A 3D APPROACH TO BASEBALL PITCHING KINEMATIC SEQUENCE

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A proximal-to-distal sequence (PDS) in baseball pitching is theorized to be more efficient and can reduce upper limb joint loads. However, previous studies did not find PDS from starting from the pelvis and ending at the throwing hand. Current methods of assessing the PDS may be improved by analysing segment rotation sequences using a 3-dimensional (3D) approach rather than using the magnitude. This study used peak angular velocities about each global axis instead of magnitude and investigated PDS from pelvis to hand during fastballs thrown by professional pitchers (n=4). PDS from pelvis to hand was used as the primary sequence about the global vertical axis for all pitchers. We observed no PDS from pelvis to hand about the other two global axes. Analyzing 3D angular velocities may advance our understanding of PDS from pelvis to hand.

KEYWORDS: baseball pitching, segment rotation, kinematic sequence

INTRODUCTION: Pitching is a full-body movement involving sequential rotation of body segments that results in a near maximum ball velocity at release (Pappas et al., 1985). The sequence at which body segments change velocity was described as the kinematic sequence (Tinmark et al., 2010). The proximal-to-distal kinematic sequence (PDS) was believed to be more efficient and less likely to cause injuries (Calabrese, 2013; Fleisig et al., 1995) and had thus been used as a means to assess pitching technique and consistency. Only two studies directly investigated the PDS in baseball pitching using a five-segment pelvis-to-hand analysis. A full PDS follows the progression of peak segment angular velocities through pelvis, trunk, upper arm, forearm, and ends with the hand. None of the pitches from any pitcher in either study used a full PDS. However, only segment angular velocity magnitude relative to the global axes (resultant value about all three axes) was investigated (Scarborough et al., 2020, 2021). There was an opportunity to analyse the components of the segment angular velocity vector about each global axis to understand how rotational dynamics relate to mechanical objectives in each global plane and relatedly, if the potentially beneficial PDS exists in certain planes.
This study investigated whether PDS was used by professional pitchers when segment angular velocity was analysed about each global axis. We hypothesized that a full PDS from pelvis to hand will be used as the primary sequence (used most often) about at least one global axis.

METHODS: Professional pitchers at the Minor League level (n=4) volunteered for this pilot study in accordance with the Institutional Review Board. They performed self-selected warmups before and after affixing 64 individual markers from a custom marker set onto 15 body segments. 3D kinematics were captured (Optitrack, OR, USA; 250 fps for pitchers 1&2 and 360 fps for pitchers 3&4 due to an update in software capabilities). Participants pitched fastballs from an overhead position from 8.2m in a lab and we excluded trials that were rated poor/unrepresentative by pitchers, resulting in 5-11 successful fastball trials for each pitcher that were all analyzed. A fourth-order, zero-lag Butterworth low-pass filter with a cut-off frequency of 10 Hz was used to process marker data (Crenna et al., 2021). The global orthogonal axes were defined with the forward horizontal axis (X) in the direction of the pitcher's throw (mound to home plate), the global vertical axis (Z), and the left axis (Y) which was a cross product of the vertical and forward axes. The pelvis, trunk, upper arm, forearm, and hand segment axes were defined according to McConville's anthropometric data (McConville et al., 1980). Segment angular velocity was calculated relative to the global axes. For the left-handed pitchers (pitcher 2 and 3), the directionality of the angular velocity about global vertical and forward axes were inverted to ensure consistency across pitchers. For each body segment, the time at which the component of angular velocity vector about each global axis reached the largest positive/negative peak is referred to as "peak time" for that segment. The progression of peak times of the five segments is the kinematic sequence (Scarborough et al., 2020). A full PDS follows the progression through adjacent segments: pelvis, trunk, upper arm, forearm, and ends with the hand. The primary sequence about each axis was the most frequently used kinematic sequence and is presented as a percent of all the analyzed trials for each pitcher. Two-tailed signed-rank tests (α=0.05) were used to compare peak times between adjacent segments within each pitcher.

RESULTS: For rotation about the global vertical axis, pitchers (P1-4) primarily used a full PDS (P1: 4/5, P2: 5/9, P3:4/6, P4: 11/11 trials). There were significant differences between peak times of each set of adjacent segments from pelvis to hand (full PDS) in pitchers 4 ($p<0.05$) (**Fig. 1A)**. For rotation about the global left axis, no pitcher demonstrated full PDS, though there were PDS from pelvis to upper arm with significant differences between peak times of each set of adjacent segments in all but pitcher 1 ($p<0.05$) (**Fig. 1B**). For rotation about the global forward axis, no pitchers demonstrated full PDS but there were PDS from trunk to upper arm with significant differences in all but pitcher 4 ($p<0.05$). No pitcher demonstrated full PDS when angular velocity magnitude was used (**Fig. 1C**), though peak angular velocity magnitudes do ascend across the segments from pelvis to hand like previous studies. For brevity, only significant differences between adjacent segments exhibiting PDS have been described, though there were some significant differences between adjacent segments (most often upper extremity) in a distal-to-proximal sequence (e.g., dotted lines of **Fig. 1**).

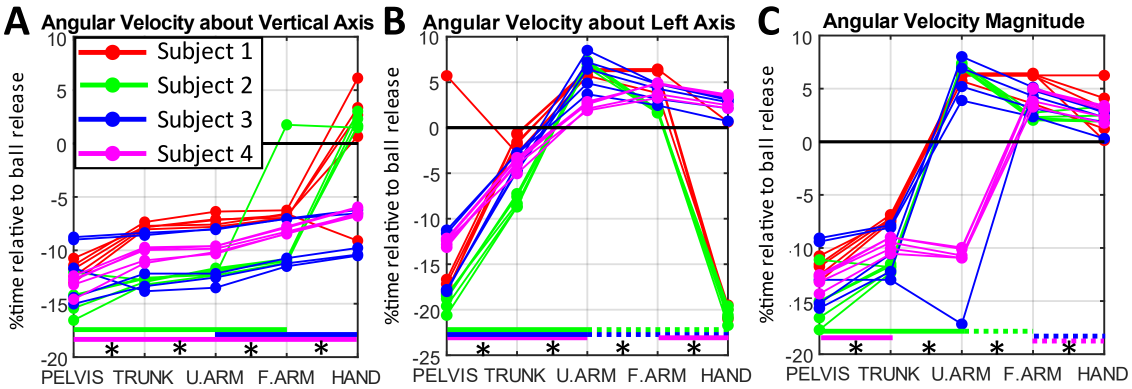

Figure 1: Peak times for pelvis, trunk, upper arm (U.ARM), forearm (F.ARM), and hand segment angular velocity for all trials and pitchers about global (**A**) vertical and (**B**) left axes. (**C**) Peak times of segment angular velocity magnitude. Ball release is at 0% time relative to ball release, with positive % time being after ball release. At the bottom of graphs, solid lines show significant proximal-to-distal differences and dotted lines show significant distal-to-proximal differences between adjacent segments color-coded by pitchers.

DISCUSSION:
The purpose of this study was to examine whether professional pitchers demonstrate full PDS from pelvis to hand when segment angular velocity was analysed about each global axis individually. All pitchers primarily used full PDS for rotation about the global vertical axis. Additionally, the differences in peak times between adjacent segments during full PDS were statistically significant for all five segments for pitcher 4. However, there was no full PDS about any other global axis, and this may explain why no full PDS was found in previous studies when only segment angular velocity magnitude was investigated (Scarborough et al., 2020, 2021).
The full PDS about global vertical axis with positive peak segment angular velocities appeared to be most closely aligned with the general perception of PDS with increased segment angular

velocities for more distal segments (**Fig. 2**). However, this was not always the dominant component of the angular velocity vector for all subjects. Angular velocity about the global vertical axis were 45-62% of the angular velocity magnitude, depending on the segment and pitcher. As the upper extremity experiences multidimensional orientations and rotations that are specific to subphases of the pitch, it could be difficult to find a full PDS pattern with this analysis. The deviation from the PDS pattern of the upper extremity segments was also found in handball throws (van den Tillaar & Ettema, 2009). Techniques such as energy flow analysis (Aguinaldo & Escamilla, 2019; Howenstein et al., 2019) may provide a kinetic context. In addition to the sequence of segment peak times, we also examined the directionality of the segment angular velocity components about each global axis. We found that segment angular velocity about each global axis had both negative and positive peaks. About the global vertical axis, for three out of nine trials for pitcher 2, the negative peak surpassed the positive peak for the forearm (**Fig. 3**). This changed the order of the sequence, despite a positive peak still occurring between the positive peaks for the upper arm and the hand. Evaluating the timeseries of these three trials catalyzed a preliminary exploration of filter choices.

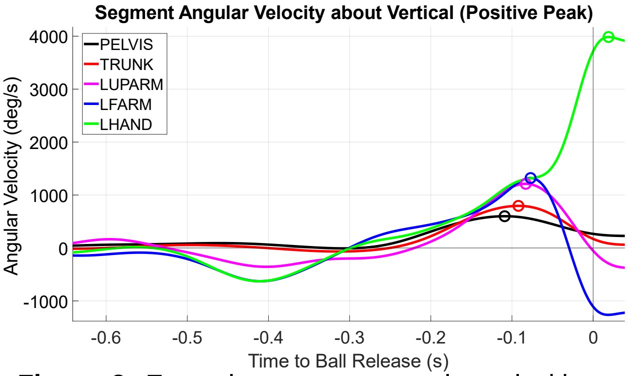

Figure 2: Exemplar segment angular velocities about the global vertical axis for pitcher 2 with positive peaks being the larger peak for all segments.

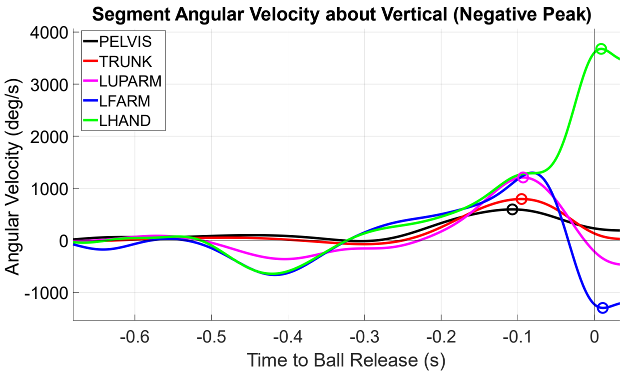

Figure 3: Exemplar segment angular velocities about the vertical axis for pitcher 2 with a larger negative peak of the left forearm.

Though a full review of biomechanical filtering lied outside the scope of this study, we would like to demonstrate the impact of selecting different filter cut-off frequency on the outcomes of the kinematic sequence. Common cut-off frequencies for lowpass filters used on biomechanical signals range from 3-10 Hz (Crenna et al., 2021). However, 18 Hz was used in the previous kinematic sequence study (Scarborough et al., 2020) and 13 Hz was used on a study examining the kinematic sequence of volleyball spikes (Serrien et al., 2018). Therefore, a preliminary analysis was performed using cut-off filter frequencies of 5, 10 (current study), 15, and 20 Hz. We found that the major of the kinematic sequence about the global vertical axis were not affected across these specific filter cut-off frequencies. However, for one of the non-PDS trials in pitcher 2, the negative angular velocity about the global axis was attenuated less with 15 Hz cut-off (**Figs. 4A, 4B**) and thus, was identified as the peak angular velocity.

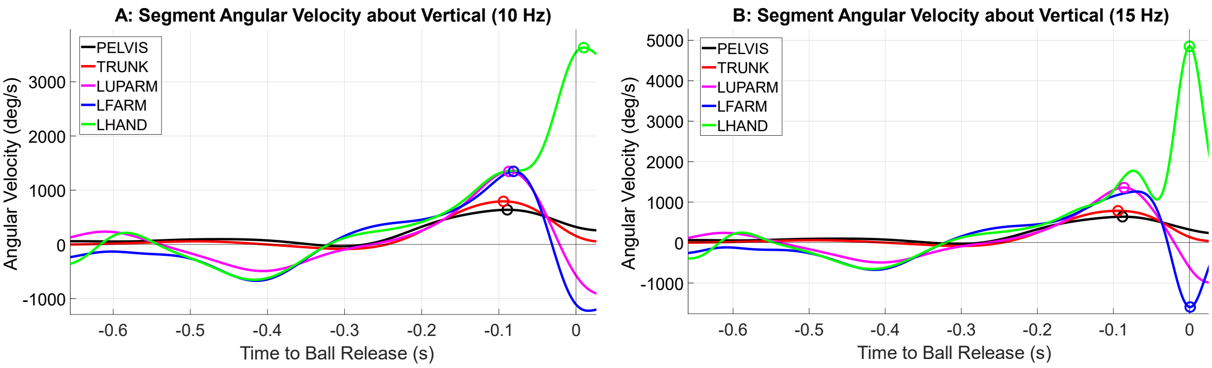

Figure 4: Segment angular velocities about vertical axis for the same trial but with cut-off frequency of A) 10 Hz and B) 15 Hz. In **Fig. 4B**, there is less attenuation of negative hand angular velocity.

There are several limitations to this study. First, the sample size is small, containing only four professional pitchers, and different kinematic sequences may be uncovered with more pitchers. Secondly, this study used segment angular velocity relative to global axes to replicate and compare to previous study. Analysing segment motion in global space also provides insights on how segmental movement ties in with global mechanical objectives of the pitch as pitchers rotate their body about the global vertical and left axes. However, studies on other overhead sports have examined kinematic sequencing using *joint* angular velocity (Serrien et al., 2018; van den Tillaar & Ettema, 2009). Thirdly, only peak segment angular velocity was examined, though *initiation* of angular velocity can provide insights into the onset of segment or joint rotations (Serrien et al., 2018; van den Tillaar & Ettema, 2009). This study was performed within a lab, so the pitching distance was short (8.2 m). In the future, we will include more pitchers and use more realistic distances.

CONCLUSION: This study revealed primarily full PDS when examining the peak times of segment angular velocity about the global vertical axis but did not reveal full PDS when using angular velocity *magnitude* only. Additionally, the directionality of the segment angular velocities and pitcher-specific differences may also be masked if only angular velocity magnitude was used. When coaches and research use kinematic sequences to assess pitching performance, analysing 3D segment angular velocity with carefully selected filters may be more suitable than magnitude alone.

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ACKNOWLEDGEMENTS: We thank the participants for volunteering and financial support from a Major League Baseball grant.