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Original Research

Association between pitching velocity and elbow varus torque

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ABSTRACT

Background: While there has been an increase in the number of biomechanical studies and usage across baseball, there often remains a dichotomy between performance enhancement and injury reduction.
Objective: To identify which variables have the highest influence on elbow varus torque while controlling for pitch velocity. The secondary purpose was to evaluate a minimal data set prediction model derived from the identified biomechanical variables.
Method: A retrospective review was performed on baseball pitchers who underwent biomechanical evaluation. Analysis of covariance and prediction modeling for varus torque and fastball velocity were utilized.
Results: 298 pitchers were included. Small associations were identified between the log of hip shoulder separation (0.12 (95 % CI: 0.01, 0.23), R^2=0.10), maximum trunk rotation velocity (0.42 (0.15, 0.70), R^2=0.12), trunk flexion at ball release (-0.11 (-0.20, -0.02), R^2=0.10), and shoulder abduction at late cocking (-0.29 (-0.52, -0.06), R^2=0.10) in relation to the log of elbow varus torque. The clinical prediction model for elbow varus torque resulted in poor prediction performance, calibration, and large error using minimal predictor variables (RMSE=1.15, R^2=0.10, Calibration=0.78 (0.41, 1.15)).
Conclusion: Optimizing pitching efficiency by improving small aspects throughout the pitching delivery has potential to accomplish an improvement in velocity while maintaining lower levels of varus torque.

Introduction

Baseball continues to present as a popular option in youth sports across the United States, with nearly half a million annual participants at the high school level.[1] From a pitching standpoint, fastball velocity has gravitated towards being one of the more important factors for player success. Increasing pitch velocity has been particularly evident at the highest levels with the average fastball increasing by 1.8 m/s (4.02 mph) from 2002 to 2019 in Major League Baseball (MLB).[2] This has undoubtedly led to an increased emphasis on developing velocity throughout the lower levels of professional baseball and into the amateur arena, adding importance during the recruitment and scouting process. Correspondingly, there has been an influx of research attempting to quantify the impacts increased pitching velocity has had on injury rates,[3] as well as training methodologies to enhance velocity. Entire fields around strength training,[4] weighted ball usage,[5] and throwing programs have shown utility in improving pitching velocity. On the opposite side, it has been well elucidated that we are seeing a rise in injury levels and missed playing time that is potentially associated with this focus on velocity.[6]

The pitching motion is a series of complex movements with the ultimate goal of force production and transmission from the ground up through ball release to accurately propel a baseball into the strike zone. Recent technological advancements have resulted in an increase of the tools available to analyze these pitching mechanics and pitching accuracy. From a biomechanical perspective, pitching arm elbow injuries have been most commonly attributed to increased elbow varus torque.[7] Prior research has outlined a cutoff of 6 % bodyweight x height (BWxH) varus torque as a practical cutoff for practitioners when discussing elbow risk.[8] Clinical practice has therefore emphasized the reduction of these forces to increase likelihood of injury avoidance in both training and competition. However, as these forces have also been associated with pitch velocity, and therefore performance, this presents a challenge for practitioners balancing player health and performance.

The ability to increase fastball velocity has been attributed to a number of biomechanical factors throughout the literature.[9] However, many of these have emphasized maximizing force and increasing overall output.[4,9] While this is likely a successful strategy for increasing

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performance, it is potentially driving increased varus torques and the corresponding injury risk seen with increasing velocity. Optimizing pitching efficiency, or the ability to better utilize forces throughout the body, has shown promise in increasing velocity while decreasing varus torque.[10] Furthermore, alterations in pitching efficiency are also modifiable through cueing and coaching, representing an important area of practicality in a complex system. As pitching efficiency is predicated on the kinematic sequence and optimal timing throughout the pitching motion to effectively and accurately pitch a baseball, this requires an interplay between variables. Modern biomechanics result in a vast array of variables to analyze; therefore, the primary purpose of this study was to identify which variables have the highest influence on elbow varus torque while controlling for pitch velocity. The secondary purpose was to evaluate a minimal data set prediction model derived from the identified biomechanical variables. Based on prior literature and concepts around the kinetic chain, biomechanical variables around rotational velocity and positions obtained at foot strike will be influential to varus torque. Additionally, it is hypothesized that the minimal data set prediction model will demonstrate adequate prediction of performance.

Methods

A retrospective review was performed on baseball pitchers from the local university, regional high schools, and baseball academies who underwent biomechanical evaluation at the University biomechanics laboratory between July 2019 and September 2022. This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE)[11] reporting guidelines and was approved by the Wake Forest University School of Medicine institutional review board.

Inclusion criteria for this study included baseball players (1) with pitcher as their primary position; (2) able to participate in all training, practices, and competitions; and (3) high school, college, or professional pitcher. Exclusion criteria comprised baseball players (1) who played a position other than pitcher as their primary position; (2) who were being treated for a musculoskeletal injury at the beginning of the season; (3) pitchers that threw submarine and (4) youth pitchers. Submarine pitchers (i.e., those that released the ball below the horizontal plane) were excluded from the analyses due to substantial differences in pitching mechanics compared to pitchers that throw overhanded.

Data were examined from reports generated as part of a pitching evaluation. As part of the evaluation, three-dimensional motion data were collected using the retroreflective marker set required for PitchTrak and a 12-camera motion analysis system (Qualisys AB, Goteborg, Sweden). The same research scientist, with over 10 years experience with baseball biomechanics, collected all data. Baseball pitching kinematic and kinetic biomechanical data have demonstrated excellent reliability (ICC $>$ 0.95).[12] Motion data were collected at 400 Hz. Ground-reaction forces were collected with 3 multicomponent force plates (AMTI, Watertown, Massachusetts) embedded in the Perfect Mound (Porta-Pro Mounds Inc, Sauget, Illinois). The mound was engineered to meet Major League Baseball specifications. Force plate data were collected at 1600 Hz. Pitchers were allowed to wear their cleats. Ball velocity was recorded with a Trackman device (Trackman, Scottsdale, Arizona).

Each pitcher went through a self-guided pregame warm-up period before pitching fastballs, breaking balls, and changeups to a catcher receiving throws at a regulation distance (18.4 m). The warmup consisted of a period of up to 15 min, with no minimum time limit. No cues for warm up were given. No simulated batter was included in warm up or during pitching. Only the fastball data were analyzed for this study. Data were processed and variables were calculated with Visual3D (C-Motion Inc). Pitching models were defined using the PitchTrak model, and segment coordinate systems were defined according to Internal Society of Biomechanics recommendations.[12] Elbow varus torques were normalized by body weight times height (BWxH).

During data processing, a cutoff of 6 % bodyweight x height (BWxH) varus torque was created as a secondary measure based on previous clinical and performance based literature.[8]

Prior to analyses missing data were assessed, with 0 % missing data for all demographic and biomechanical variables. All demographic and pitching biomechanical data were calculated as mean (standard deviation) or count (percent).

An *a priori* sample size calculation was performed.[13] From previous research,[9,14] elbow varus torque mean was 3.7 % BWxH with a standard deviation of 1.1 and the R^2 was 0.41. Pitch velocity mean was 36.4 m/s with a standard deviation of 3.4, and the R^2 was 0.45. A total of 243 pitchers, including up to 9 parameters (degrees of freedom) were required to reduce the risk of overfitting.

To assess the association of specific modifiable pitching biomechanical factors in relation to 1) elbow varus torque and 2) pitching velocity, a series of regressions were performed. Non-linear relationships between each modifiable pitching biomechanical factor and the outcome (elbow varus torque or pitching velocity) were assessed prior to model building. All relationships were observed to be linear with log transformations. Log transformations were performed due to residual model checking (Supplementary material 1). Log transformations are interpreted as percent change.

The association of specific modifiable pitching biomechanical factors in relation to elbow varus torque controlled for pitching velocity to identify potential biomechanical factors that could be modified without reducing pitching velocity (i.e., pitching performance potential). Models further controlled for age, hand dominance, and competition level. The association of specific modifiable pitching biomechanical factors in relation to pitching velocity controlled for age, hand dominance, and competition level. Log transformations were performed for explanatory variables (modifiable pitching biomechanical factors) and outcomes (elbow varus torque or pitch velocity), and the covariate age.

Analyses of covariance (ANCOVA) were performed to assess potential differences in pitchers identified as at risk of elbow injury by current pitching biomechanical guidelines for the outcome of pitch velocity. A dummy variable of elbow varus torque was created for pitchers at or above 6 % BWxH elbow varus torque. ANCOVAs were controlled for age, hand dominance, and competition level. No log transformations were performed for these analyses.

The specific modifiable pitching biomechanical factors were included in the development of two separate prediction models: 1) elbow varus torque; 2) pitching velocity prediction models to compare to previously developed baseball pitching prediction models.[9,14] Both prediction models were developed with the predictors of: 1) Maximum hip shoulder separation, 2) Lateral trunk tilt at release, 3) Forward trunk flexion at release, 4) Maximum pelvis rotation velocity, 5) Maximum trunk rotation velocity, 6) Shoulder abduction at late cocking, 7) Age, 8) Hand dominance, 9) Competition level. Log transformations were performed for all outcomes and predictors, except hand dominance and competition level, as these are nominal and ordinal based predictors. Models were internally validated through 10-fold cross validation. Model performance was assessed through calibration, root mean square error (RMSE), and R^2.[15–17] All statistical analyses and model building were performed in R 4.02.

The Transparent Reporting of multivariable prediction mode for Individual Prognosis or Diagnosis (TRIPOD) guidelines were followed for reporting.[18]

Results

A total of 298 pitchers with a mean age of 18.73 years (SD, 3.02 years) and BMI of 26.27 kg/m^2 (SD, 7.80) were included in this study. A majority were right-handed (76 %) and participating in high school baseball (46 %) at the time of data collection (Table 1).

There was a positive association between the log of hip shoulder separation (0.12 (95 % CI: 0.01, 0.23), $p = 0.036$; $R^2 = 0.10$) and log of maximum trunk rotation velocity (0.42 (95 % CI: 0.15, 0.70), $p = 0.002$;

Table 1
Pitcher demographics.

Variable	All Participants (n = 298)	Elbow Varus Torque >6 % BWxH (n = 158)	Elbow Varus Torque <6 % BWxH (n = 140)
Age	18.73 (3.02)	18.90 (3.02)	18.55 ± 3.02
Body Max Index (kg/m^2)	26.27 (7.80)	26.86 (10.29)	25.60 ± 3.08
Hand Dominance (% Left)	7123.8 %)	42(26.6 %)	2920.7 %)
Competition Level (% High School)	13,846.3 %)	6641.8 %)	7251.4 %)
Pitch Velocity (m/s)	37.60 (1.99)	38.06 (1.92)	37.08 (1.94)
Pitch Velocity (mph)	84.12 (4.45)	85.15 (4.30)	82.95 (4.34)
Hip Shoulder Separation at Foot Strike °	49.20 (9.70)	50.15 (9.59)	48.13 (9.75)
Lateral Trunk Tilt at Ball Release °	26.85 (8.73)	26.95 (9.08)	26.74 (8.34)
Trunk Flexion at Release °	36.77 (8.92)	36.26 (8.71)	37.35 (9.15)
Maximum Pelvis Rotation Velocity°/s	692.41 (95.45)	693.39 (94.47)	691.31 (96.87)
Maximum Trunk Rotation Velocity°/s	1069.42 (86.02)	1082.40 (80.08)	1054.77 (90.33)
Shoulder Abduction at Late Cocking °	171.68 (12.03)	171.16 (12.83)	172.28 (11.07)

BW = Body Weight.
H = Height.
kg = kilograms.
mph = miles per hour.
m = meters.
s = seconds.
Results are reported as mean (standard deviation) or frequency (%).

R^2 = 0.12; Fig. 1) in relation to the log of elbow varus torque when controlling for pitch velocity, age, hand dominance, and playing level. There was a negative association between the log of trunk flexion at ball release (−0.11 (95 % CI: −0.20, −0.02), p = 0.031; R^2 = 0.10) and log of shoulder abduction at late cocking (−0.29 (95 % CI: −0.52, −0.06), p = 0.022; R^2 = 0.10) in relation to the log of elbow varus torque, when controlling for pitch velocity, age, hand dominance, and playing level (Table 2). For all models, refer to Supplementary material 2.

When splitting groups by elbow varus torque of 6 %, pitchers who presented with a 6 % or higher elbow varus torque demonstrated decreased trunk flexion at release (−2.16° (95 % CI: −4.1, −0.21), p = 0.0311; R^2 = 0.04) and decreased shoulder abduction at late cocking (−2.36° (95 % CI: −4.39, −0.33), p = 0.023; R^2 = 0.08) compared to pitchers with <6 % elbow varus torque, when controlling for pitch velocity, age, handedness, and competition level. Pitchers who presented with a 6 % or higher elbow varus torque demonstrated increased maximum trunk rotation velocity (20.72° */sec* (95 % CI: 0.90, 40.54), p = 0.041; R^2 = 0.07) compared to pitchers with <6 % elbow varus torque, when controlling for pitch velocity, age, handedness, and competition level (Table 2).

There was a positive association between the log of hip shoulder separation (0.06 (95 % CI: 0.03, 0.08), p < 0.001; R^2 = 0.43), log of lateral trunk tilt (0.01 (95 % CI: 0.00, 0.03), p = 0.012; R^2 = 0.39), log of forward trunk flexion at release (0.05 (95 % CI: 0.04, 0.07), p = 0.002; R^2 = 0.44), and log of maximum trunk rotation velocity (0.10 (95 % CI: 0.03, 0.18), p = 0.007; R^2 = 0.41) in relation to the log of maximal pitch velocity.

The elbow varus torque prediction model after internal validation demonstrated a R^2 of 0.10, calibration of 0.78 (95 % CI: 0.41, 1.15), and an RMSE of 1.15. The pitch velocity prediction model after internal validation demonstrated an R^2 of 0.50, calibration of 1.01 (95 % CI: 0.90, 1.12), and an RMSE of 1.41.

Discussion

Small significant associations were seen using linear regression with hip shoulder separation at foot strike, lateral trunk tilt at ball release, trunk flexion at release, maximum pelvis rotation velocity, maximum trunk rotation velocity, and shoulder abduction at late cocking. These data are consistent with prior research showing that while pitch velocity has an association on varus torque, other variables within the pitching motion are also influencing medial elbow torque.[19] Throwing a baseball is a complex motion that is dependent on many factors and forces that ultimately produce the desired outcome. While this analysis focused on upper extremity torques, it supports the theory that all aspects of the pitching delivery are likely important and dependent on each other.

Controlling for pitch velocity is an important distinction in this study because it remains a main goal of performance enhancement. Enhancing ground reaction forces through the lower half,[20] increasing maximal humeral rotation velocity,[9] and maximizing elbow extension velocity[9] have all been associated with increasing pitch velocity. However, these increases in overall forces and torques have been correspondingly associated to increased varus torque. The results from this analysis suggest that when attempting to reduce varus torque while maintaining pitch velocity, a multi-faceted approach with small gains across multiple areas is likely important. This is critical when considering coaching and implementing pitching mechanics changes, as this emphasizes the importance of a comprehensive assessment process focusing on small gains across multiple categories.

Very small differences were seen when players were split into groups of high varus torque and low varus torque. Dichotomizing this continuous variable assumes that there are distinct clinical differences based on this cut point. Separating these players into buckets remains helpful from a practicality standpoint and has been shown in prior research as a potential tipping point in risk.[8] However, similarly to the discussion on overall torque, this does not seem to be a particularly high yield strategy for seeing improvements across groups of players. This is likely due to a fairly narrow distribution around the 6 % mark and supports the use of overall numbers versus splitting these players into groups.

Hip shoulder separation at foot strike, lateral trunk tilt at ball release, trunk flexion at release, and maximum trunk rotation velocity all showed moderate associations to pitch velocity. This is consistent with prior research and with a large sample size brings further validation concerning the influence of these pitching mechanic variables and pitch velocity.[21] Notably, maximum pelvis rotation velocity was not shown to be significantly associated with pitch velocity. While lower extremity peak forces, particularly lead leg ground reaction forces,[22] have shown positive associations with velocity, timing of lower half movements and the additive associations of proper kinematic sequencing may play a bigger role in pitch velocity than peak kinematics in isolation. Further, as there is a small positive association between thoracic rotation velocity and arm kinetics, how energy generation is applied to baseball propulsion may influence elbow and shoulder kinetics. As this association was observed between thoracic rotational velocity and not pelvic rotational velocity, it suggests that the oblique musculature may play a significant role in force generation through the upper half. Injuries to the throwing arm, namely the elbow and shoulder, are clearly of paramount importance based on their proclivity for lost time. However, oblique injuries are also a significant injury to pitchers, with prior studies suggesting oblique strains to have higher incidence across professional baseball than ulnar collateral ligament injuries.[23] While the focus of this study was on varus torques at the elbow, further inquiry is needed to better elucidate this relationship.

The clinical prediction model for elbow varus torque resulted in poor prediction performance, calibration, and large error using minimal predictor variables. This is in contrast to previous research, where including a large number of biomechanical pitching predictors demonstrated good prediction performance and low error.[9,14] Within this minimal predictor data set prediction model, the overall RMSE was 1.15.

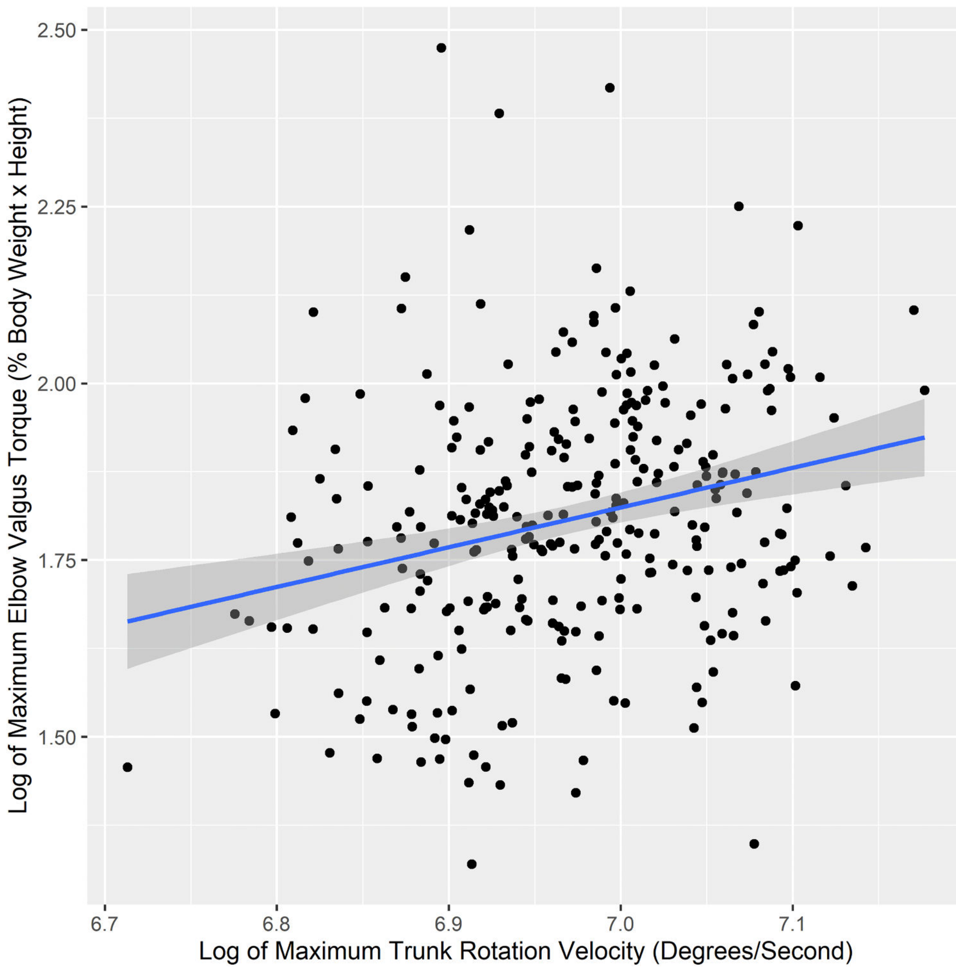

Fig. 1. Association of log of maximum trunk rotation velocity and log of maximum elbow varus torque.

Table 2
Pitching biomechanics log transformed linear regression and analyses of variance results in relation to elbow varus torque.

Variable	Beta (95 % Confidence Interval)	R^2	P-Value
Log Transformed Linear Regression			
Hip Shoulder Separation at Foot Strike °	0.12 (0.01, 0.23)	0.10	0.036
Lateral Trunk Tilt at Ball Release °	0.05 (0.00, 0.10)	0.10	0.072
Trunk Flexion at Release °	−0.11 (−0.20, −0.02)	0.10	0.031
Maximum Pelvis Rotation Velocity°/s	0.04 (−0.12, 0.20)	0.09	0.659
Maximum Trunk Rotation Velocity°/s	0.42 (0.15, 0.70)	0.12	0.002
Shoulder Abduction at Late Cocking °	−0.29 (−0.52, −0.06)	0.10	0.022
Analyses of Variance Comparing >6 % and <6 % BWxH Elbow Varus Torque* Pitchers			
Hip Shoulder Separation at Foot Strike °	1.48 (−0.65, 3.62)	0.15	0.175
Lateral Trunk Tilt at Ball Release °	0.04 (−1.95, 2.03)	0.09	0.969
Trunk Flexion at Release °	−2.16 (−4.1, −0.21)	0.04	0.0311
Maximum Pelvis Rotation Velocity°/s	−4.27 (−26.79, 18.25)	0.03	0.711
Maximum Trunk Rotation Velocity°/s	20.72 (0.90, 40.54)	0.07	0.041
Shoulder Abduction at Late Cocking °	−2.36 (−4.39, −0.33)	0.08	0.023

s = seconds.
BW = Body Weight.
H = Height.
*All models controlled for age, hand dominance, and competition level.

This sample observed narrow variance for elbow varus torque, clustered around 6 % BWxH. An RMSE of 1.15 BWxH is beyond the difference between clinical identification of 'high' and 'low' elbow torque; thus, providing no clinical meaningfulness for identifying elbow injury risk pitchers. These prediction results suggest that at this time, a large number of biomechanical predictors are required to accurately predict arm kinetics and this minimal predictor model should not be used.

As with any research, there are multiple limitations to the current study that must be acknowledged. Warmup varied between each individual pitcher, which could affect pitching biomechanical outputs and inferences. Pitching balls and strike accuracy was not obtained, decreasing the translation of the results. As previously discussed, modern biomechanical analysis has led to a sizeable amount of data points encompassing various stages of the throwing motion and various forces and ranges of motion at play. The current analysis looked exclusively at the core and upper body, utilizing six metrics that were previously defined in the literature to warrant merit. It is certainly plausible that different variables belong in this grouping and represents an area for future research. The authors would also postulate that the main takeaway, small changes in multiple areas, will be true with different sets of variables. Similarly, 6 % was utilized as a cutoff for varus stress and used to identify high and low risk pitchers. While this is based on prior research,[8] it is certainly plausible that this cutoff mark is different for various levels of play and age, among other variables. Alterations to this cut point could have affected the ultimate outcome of the analysis of variance. Finally, while the study was adequately powered and results were controlled by age and competition level, the variance amongst these groups does remain a limiting factor to broad level analysis. Prior research has shown notable biomechanical differences amongst competition level and it must be acknowledged that there remain differences even within the groups analyzed.[24] For example, while low A pitchers and MLB pitchers are classified as professional, there is likely a bigger gap here in competition level than to Division 1 College pitchers. We are hopeful that larger data sets will be able to control for most of these variables in the future.

Conclusion

Improving pitch velocity while maintaining or reducing elbow varus torque is an important biomechanical goal to produce the result of increased performance with decreased elbow injury risk. While the biomechanical variables analyzed showed better associations with pitch velocity, there were minor associations seen with the reduction of varus torque that can be utilized in conjunction to help maximize athletic performance and health. Utilizing a small number of predictors demonstrated poor prediction performance, suggesting that these prediction models should not be used. Optimizing pitching efficiency by improving small aspects throughout the pitching delivery has potential to accomplish a maintenance in elbow varus torque while improving velocity by means of actionable coaching and modifiable cues.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare no competing interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.bjpt.2025.101222.

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