to contribute the greatest to ball velocity, rather than constituent momentums from the throwing arm segments themselves (Bahamonde, 2000; Lin et al., 2003).

Yet, it remains unknown whether modifying stride length (the horizontal distance between the drive and stride foot calcanei) can alter intrinsic lower extremity mechanics and inter-segmental momentum transfers to the pelvis and torso, potentially to the detriment of synchronous proximal–distal trunk-throwing arm mechanics.(Lin et al., 2003; Stodden et al., 2006). Perhaps modifying stride length indirectly influences mechanical loading of the throwing arm (Marshall & Elliott, 2000; Reid, Elliott, & Alderson, 2008; Wang, Lin, Lo, Hsieh, & Su, 2010; Wight, Richards, & Hall, 2004). In light of this, the purpose of this study was to challenge pitcher's throwing mechanics by modifying stride length. The aim was to determine whether shortening or lengthening the pitcher's stride influences total body and throwing arm linear momentums; and, specifically to differentiate whether the relative contribution between throwing arm and total body momentums change, as evidenced by the momentum compensation ratio. Perhaps a change in relative momentum between the total body and throwing arm suggests compensatory adaptation owing to altered throwing kinematics and kinetics. It was hypothesized that a change in pitchers' stride lengths would alter peak and mean forward and downward total body linear momentum, which would be evident at each hallmark event and at discrete phases in the pitching cycle. Moreover, the relative percent contribution of the throwing arm to total body momentum (defined as momentum compensation ratios) was expected to differ between stride conditions. Yet frontal plane momentum and momentum compensation ratios were expected to remain unchanged throughout the pitching cycle across stride conditions.

2. Methods

2.1. Subject recruitment

Twenty collegiate and highly skilled high school pitchers (16 right, 4 left handed) were recruited from local collegiate and travel baseball programs using flyers and personal contact. Of the twenty pitchers, one withdrew owing to conflicts with collegiate baseball obligations (15 collegiate, 4 high school competitors; height 1.84 ± 0.054 m; mass 82.14 ± 0.054 kg; age 18.63 ± 1.67 years). All were competitive for at least five seasons, were uninjured or had fully recovered from previous injury at time of testing, and none experienced throwing arm injury that required surgery. Testing was undertaken indoors in a Biomechanics Laboratory. Testing procedures were explained to all participants, who then signed an informed consent afterward. Parental consent was signed and obtained for minors. The University at Buffalo's Children and Youth Institutional Review Board approved the research study and informed consent documents for both adult and minor participants.

2.2. Subject preparation and data collection overview

A blinded randomized crossover design was used to assign pitchers to throw two simulated games, beginning with either (i) a 25% increased stride length (OS) or (ii) a 25% reduced stride (US) from their desired stride length (DSL). Pitchers were crossed over to the alternate condition after a minimum of 72 h rest had elapsed. Allocation to a stride condition was determined by simple randomization from a random numbers table.

Anthropometric measures of height and weight were first obtained. Sixty-three, retro-reflective markers (19 mm and 25 mm) were then affixed bilaterally over anatomical landmarks to distinguish body segments and joint centers, the details of which are described elsewhere (Crotin, Kozlowski, Horvath, & Ramsey, 2014). A rigid thermoplastic shell affixed with three non-collinear markers was secured over the sacrum using Velcro and elastic overwrap (SuperWrap™, Fabrifoam, Inc., Exton, PA) around the waist to track pelvic movement. Reflective tape was secured to the baseball to determine the instant of ball release from the throwing hand. Full body segmental motion was tracked and reconstructed in three dimensional space using an 8-camera motion analysis system (Vicon Nexus 1.8, Oxford Metrics, UK) while simultaneous ground reaction force was measured from two floor mounted force platforms (Kistler Instrument Corp., Amherst, NY) aligned in series, which enabled the drive and stride legs to contact the opposing force platforms. Motion and force plate recordings were sampled at 240 Hz and 960 Hz then stored on a pc for later post-processing.

2.3. Global reference frame and subject calibration

The measurement volume was calibrated with the laboratory frame of reference oriented with the $+Y$ axis directed anteriorly (corresponding to the direction of the intended throw), the $+Z$ axis superior, and the $+X$ axis orthogonal to the plane of progression and directed laterally to the right. Static standing calibrations were recorded with subjects adopting a T-Pose, their hands outstretched and thumbs directed upward and foot placement standardized with the laboratory frame of reference. This calibration posture was to derive the joint centers of rotation, define respective segmental coordinate axes, and to establish neutral (zero) alignment from which subsequent kinematic measures were referenced. Both the dominant and non-dominant shoulder and elbow joint centers were estimated as described in previous study (Aguinaldo & Chambers, 2009; Aguinaldo, Buttermore, & Chambers, 2007). A right handed coordinate system was employed for right handed pitchers whereas left handed pitchers were accounted for by reflecting (negating) the Y axis (frontal) and Z axis (transverse) from right to left in the software, thereby utilizing a left-handed coordinate system to describe rotations.

Subjects performed separate functional hip movement trials to calculate hip joint centers. Standing on their contralateral leg to allow the ipsilateral foot to clear the ground, subjects performed continuous hip flexion, abduction, and circumduction within a range of motion of 30°. Hip joint centers and axes were identified using geometric centering calculations (Visual 3D, C-Motion Inc, Rockville, MD, USA). After completing functional hip trials calibration markers were removed and subjects began a general full-body warm up that followed a generalized professional baseball routine in preparation for pitching.

2.4. Stride length determination preceding and during simulated game conditions

Following the general warm-up, pitchers progressively warmed-up by increasing throwing intensity over 30–40 pitches into a catch net (Rawlings Group, St. Louis, MO) at a distance of 5.69 m. The first 25 pitches were thrown at the desired stride length (DSL), whereas the remaining pitches were thrown with compensated strides (±25% DSL). Baseballs (Rawlings Group, St. Louis, MO) were thrown directly toward a radar gun (Jugs Sports, Tualatin, OR) accurate to within ±0.5 mph (±0.80 km/h) positioned behind the net at a height of 1.02 m to best track ball velocity. Ball velocity was relayed to the pitcher via an LED display (Jugs Sports, Tualatin, OR) for instantaneous feedback to ensure fastballs were thrown maximally.

Motion recordings and ball velocities were obtained for the 20th through 25th warm up pitches while throwing at 100% effort at the desired stride length. Kinematic and kinetic data were visually inspected using proprietary software (Vicon Nexus 1.8, Oxford Metrics, UK). Stride leg peak knee height was identified as the highest vertical displacement of the supra-patellar marker during the wind-up. Ground reaction force for both drive and stride legs were normalized to bodyweight, from which stride foot contact was determined when the leading (stride) foot contacted the second (opposing) force plate and registered vertical ground reaction force that exceeded a 5% body weight. The trials with the two fastest pitches between the 20th and 25th warm-up throws were selected and the desired stride length was calculated as the mean horizontal distance between the drive foot calcaneus at peak knee height and the stride foot calcaneus at stride foot contact (Fig. 1), which has been illustrated previously (Crotin et al., 2014). Thereafter, the desired stride length was manipulated by either increasing or decreasing stride by 25%, which represents respective overstride (OS) and understride (US) pitching conditions.

Areas over the force platforms were marked to indicate drive foot and stride foot placement for both OS and US conditions. The investigator provided feedback during the simulated game conditions to encourage participants to contact the targets. All stride lengths (DSL, OS, and US) expressed in meters were normalized to percent body height. Ample warm-up pitches prior to motion recordings were provided to acclimatize pitchers to the OS or US conditions. Twenty pitches were thrown per inning with a ratio of 3 fastballs to 1 change-up during simulated play, which regulated the orthopaedic and physiologic effort provided by each participant. Approximately 15 s rest was allocated between pitches with 9 min rest prescribed between innings. Five warm-up pitches were allocated before each inning. Testing ceased after the 80th pitch. In total, each pitcher threw approximately 130 pitches per simulated game.

2.5. Data management and post processing of kinematic and kinetic data

Visual 3D software (Visual 3D, C-Motion Inc., Rockville, MD, USA) was used for post-processing kinematic and kinetic data. Subjects were modeled with 12 linked rigid segments with six degrees of freedom, which was comprised of the trunk and pelvis, the non-throwing and throwing upper arm, the forearm with hand, and the ipsi- and contra-lateral thigh, shank and foot. Marker trajectories

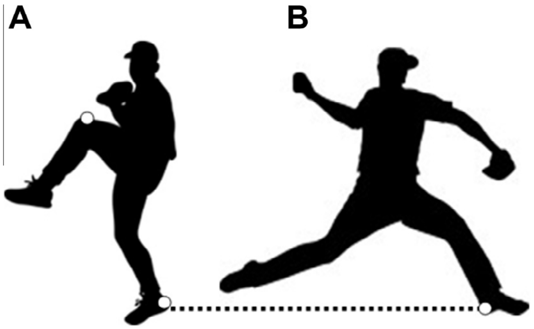

Fig. 1. Determination of Stride Length. Normalized stride length determination. Stride length calculated as the horizontal distance between calcaneal markers from peak knee height (A) to stride foot contact (B). Vertical ground reaction force exceeding 5% body weight indicated stride foot contact. Normalized stride lengths; Overstride OS (76% body height); Understride US (52% body height).

and ground reaction force data were filtered using a 4th order dual-pass Butterworth filter at 13.4 Hz (Elliott, Grove, Gibson, & Thurston, 1986; Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998; Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999; Fleisig et al., 2006) and 40 Hz respectively. Segmental mass was derived relative to total body mass using standard regression equations (Hanavan, 1964) whereas body segment parameters, i.e., segmental center of mass location and principle moments of inertia, were based on the Hanavan human body model (Hanavan, 1964). The rate of change in position of the segmental center of mass was used to derive linear velocity.

Peak knee height, stride foot contact, maximal external shoulder rotation, and ball release were then identified to signify hallmark events in the pitching cycle. Maximal external rotation was identified when pitchers achieved the greatest negative humeral axial rotation. Ball release coincided with peak linear hand velocity. The time at which the ball was released was used to terminate the pitching cycle, and was identified by visual inspection of ball and hand marker trajectories when the distance between the hand marker and reflective baseball increased 1 cm. The pitching cycle, from peak knee height to ball release, was then time normalized to 100% with peak knee height coincident with 0% and ball release terminating at 100% (Fig. 2). The intervals between hallmark events defined three phases; (i) peak knee height to stride foot contact characterized the Generation phase, (ii) stride foot contact to maximal external rotation defined the Brace-Transfer phase, and (iii) maximal external rotation to ball release denoted the Acceleration phase, which differed between conditions (Fig. 2).

2.6. Calculations

Of the 80 pitches thrown, the two highest velocity pitches recorded with the radar gun during the first and last innings (4 trials) were selected to control for fatigue bias in the results. Three dimensional total body and segmental linear momentum profiles (the product of segment mass and respective instantaneous linear velocity center of mass) were ensemble averaged over the time normalized pitching cycle for both US and OS stride conditions, to produce representative profiles for each subject. Total body momentum, described relative to the global reference frame, was computed as the sum of the 12 segmental momenta used in the model whereas throwing arm momentum was cumulative of all throwing arm segments, including the point mass of the baseball. From each subject's momentum profile, peak momentum at discrete hallmark events and means for each of the 3 phases were extracted, then averaged across subjects. An overall ensemble average was computed across subjects to depict a composite total body and throwing arm momentum profile for US and OS pitching conditions, and is used for visual purposes only. Subscripts P_x, P_y, P_z denote directional movement of the orthogonal segmental coordinate systems relative to the global frame of reference, with P_y anterior in the direction of the throw, P_z superior–inferior, and P_x lateral. In addition, momentum compensation ratios (MCR), which we define as throwing arm momentum as

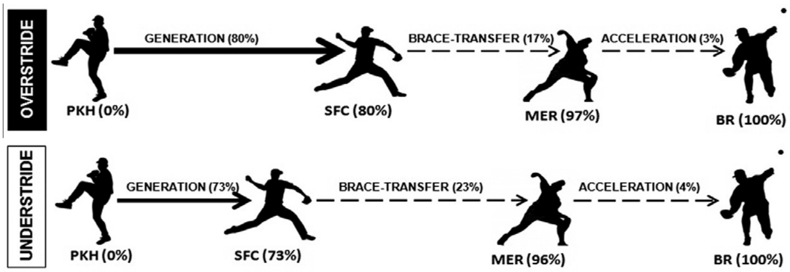

Fig. 2. Normalized pitching cycle and hallmark events for stride length conditions. Normalized pitching cycle (% time) for overstride and understride conditions. Peak knee height (PKH) initiates all pitching deliveries; Percent time for stride foot contact (SFC) and maximal external rotation (MER) were impacted stride length. Phases are linked by hallmark events; Generation (GEN) from PKH to SFC; Brace-Transfer (BT) from SFC to MER; and Acceleration (ACC) from MER to Ball release (BR). Ball release terminates the pitching cycle. Greater generation phase times in single support and reduced brace-transfer phase times in double support were seen with longer strides, whereas shorter stride pitching demonstrated an opposite temporal effect.

a proportion of the total body momentum, were also derived. Momentum calculations are described below:

a. Segment linear momentum;

$$P_x = m_{seg} x V_x, \quad P_y = m_{seg} x V_y, \quad P_z = m_{seg} x V_z * \text{Segment Mass; } m_{seg}$$

b. Total Body Linear Momentum;

$$TBP_x = \sum(m_{seg} V_x), \quad TBP_y = \sum(m_{seg} V_y), \quad TBP_z = \sum(m_{seg} V_z)$$

c. Throwing Arm Linear Momentum;

$$\begin{aligned} TAP_x &= (m_{humerus} x V_x) + (m_{forearm} x V_x) + (m_{hand+ball} x V_x) \\ TAP_y &= (m_{humerus} x V_y) + (m_{forearm} x V_y) + (m_{hand+ball} x V_y) \\ TAP_z &= (m_{humerus} x V_z) + (m_{forearm} x V_z) + (m_{hand+ball} x V_z) \end{aligned}$$

d. Linear Momentum Compensation Ratios;

$$MCP_x = \frac{TAP_x}{TBP_x}, \quad MCP_y = \frac{TAP_y}{TBP_y}, \quad MCP_z = \frac{TAP_z}{TBP_z}$$

Statistical analyses were performed using SPSS 19 (SPSS Inc., Chicago, IL) utilizing pairwise two-tailed *t*-tests for comparing peak and mean throwing arm and total body linear momentums as well as momentum compensation ratios (MCR) between stride conditions, for each of the four discrete hallmark events and three phases respectively. Statistical significance determined *a priori* was set at $p \leqslant .05$ for all statistical tests.

3. Results

Depicted in Table 1 are the mean total body and throwing arm linear momentum data at hallmark events and phases during the pitching cycle, with respective profiles plotted in Fig. 3. Mean fontal plane (P_x) whole body momenta (side to side displacement where positive momenta is directed laterally to the right or third base) were significantly higher at stride foot contact ($p \leqslant .05$) and throughout the brace transfer phase, ($p \leqslant .05$) with the OS condition (Table 1). Direction and magnitude however were divergent during the acceleration phase, with negative momentums evident with OS (directed left toward first base) as opposed to positive with US ($p \leqslant .001$). As shown in Fig. 3a, total body momentum profiles were similar between stride conditions with coincident peaks (demonstrating equivalent timing) although SFC occurred later in the pitching cycle with OS, thereby affecting both the generation (single support) and brace transfer phases (double support). Overall, total body momentums progressed medially during the first half of the pitching cycle (prior to stride foot contact), then proceeded laterally peaking midway in the brace transfer phase, and reverted back medially thereafter through to ball release (Fig. 3a). Throwing arm momentum exhibited similar profiles with peaks coincident with maximal external shoulder rotation (Fig. 3b). Statistically higher magnitudes were observed with US during acceleration ($p \leqslant .05$), whereas greater positive (lateral) momentums were evident with OS throughout brace transfer ($p \leqslant .001$). Momentum compensation ratios were unaffected despite the significantly different whole body and throwing arm momentums between stride conditions.

In the sagittal plane (P_y), total body momentum progressed anteriorly in the intended throwing direction and remained positive throughout as expected, peaking just after foot contact (Fig. 3c) while statistically higher magnitudes were observed at stride foot contact, maximal external shoulder rotation, and brace transfer (Table 1) when throwing with the longer strides ($p \leqslant .001$). The same characteristics were observed during the generation ($p \leqslant .05$), brace transfer ($p \leqslant .001$), and acceleration ($p \leqslant .05$) phases with OS compared to US. As shown in Fig. 3d throwing arm momentum profiles are also always forward directed, with peak achieved just prior to ball release although magnitudes

Table 1
Stride length impacts on linear momentum characteristics.

	PKH	SFC	MER	BR	GEN	BT	ACC
Mediolateral *X* axis							
Frontal plane							
Total body (P_x) (kg m/s)							
Overstride	−0.49 (1.20)	4.86* (3.49)	4.58 (4.61)	−3.83 (2.75)	−1.19 (1.41)	12.9* (4.83)	−1.01** (4.71)
Understride	−0.47 (1.16)	2.21 (3.32)	7.23 (5.33)	−3.94 (2.87)	−1.58 (1.13)	8.67 (6.20)	3.59 (4.23)
Throwing Arm (P_x) (kg m/s)							
Overstride	1.07 (4.01)	4.03 (12.3)	10.7 (12.4)	0.84* (9.234)	−0.13 (1.49)	10.4** (1.55)	3.70* (3.65)
Understride	0.28 (3.57)	−0.60 (8.12)	13.5 (6.58)	7.11 (7.15)	−0.88** (0.65)	8.48 (4.31)	11.0 (2.34)
MCR (P_x) (%)							
Overstride	218.0 (29.9)	82.9 (41.6)	234.0 (97.2)	109.4 (79.2)	10.9 (94.6)	80.6 (215.0)	762.4 (129.0)
Understride	59.6 (72.5)	27.1 (40.9)	186.7 (81.0)	231.2 (82.7)	55.7 (94.0)	78.5 (144.0)	646.3 (244.0)
Antero-posterior (leading) *Y* axis							
Sagittal plane							
Total Body (P_y) (kg m/s)							
Overstride	22.2 (18.6)	178.0** (23.0)	120.9** (20.5)	102.8** (20.6)	83.3* (51.6)	155.3** (20.2)	108.1* (5.19)
Understride	21.9 (13.8)	128.7 (22.9)	92.5 (18.2)	79.1 (16.1)	62.4 (34.3)	118.1 (11.9)	83.4 (4.46)
Throwing arm (P_y) (kg m/s)							
Overstride	0.98 (0.90)	13.4* (2.76)	41.1 (5.81)	40.4 (6.06)	4.21* (4.10)	21.9 (10.7)	41.8* (1.03)
Understride	0.79 (0.62)	10.7 (2.25)	39.5 (5.83)	38.8 (5.28)	2.88 (2.63)	16.5 (9.61)	39.9 (1.00)
MCR (P_x) (%)							
Overstride	4.41 (4.84)	7.53 (12.0)	34.0** (28.3)	33.4** (29.4)	5.05 (7.95)	14.1 (53.0)	38.7** (19.8)
Understride	3.61 (4.49)	8.31 (9.83)	42.7 (32.0)	49.1 (32.8)	4.62 (7.67)	14.0 (80.8)	47.8 (22.4)
Vertical *Z* axis							
Transverse plane							
Total Body (P_z) (kg m/s)							
Overstride	−19.5 (17.3)	−18.1* (15.7)	−4.69 (18.0)	3.82 (17.9)	−29.5 (18.1)	−17.8** (5.94)	1.52* (3.05)
Understride	−13.5 (13.3)	−2.26 (17.0)	2.05 (19.9)	9.59 (19.6)	−25.3 (19.0)	−9.40 (5.84)	6.99 (3.07)
Throwing arm (P_z) (kg m/s)							
Overstride	−2.32 (1.97)	2.92 (2.22)	6.09 (4.98)	−5.33 (3.79)	−0.74 (4.48)	4.40 (2.63)	0.46 (4.22)
Understride	−1.48 (1.69)	5.30 (1.97)	4.99 (4.77)	−5.81 (4.23)	−0.45 (4.24)	4.38 (1.82)	0.44 (4.03)
MCR (P_z) (%)							
Overstride	11.9 (11.4)	16.1 (14.1)	129.9 (27.7)	139.5 (21.2)	2.51 (24.8)	24.7 (44.3)	30.3* (138.4)
Understride	11.0 (12.7)	235.0 (11.6)	243.4 (24.0)	60.6 (21.6)	1.78 (22.3)	46.6 (31.2)	6.29 (131.3)

Linear momentum analyses. Mean (SD) for mediolateral (P_x), leading (P_y), and vertical (P_z) total body momentum, throwing arm momentum, and momentum compensation ratios (MCR). Significant differences indicated ($p \leqslant .001$)** and ($p \leqslant .05$)*. PKH, Peak Knee Height; SFC, Stride Foot Contact; MER, Maximal External Rotation, BR, Ball Release; GEN, Generation Phase; BT, Brace-Transfer Phase; ACC, Acceleration Phase.

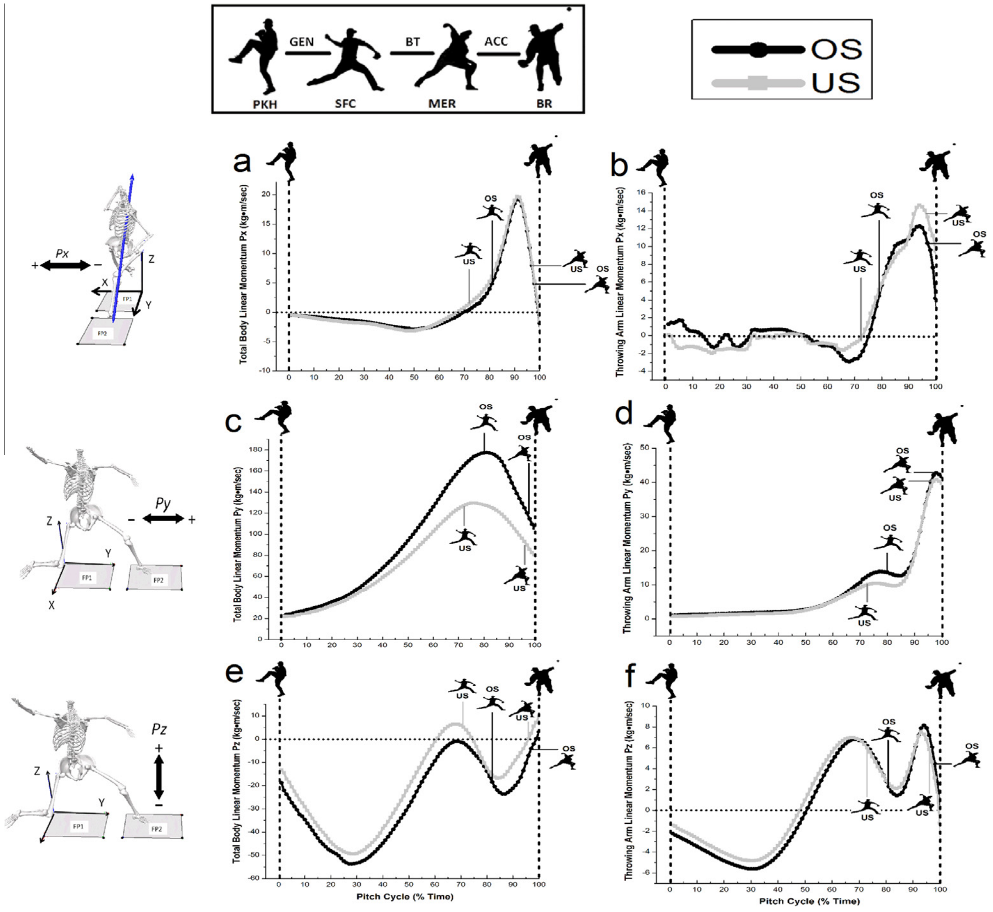

Fig. 3. Linear momentum profiles for the total body and throwing arm. Total body (a, c, e) & throwing arm linear momentum profiles (b, d, e). Mediolateral axis; $+P_x$ indicates rightward segment motion (lateral, third base), $-P_x$ leftward motion (medial, first base). Anterior axis; $+P_y$ indicates segment motion progressing toward home plate, $-P_y$ motion directed toward second base. Vertical axis; $+P_z$ indicates upward segment motion while $-P_z$ is downward. Normalized events and phases; PKH, Peak Knee Height; SFC, Stride Foot Contact; MER, Maximal External Rotation, BR, Ball Release; GEN, Generation Phase; BT, Brace-Transfer Phase; ACC, Acceleration Phase. Normalized stride lengths; Overstride (OS; 76% body height); Understride (US; 52% body height).

were significantly higher with the OS condition (Table 1) at stride foot contact ($p \leqslant .05$) and during the generation and acceleration phases ($p \leqslant .05$). As a result of the significantly higher total body forward momentum observed with OS, throwing arm contribution relative to whole body momentum were significantly lower at the critical throwing-events maximal external shoulder rotation and brace transfer, and during the acceleration phase ($p \leqslant .001$).

The vertical total body momentums (P_z) were observed to be directed inferiorly (downward) at stride foot contact ($p \leqslant .05$), throughout brace transfer ($p \leqslant .001$), and during acceleration ($p \leqslant .001$) with statistically greater magnitudes found with longer strides, whereas throwing arm momentum remained unchanged between stride conditions (Table 1). Also evident were significantly higher contributions of throwing arm momentums during acceleration for OS pitching ($p \leqslant .005$). As shown in Fig. 3, sagittal and frontal plane total body and throwing arm momentum exhibit similar trajectories, although anterior and vertical total body momentum profiles are offset between stride conditions, with OS exhibiting greater overall anterior and downward momentums compared with US.

4. Discussion

A pitcher's stride length is an important determinant in the baseball pitching delivery, which is necessary for appropriating sequential segment motion from the lower body to the throwing hand (Seroyer et al., 2010). Evidence suggests highly skilled and proficient baseball pitchers throw with desired stride lengths that range between 80% and 85% body height (Elliott et al., 1986; Escamilla et al., 1998). For this study, we opted to manipulate desired stride lengths ±25% relative to body height in order to challenge throwing mechanics. Preliminary findings from a study that examined the effect of stride length on physiologic stress suggest an extended stride may be more physiologically demanding, exemplified by increased perceived exertion, heart rate, and metabolic responses (Crotin et al., 2014). In this study our hypothesis was confirmed, that total body and throwing arm linear momentums were altered by the ±25% change in stride length (distance between drive and stride foot calcanei normalized to body height). Analysis of total body linear momentums, specifically those directed anteriorly (forward toward home plate), increased with extended pitching strides. Despite the increased total body and throwing arm momentum observed with OS, momentum compensation ratios decreased more than 9% compared to shorter strides, which may be attributable to the reduced contribution or proportion of throwing arm momentum relative to the total body, and perhaps infers that longer strides may be beneficial in mitigating throwing arm stress. Reported momentum profiles and proportions have the potential to describe competitive responses when throwing at desired stride lengths, given collegiate and skilled high school baseball pitchers involved in this study threw at 76% (OS) and 52% (US) when normalized to body height, which concur with earlier studies that involved throwing from a mound (Dun, Loftice, Fleisig, Kingsley, & Andrews, 2008; Fleisig et al., 2006).

Evident in the frontal plane profile is that early in the pitching delivery during generation, when the drive leg is in single support, both total body and throwing arm momentums progress medially toward the stride leg as it advanced prior to stride foot contact. This is likely the result from the combined effect of trunk extension and swinging the throwing arm back prior to foot contact (Lin et al., 2003). Whereas forward and downward momentum are likely regulated through muscular action, controlling mediolateral momentum is also dependent on appropriate foot placement, either by larger or narrower step lengths and widths (Simoneau & Krebs, 2000). After stride foot contact when both feet are in double support, total body momentum shifted laterally with peak occurring prior to maximal external shoulder rotation and early in the brace-transfer phase, with greater magnitudes observed with longer strides. Throughout arm acceleration, linear momentum was redirected toward the stride leg on which body mass was transferred toward the non-dominant arm. We attribute these frontal plane momentum shifts to initial lateral trunk flexion and the outstretched throwing arm which culminated with medial repositioning of both segments toward first base later in the pitching delivery (Lin et al., 2003; Matsuo & Fleisig, 2006).

The greater medially directed (negative) throwing arm momentums experienced during the generation phase with the shorter strides suggest faster arm motion as it is swung behind the trunk, perhaps to set an earlier cocking position in response to the shorter time spent in single support. From stride foot contact to maximal external rotation (cocking of the throwing arm) throwing arm momentum progressed laterally away from the trunk, with greater magnitudes evident with longer strides during the brace-transfer phase. What is evident in Fig. 3b and substantiated in Table 1, the higher segmental momentum directed laterally toward 3rd base during arm acceleration with US is indicative of a more lateral and extended arm motion, that perhaps may predispose the medial elbow to greater valgus stress (Fleisig & Escamilla, 1996). These frontal plane profiles of total body and throwing arm momentum profiles align with previous results (Lin et al., 2003) and may reflect trunk-throwing arm kinematic couples as described by Matsuo and Fleisig (2006). Based on synchronous lateral flexion and shoulder abduction simulated motions, Matsuo and Fleisig (2006) associated valgus elbow stress with frontal plane segment velocities. Although the influence of stride length was not previously considered, it could be speculated the similar total body and throwing arm momentum profiles as shown in Fig. 3 mirror lateral trunk flexion, where perhaps undesirable stride lengths may exacerbate injury risk by increasing shoulder abduction velocities that arise throughout throwing arm acceleration (Fleisig & Escamilla, 1996; Matsuo & Fleisig, 2006).

As expected, forward or anteriorly-directed total body momentum comprised the highest magnitudes, which confirm earlier studies (Lin et al., 2003), with peaks coincident with stride foot contact for both stride conditions then slowing thereafter to increase throwing arm momentum. Our data demonstrate forward momentum to be most sensitive to stride length changes, where longer strides augmented total body and throwing arm anterior axis momentums throughout all phases of pitching. Despite greater total body momentum, a lower throwing arm momentum proportion was seen compared to shorter stride pitching during the acceleration phase.

Total body momentum was observed to mirror trunk momentum, with coincident increasing and decreasing momentum profiles throughout the pitching delivery, and confirms previous findings (Lin et al., 2003). Therefore, regulating total body momentum with longer strides demonstrates an inherent ability to reduce throwing arm momentum contributions, which is thought to result from an intersegmental trunk effect (Escamilla et al., 2007; Lin et al., 2003; Matsuo et al., 2001; Matsuo & Fleisig, 2006). The humerus, the segment contributing the greatest to arm mass, interacts with the trunk via the glenohumeral joint whereby increasing forward trunk velocity (intended throwing direction) has the potential to augment its segmental motion. Shorter strides demonstrated a potentially less effective intersegmental momentum transfer, as the throwing arm occupied a greater proportion of total body momentum during the acceleration phase, which infers reduced intersegmental momentum transferred by the trunk.

Momentum compensation ratios (MCR) offer a novel way to differentiate contribution of the throwing arm relative to total body momentum. Expressed as a percentage, MCRs describe the efficiency of proximal–distal momentum transfers at hallmark events during the pitching cycle, and perhaps may better explain the influence of stride length. Given throwing arm motion is fastest during arm acceleration (from maximal external rotation to ball release), perhaps a change in MCR may highlight an inability to decelerate trunk linear momentum which in turn may diminish throwing arm linear momentum. Perhaps injury susceptibility may be associated with elevated linear MCRs at critical time points (Lin et al., 2003; Reid et al., 2008; Wight et al., 2004) although additional studies are necessary to verify this notion.

Altered timing of hallmark events and phases in the pitching cycle owing to changing stride length, specifically onset of stride foot contact and respective single and double support phases, may be responsible for the divergent linear momentum profiles. As shown in the time normalized pitching sequence in Fig. 1, earlier onset of stride foot contact (73% time) with the shorter strides is thought to reduce time in single support for generating forward momentum, whereas greater time in double support allows for forward momentum to be inhibited through better braking. Conversely, later stride foot contact onsets (80% in the pitching cycle) with longer strides increase time in single support thereby promoting forward momentum, while shorter periods in double support inhibit bracing and allows for faster total body momentum in contributing to greater overall intersegmental velocities throughout the acceleration phase.

Short brace-transfer intervals during double support from stride foot contact to maximal external shoulder rotation has been associated with increased ball velocity, which is speculated to be attributable to increased stride length and corresponding anterior axis momentum(Werner, Suri, Guido, Meister, & Jones, 2008). Despite significantly different momentum profiles between stride conditions ball velocity (as monitored with the radar gun) remained unchanged. This suggest skilled pitchers innately overcome insufficient forward trunk momentum (Lin et al., 2003; Seroyer et al., 2010; Stodden et al., 2006), which is considered the greatest contributor to ball velocity (Lin et al., 2003; Stodden et al., 2006). Perhaps skilled pitchers compensate for the shorter strides by increasing transverse angular momentum to overcome momentum deficits in the forward direction.

In addition, changes in vertical momentum profiles may impact pitch location. Greater downward total body linear momentum was evident with the longer strides throughout the pitching delivery, with large discrepancies seen in double support. A lowered position when the arm is accelerated is thought to enhance ball delivery toward the bottom of the strike zone. In contrast shorter strides saw greater upward total body momentum before foot contact with diminished downward momentum thereafter when compared to longer stride pitching, which is indicative of an overall higher trunk elevation. A higher trunk elevation late in the pitching delivery (in proximity or during arm acceleration) may be detrimental to performance by raising the plane of contact and improving batters' hitting odds. Yet vertical throwing arm momentum remained unchanged despite a fivefold increase in MCR that was observed with the longer strides. A higher MCR suggests more effective trunk and throwing arm momentum transfers, conceivably by improving trunk stabilization to which we speculate reduces upward trunk momentum and benefits the throwing arm (Fleisig, Andrews, Dillman, & Escamilla, 1995).

The ability to generalize the findings to wider groups however is not possible, given only skilled high school and collegiate pitchers participated. Moreover, a number of limitations must also be acknowledged, in particular the absence of a pitching mound. Professional pitchers throwing from a mound present greater stride lengths relative to body height (approximately 80–86% BH), by comparison to our OS pitching population (76% BH) (Elliott et al., 1986; Escamilla et al., 1998). Stride length to percent body height enables comparisons to other published works using the same approach, although a novel approach would be to standardize stride length to leg length and is perhaps a method to adopt in future work. Despite the inherent differences in stride length at foot strike when pitching from a mound or level ground and the intuitive disparities in kinematics and kinetics between the two conditions, our findings suggest momentum differences as a result of lengthening, or shortening the pitching stride.

5. Conclusion

Stride length was shown to influence segmental linear momentum, particularly directed anteriorly in the intended throwing direction. The trunk, which acts proximally in the energy transfer to the throwing arm, contributes most to total body momentum due to its mass proportion (Lin et al., 2003). Altering proximal momentum transfers as a result of manipulating stride length appears to influence the relative contribution of throwing arm momentum relative to the total body, which perhaps may exceed trunk-to-throwing arm momentum transfers and overwhelm joint constraints. In light of the recent findings demonstrating stride length influences lower body muscular effort and results in significantly different physiologic outcomes (Crotin et al., 2014), when combined with shortened stride lengths around 50% body height the increased throwing arm's anteriorly-directed momentum relative to the total body may be detrimental to throwing arm health. Moreover, with vertical trunk stability compromised by the shorter strides, perhaps performance may decline given pitches tend to elevate in the strike zone and therefore improve odds favoring batters. Further analysis of baseball pitching mechanics with emphasis on distinguishing efficient proximal–distal momentum transfers is therefore warranted, perhaps leading to development of subject-specific stride lengths for optimal baseball pitching mechanics or to other overhand sports.

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