MULTI-SEGMENT CONTRIBUTIONS TO INDUCED BALL VELOCITY IN COLLEGIATE BASEBALL PITCHERS

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The purpose of this study was to implement an induced acceleration analysis (IAA) to estimate the contributions of multi-segment motion to the forward velocity of the ball in collegiate baseball pitchers. Marker-based motion capture and ground reaction force data were collected from a sample of 17 pitchers throwing off an instrumented mound. Kinematic and kinetic data were extracted to drive the IAA model to calculate the muscular and non-muscular contributions to ball velocity. The shoulder joint torque and velocity-dependent torque collectively made up the largest contribution to the total induced velocity of the ball at 61% and 37%, respectively. The model underestimated ball speed by 16%, owing to limitations in distal segment definitions. Although this IAA showed that the proximal segments make a small, direct contribution to forward ball velocity, decomposition of the velocity-dependent torque could further clarify the extent to which the legs, pelvis, and trunk indirectly contributes to ball velocity.

KEYWORDS: induced acceleration analysis, kinetics, pitching.

INTRODUCTION: Baseball pitching performance is typically evaluated by ball velocity, which is determined by movements produced by muscle and joint actions throughout the body. In an open kinetic chain such as overhand throwing, the velocity of the throwing arm is affected by the flow of energy through the chain via coordination of proximal-to-distal segmental motion, where muscular torques can induce accelerations of anatomically remote segments through dynamic coupling (Aguinaldo & Escamilla, 2020; Naito, Takagi, & Maruyama, 2011). However, decomposing the muscular and velocity-dependent (Coriolis, centripetal) components of segmental motion cannot be performed using conventional inverse dynamics approaches (Fregly & Zajac, 1996; Naito et al., 2011). One method used to understand the coupled dynamics of multi-articular body motion is an induced acceleration analysis (IAA), which quantifies how muscular torques cause accelerations of both adjacent and non-adjacent segments in the kinetic chain (Kepple, 2011; Zajac, Neptune, & Kautz, 2002). Previous IAA studies have shown that during overarm throwing, the cumulative effect of velocity-dependent torques strongly contributes to the rapid angular velocity of the throwing arm (Hirashima et al., 2008; Naito et al., 2017). Likewise, Alderink et al. (2008) extended an IAA by integrating the acceleration curves to determine how muscular and non-muscular torques contribute to the forward velocity of the baseball. Their study showed that the shoulder joint and velocity-dependent torques comprised most of the total contribution to the induced velocity of the ball. However, their IAA was limited to data from six high school pitchers who threw on force platforms embedded on flat ground. It is unclear how muscular and non-muscular actions contribute to ball velocity in adult pitchers throwing off a baseball mound, which involves differences in kinematics and kinetics to those of flat-ground throwing (Slenker et al., 2014). Therefore, the purpose of this study was to use IAA to examine how muscular torques, gravity, and velocity-dependent effects contribute to the forward velocity of a ball pitched off an instrumented mound in collegiate baseball players.

METHODS: This retrospective study was approved by the institutional review board of the School of Medicine at Wake Forest University. Data from seventeen collegiate pitchers (age = 20.4 ± 1.2 years, height = 1.87 ± 0.05 m, mass = 94 ± 7 kg) were examined from reports

generated as part of their in-season pitching evaluations. Each pitcher went through a normal pregame warm-up period, before pitching four fastballs, four breaking balls, and four change-ups to a catcher receiving throws at a regulation distance (18.4 m). One representative fastball was extracted for this study in which 3D motion data was collected using a 38 reflective marker set (Aguinaldo & Escamilla, 2019) and a 12-camera motion analysis system (Qualisys, Göteborg, Sweden) at a sampling rate of 400 Hz. Ground reaction forces (GRF) were collected with three multi-component force platforms (AMTI, Watertown, Massachusetts) embedded in the Perfect Mound (Porta-Pro Mounds Inc, Sauget, Illinois). The mound was engineered to meet Major League Baseball (MLB) specification. The force plates were mounted on concrete poured to allow the force plate surfaces to be level with the fiberglass surface of the mound. One plate was positioned under the pitching rubber with the front edge 6 inches in front of the rubber. The other two plates were angled at 4.8° and covered the landing zone. Each plate was covered with 4.4 cm infilled artificial turf to match the rest of the mound. GRF data were collected at 1000 Hz. Ball speed was recorded with a pitch flight analysis device (Rapsodo, Brentwood, Missouri).
Joint kinematic and kinetic data were calculated using a 14-segment model, which included the feet, shanks, thighs, pelvis, trunk (combined thorax-abdomen-head), upper arms, forearms, and hands. The model was configured and implemented using Visual3D (C-Motion, Germantown, Maryland). The joints of the hip, shoulder, and waist (connection of distal trunk to proximal pelvis) were modelled as three degrees-of-freedom (DOF) ball-and-socket joints. The elbow and ankle joints were modelled as two DOF universal joints while the knee joint was modelled as a hinge joint allowing flexion-extension. The distal segment of the throwing arm was modelled as a single segment representing the forearm, hand, and ball.
The joint acceleration produced by muscular, velocity-dependent, and gravity forces can be expressed by the following induced acceleration analysis equation:

$$\ddot{\boldsymbol{\theta}} = \boldsymbol{I}^{-1}(\boldsymbol{\theta})[\boldsymbol{\tau} + \boldsymbol{V}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{g}(\boldsymbol{\theta})] \tag{1}$$

where $\ddot{\boldsymbol{\theta}}$ is the generalized accelerations vector, $\boldsymbol{I}^{-1}$ is the inverse of the system inertia matrix, $\boldsymbol{\tau}$ is the vector of the net muscular torques, $\boldsymbol{V}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$ is the vector due to velocity-dependent (Coriolis, centripetal) forces, and $\boldsymbol{g}(\boldsymbol{\theta})$ is the vector of generalized forces due to gravity. The IAA model was implemented as a Visual3D plug-in developed using the dynamics equations derived in SD/Fast (PTC, Cambridge, Massachusetts). The induced acceleration was calculated from equation (1) by setting all torques to zero except the torque whose contribution to the forward acceleration of the ball was being estimated. To calculate the induced velocity of the ball, the induced acceleration from each source was time-integrated between the instants of maximum knee height of the front leg in the stride phase and ball release. The concurrent validity of the IAA model was analysed with the Spearman rho (ρ) coefficient (α = 0.05) by comparing the total induced velocity of the ball with the speed of the ball obtained from the pitch flight device.

RESULTS: Muscular torque of the throwing shoulder and the velocity-dependent torque made the largest contributions to ball velocity at 61% and 37%, respectively, at release (Figure 1). Conversely, muscle torques by the lower extremities, trunk, and elbow made small or negative direct contributions to ball velocity. Likewise, gravity had a negligible effect on forward ball velocity.
The forward velocity of the ball estimated by the IAA model was 32.9 ± 5.4 m/s (73.5 ± 12.1 mph) while the recorded flight speed of the ball was 39.1 ± 0.9 m/s (87.5 ± 2.1 mph), representing a difference of 6.3 m/s (14 mph) between the two methods. The IAA model underestimated ball speed with a 16% error and exhibited low concurrent validity (ρ = -.177, p = .498).

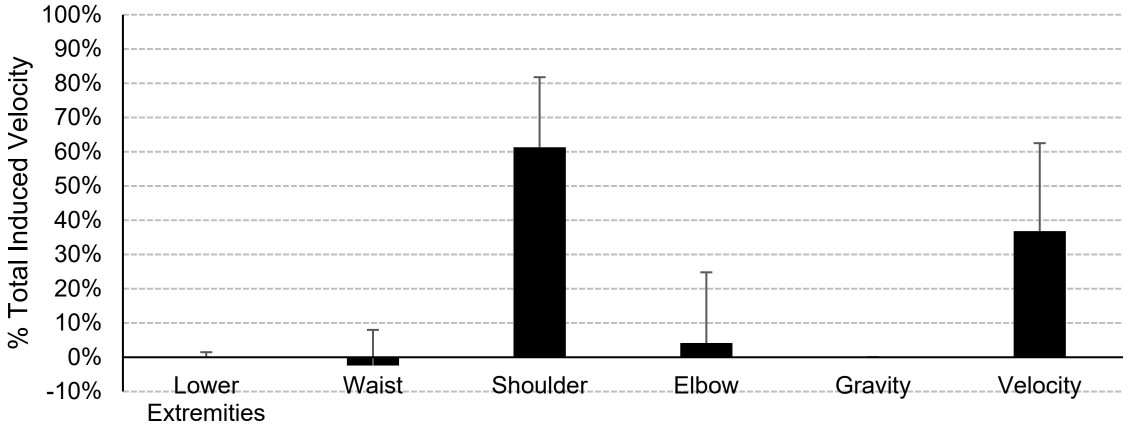

Figure 1: Mean contributions (%) to the total induced forward velocity of the ball (n=17).

DISCUSSION: This study aimed to measure the direct contributions of joint torques, gravity, and velocity-dependent effects to the forward velocity of the ball at release in collegiate baseball pitchers. The results of the IAA indicated that the largest contribution to ball velocity came from the shoulder torque followed by velocity-dependent forces (Coriolis, centripetal). This finding contrasts with that of Alderink et al. (2008), who reported that the velocity-dependent torque induced the largest contribution (57%) of the ball's forward velocity. However, their IAA was limited to data collected from high school pitchers, who threw on flat-ground whereas the current IAA is based on adult pitchers throwing at a higher average ball speed off an instrumented mound. The discrepancy in IAA results could most likely be due to differences in competitive level and in joint kinematics between flat-ground and mound throwing (Fleisig, Diffendaffer, Ivey, & Oi, 2018; Slenker et al., 2014). Furthermore, while the pelvis and trunk did not directly contribute to the induced velocity of the ball, these segments made an indirect contribution to accelerate the distal end of the throwing arm by way of the velocity-dependent torque (Hirashima et al., 2008). The induced power analysis by Aguinaldo and Escamilla (2019) showed that the components of trunk motion of the velocity-dependent torque provided the largest contribution to the energy level of the forearm. In the arm-cocking phase, the velocity-dependent torque induces deceleration of the upper arm, resulting in an increase in energy storage that is released during arm acceleration (Aguinaldo & Escamilla, 2020; Roach & Lieberman, 2014). This energy redistribution mechanism is reinforced by the current IAA, which showed that the forward ball velocity was induced by a direct contribution of shoulder rotation and an indirect contribution of the trunk via the velocity-dependent torque. However, a decomposition of the velocity-dependent torque is needed to further quantify the indirect components of induced ball velocity (Hirashima et al., 2008; Naito et al., 2017).

The current IAA model underestimated ball speed and exhibited a weak association with the speed recorded by pitch flight tracking. This disagreement may be due to a couple of factors. First, the IAA model only outputs the horizontal component of the resultant velocity of the ball while the pitch flight tracker measures the magnitude of the ball's velocity. However, since the vector of a pitched ball is mostly horizontal, this factor would only account for a small difference in speed. Second, the forearm, hand, and ball were defined as one rigid segment due to limitations in tracking the ball with the motion capture system and in the IAA model implementation. It is likely that the wrist and fingers flex and the ball moves relative to the hand near release. Consequently, not capturing this motion could introduce an error in the total induced velocity of the ball. Taking into account these sources of error, therefore, a 16% underestimation in total ball velocity is a reasonable offset.

CONCLUSION: The shoulder joint torque and the velocity-dependent torque made up the largest contribution to the forward velocity of the ball at release in a sample of collegiate baseball pitchers. The IAA model, however, underestimated ball speed, which can be attributed to differences in vector computations and model segment definitions. It is hoped that the decomposition of the velocity-dependent effects will further clarify the extent to which the proximal segments indirectly contribute to forward ball velocity. The findings of these analyses may challenge conventional wisdom regarding training and rehabilitation methods that are based on the current understanding of pitching biomechanics.

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