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Optimal initial position and technique for the front foot contact phase of cricket fast bowling: Commonalities between individual-specific simulations of elite bowlers

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ABSTRACT

Group-based and individual-based studies in cricket fast bowling have identified common technique characteristics associated with ball release speed. The applicability of these findings to individual bowlers is often questioned, however, due to research approach limitations. This study aims to identify whether the optimal initial body position at front foot contact and subsequent technique to maximise ball release speed exhibit common characteristics for elite male cricket fast bowlers using individual-specific computer optimisations. A planar 16-segment whole-body torque-driven simulation model of the front foot contact phase of fast bowling was customised, evaluated, and the initial body position and subsequent movement pattern optimised, for ten elite male fast bowlers. The optimised techniques significantly increased ball release speed by 4.8 ± 1.3 ms^{-1} (13.5 ± 4.1%) and ranged between 37.8 and 42.9 ms^{-1}, and in lower peak ground reaction forces and loading rates. Common characteristics were observed within the optimal initial body position with more extended front knees, as well as more flexion of the front and bowling arm shoulders than in current performances. Delays to the onset of trunk flexion, front arm and bowling arm shoulder extension, and wrist flexion were also common in the subsequent movement during the front foot contact phase. Lower front hip extensor and front shoulder flexor torques, as well as greater bowling shoulder extensor torques were also evident. This is useful knowledge for coach development, talent identification, and coaching practice.

1. Introduction

Cricket, the world's second most popular sport, is played between two teams consisting of batters and bowlers. Fast bowlers attempt to reduce the number of runs and dismiss the batters primarily using the speed of the delivery (Worthington et al., 2013a) with research focusing on linking ball release speed with technique parameters employing group-based and individual-based studies.

Group-based studies have taken two approaches: contrasting the mean of individual technique parameters between two heterogeneous groups of fast bowlers (Felton et al., 2019a; Phillips et al., 2012), or correlating technique parameters with ball release speed within a homogeneous group (Salter et al., 2007; Wormgoor et al., 2010; Worthington et al., 2013a). The fastest bowlers were characterised by a combination of technique parameters within the front foot contact phase (period between front foot contact and ball release), which includes a more extended front leg, increased upper trunk flexion, and greater flexion of the bowling arm shoulder angle (representative of 'delay') at front foot contact (Worthington et al., 2013a). The individual applicability of these findings, however, has been challenged with some arguing that between-bowler findings only permit probabilistic 'on average' statements about the group rather than the individuals within it (Glazier and Mehdizadeh, 2019). For example, the relationship between run-up speed and ball release speed is linear within a group (Worthington et al., 2013a) but quadratic for individuals. Furthermore, implementing this knowledge in talent identification has also been questioned since numerous elite international fast bowlers do not exhibit all of these characteristics (Glazier and Mehdizadeh, 2019).

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Table 1
Means, standard deviations, and differential statistics for selected discrete parameters associated with performance and injury during the front foot contact phase of fast bowling.

parameters	current (mean ± SD)	optimised (mean ± SD)	paired difference (±95% CI)	p	ES
ball release speed (ms^{-1})	35.9 ± 1.5	40.7 ± 1.6	4.80 (±1.0)	<0.001	3.1
time (ms)	101 ± 8.4	102 ± 6.0	0.26 (±3.5)	0.888	0.04
peak horizontal braking force (BW)	4.13 ± 0.7	3.94 ± 0.4	−0.19 (±0.5)	0.394	0.33
peak vertical force (BW)	6.03 ± 1.3	5.68 ± 0.8	−0.35 (±0.5)	0.093	0.33
horizontal braking loading rate ($BW{\cdot}s^{-1}$)	154 ± 39	128 ± 45	−25.5 (±17)	0.008	0.60
vertical loading rate ($BW{\cdot}s^{-1}$)	249 ± 118	172 ± 70	−76.7 (±107)	0.022	0.70
horizontal braking impulse (BW·s)	0.15 ± 0.05	0.15 ± 0.05	0.001 (±0.01)	0.882	0.02
vertical impulse (BW·s)	0.31 ± 0.05	0.29 ± 0.06	0.02 (±0.04)	0.383	0.23

To improve the individual applicability of technique findings in cricket fast bowling, individual-based studies have been utilised and taken two approaches: experimentally analysing the individual variation of an elite bowler's technique parameters and its effect on ball release speed (Salter et al., 2007), and theoretically investigating the optimal technique of an elite male bowler to maximise ball release speed using an individual-specific forward-dynamics computer simulation model (Felton et al., 2020). Although similar technique parameters to the group-based findings were observed, the applicability of translating individual-specific optimum techniques beyond the intended bowler has also been challenged (Glazier and Mehdizadeh, 2019). It is argued that translating findings derived from one individual bowler to another is inappropriate since individual-specific movement patterns are influenced by an individual's intrinsic dynamics which may not be suitable or even attainable for other individuals. It is also not possible to validate the veracity of the group-based findings using one individual-based study. To conclude that these characteristics are commonalities of the optimum technique for ball release speed in elite male fast bowling therefore requires more evidence.

To identify commonalities of the optimal technique for ball release speed in elite male fast bowling, an individual-based approach could be used for multiple bowlers with the findings explored for trends. Previously, limitations with each of the individual-based approaches has prevented this. Experimental methodologies similar to Salter et al. (2007) for example require sufficient natural variation in technique to identify relationships statistically. Although this could be manipulated by constraining elements of technique (Greig and Yeadon, 2000), this may not always be possible in elite athletes and could lead to unrepresentative techniques being investigated. To overcome these limitations, forward-dynamics computer simulation models have been adopted which provide control of the motor system constraints and allow individual-specific cause and effect relationships to be determined by comparing simulated and current movement patterns (McErlain-Naylor et al., 2021). Due to the computational processing power requirements and time limitations involved in the customisation, evaluation, and optimisation of these models, however, most applications have been individually based. Nevertheless, this approach allows individual-specific cause and effect relationships to be determined, which can be compared between multiple bowlers to find commonalities in optimal technique for ball release speed in elite male fast bowling.

This study therefore aims to identify commonalities in the optimal initial body position at front foot contact and subsequent technique to maximise ball release speed for elite male cricket fast bowlers.

2. Methods

2.1. Participants

Ten males (age: 20.7 ± 2.4 years; height: 1.91 ± 0.08 m; mass: 86.9 ± 8.5 kg) who were all members of the England and Wales Cricket Board (ECB) elite fast bowling group participated in the study. All procedures were approved by Loughborough University's Ethics Committee and written informed consent was obtained prior to the study commencing.

2.2. Simulation model

A 16-segment planar torque-driven computer simulation model previously used to investigate the front foot contact phase of the cricket fast bowling action was employed (Felton et al., 2020). This phase was investigated due to previous research identifying technique between front foot contact and ball release as fundamental to maximising fast bowling performance (Worthington et al., 2013a, Felton et al., 2020). The simulation model comprised 14 rigid segments: head plus trunk, two upper arms, two thighs, two shanks, two two-segment feet, forearm plus hand (non-bowling arm), forearm (bowling arm), hand (bowling arm) with wobbling masses connected via non-linear spring dampers included within the shank, thigh, and trunk representations. Two massless segments (pelvis and shoulder girdle), whose length and orientation were varied using a Fourier series function of the trunk orientation angle, connected the bilateral hip and shoulder joint centres, allowing non-coincident hip joint centres and non-coincident shoulder joint centres. Similarly, to incorporate lateral side-flexion, the length of the torso plus head segment were varied using a Fourier series function of the trunk orientation angle while adjusting the inertia parameters to reflect the change in length (Felton et al., 2019b). The foot–ground interface was represented using horizontal and vertical linear spring-dampers at three points of contact (heel, metatarsophalangeal joint (MTP), and toe) of the front foot (Felton et al., 2019b). A point mass was used to represent the ball and attached to the end of the bowling hand using a viscoelastic spring to ensure a smooth release (Felton et al., 2019).

The model was driven using torque generators consisting of contractile and series elastic components to flex and extend both shoulder and hip joints, as well as the knee, ankle and MTP joints on the front leg, and the elbow and wrist joints on the bowling arm (King et al., 2006). The activation of each torque generator at any given time was governed by a quintic function with zero accelerations and velocities at the end points (Yeadon and Hiley, 2000). Activation profiles were limited to a minimum ramp time of 70 ms (Yeadon et al., 2010) and constrained to either: ramp up- ramp up; ramp up - ramp down; ramp down - ramp up; ramp down - ramp down (Felton et al., 2020). Passive elastic elements were used at these joints to prevent the joints exceeding their anatomical limit (Felton et al., 2020). The elbow on the non-bowling arm, and the MTP, ankle and knee joints on the rear leg were angle-driven since there are no established links between the movement of these joints during the front foot contact phase and fast bowling performance (Ferdinands et al., 2014).

Input to the simulation model comprised the segmental inertia parameters; the initial centre of mass, trunk orientation, and torque-driven joint kinematics; the joint-angle time histories of the angle-driven joints; the Fourier series parameter values for the massless segment orientations and lengths, and the trunk + head segment length; the viscoelastic parameter values for the wobbling masses and foot–ground interface; and the torque parameters and the activation profiles for each of the torque generators (Felton et al., 2020). Output from the model comprised the mass centre position, trunk orientation and joint

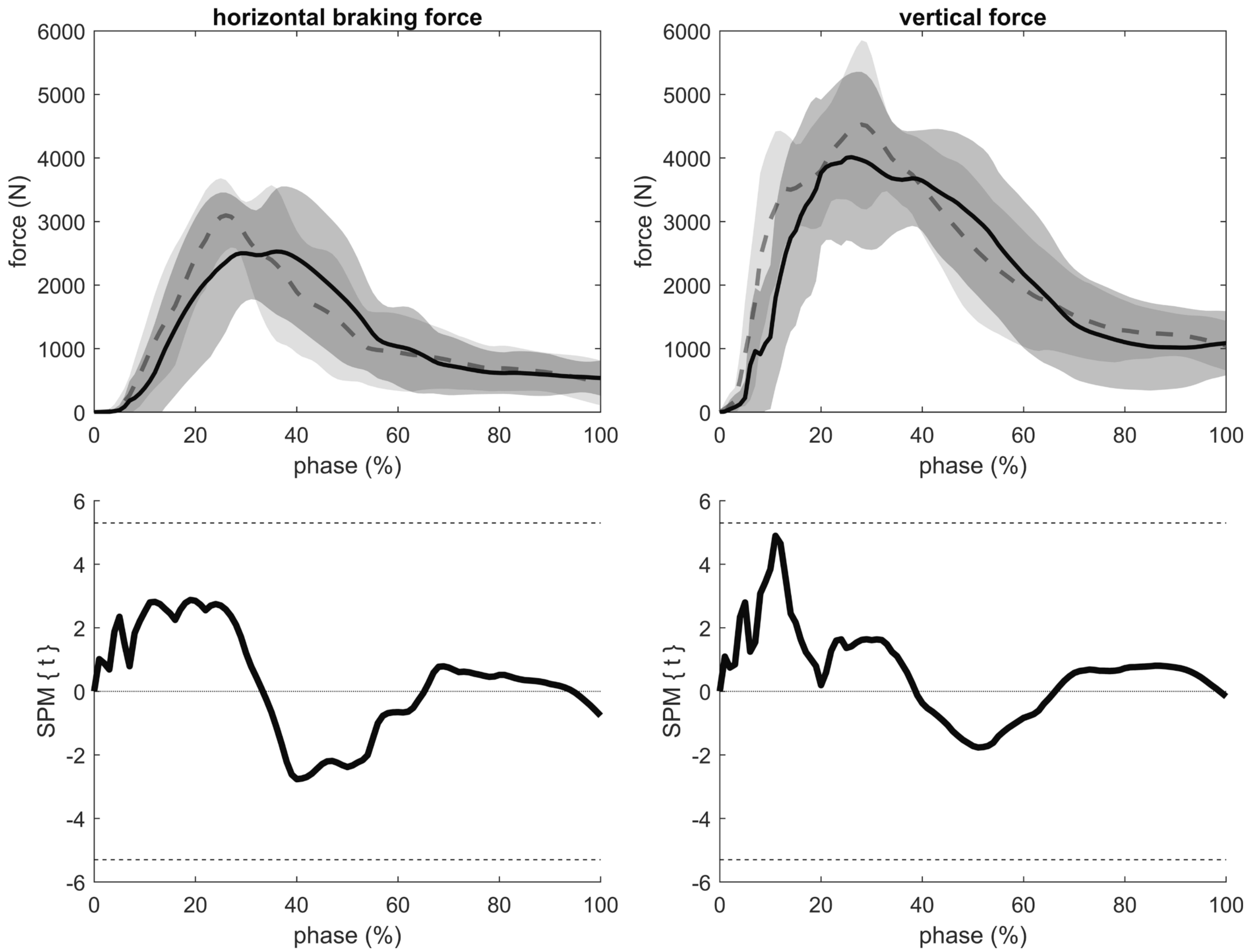

Fig. 1. (top) Mean and standard deviation of the horizontal braking and vertical force for the current techniques (grey dashed line) and optimised techniques (black solid line); (bottom) the SPM1D paired *t*-test analysis comparing the horizontal braking and vertical ground reaction force between the current technique and optimised technique. The grey dashed lines represent the t-value threshold for a significant alpha value of 0.05. Positive t-values indicate the current technique had greater force during that part of the phase compared to the optimised technique.

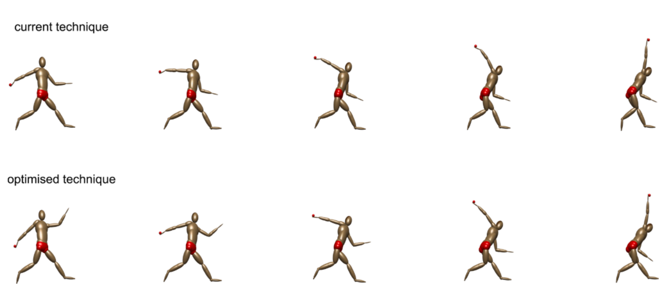

Fig. 2. Current technique (top) verse optimised technique (bottom) between front foot contact and ball release for a representative example (bowler with the fastest optimised ball release speed – 42.9 ms^{-1}).

configuration angles, joint torques, ground reaction forces and ball release velocity.

2.3. Model customisation

The simulation model was customised to each participant and evaluated to ensure it provided a realistic representation of their current fast bowling technique (Felton et al., 2020). Individual-specific inertia parameters were determined from 95 anthropometric measurements of each bowler using a geometric inertia model (Yeadon, 1990). Data collected at the ECB National Cricket Performance Centre at Loughborough University (an indoor practice facility where bowlers are able to use a full length run-up on a standard sized artificial cricket pitch) were used to determine the kinematic and kinetic inputs for the model. Eighteen MX13 Vicon (OMG Plc, Oxford, U.K.) cameras sampling at 300 Hz and spanning a volume of 7 × 3 × 3 m were used to capture fifty 14 mm retroreflective markers attached to each bowler's body, as well as an additional 15 × 15 mm reflective patch attached to the ball (Worthington et al., 2013a). A Kistler force platform (Type 9287B, Kistler AG, Switzerland) orientated with the centre of the volume, sampling at 1800 Hz, and synchronised to the Vicon motion capture system, recorded front foot ground reaction force. Each bowler bowled 12 maximal effort deliveries of a good length (directed towards and landing 6–8 m in front of the target wickets). To verify the effort and length of each delivery, a Doppler radar system (Trackman A/S, Denmark) was used to provided immediate ball release speed and pitch location.

The best trial for each bowler (greatest ball velocity and minimal marker loss) was processed within Vicon's Nexus Software to determine joint centre time histories between front foot contact and ball release

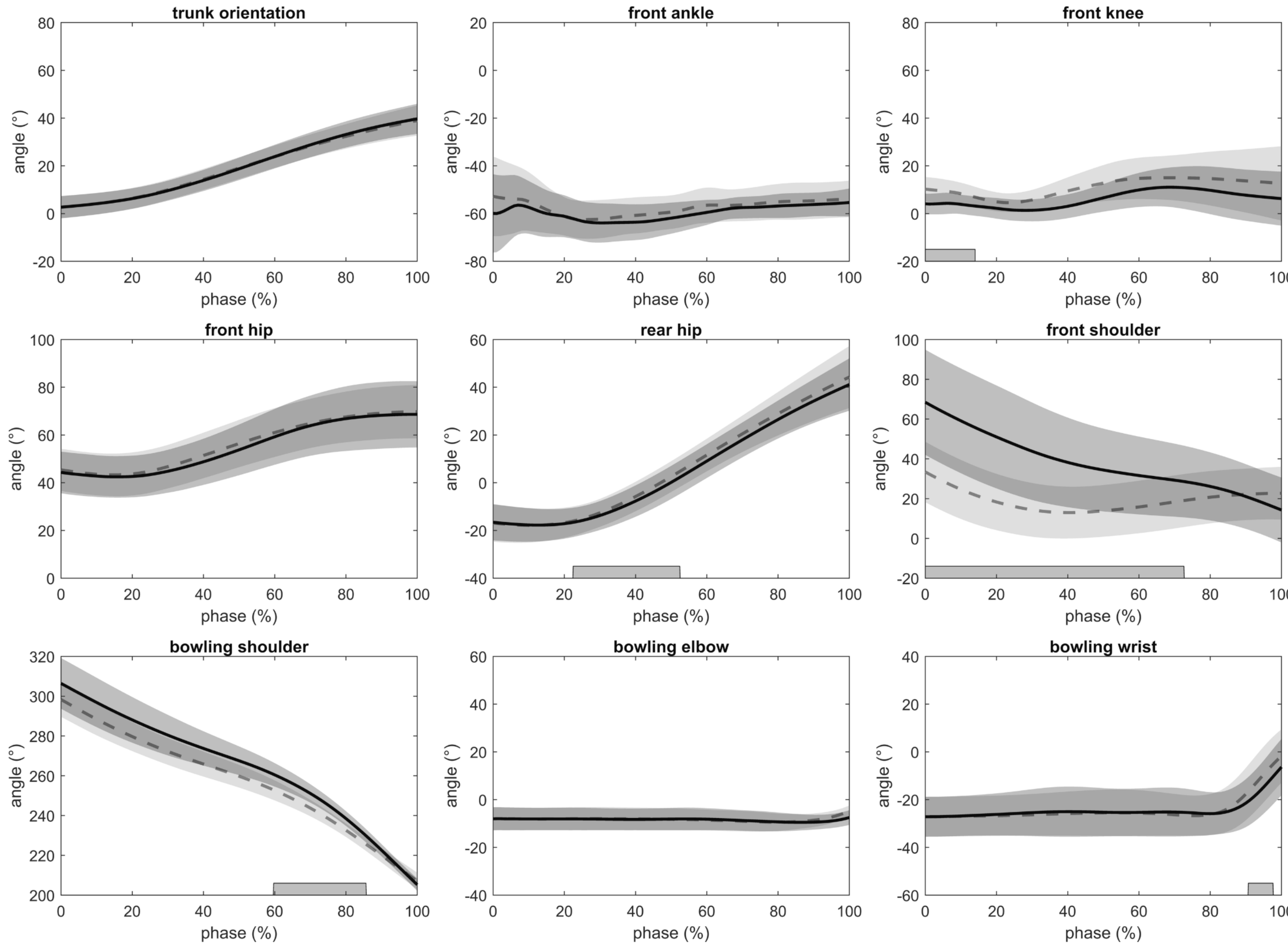

Fig. 3. Mean and standard deviation of the kinematic variables for the current techniques (grey dashed line) and optimised techniques (black solid line). The anatomical position of the trunk and the ankle, knee, hips, shoulders, elbow, and wrist joints are defined as 0°, with positive increases representing flexion. The statistically significant difference regions ($p < 0.05$) are marked for each variable by the grey bar on the horizontal axis.

(Felton et al., 2019b). The trunk orientation angle, the joint configuration angles, and the centre of mass position were determined using the projections of the joint centres onto the sagittal plane. Quintic splines (Wood and Jennings, 1979) were fit to smooth the data appropriately and determine the initial kinematics or as input to the simulation model to drive the angle-driven joints (Felton et al., 2020). Two-dimensional joint centre projections of the shoulders and hips were also used to determine the coefficients for the third-order Fourier series approximation used to drive the lengths and orientations of the massless segments, and the length of the trunk + head segment (Felton et al., 2020).

Viscoelastic parameters representing the wobbling masses and the foot–ground interface were determined via optimisation using a 16-segment angle-driven model and three recorded trials (the best trial plus an additional two). These parameters were varied to minimise the difference between the three recorded and simulated performances with appropriate penalties employed to prevent excess wobbling mass movement and compression at the ground (Felton et al., 2019b).

Individual-specific torque parameters for flexion and extension of the ankle, knee, hip, shoulder, and wrist joints were determined using maximal voluntary joint torque data to produce a nine-parameter joint torque function (Yeadon et al., 2006). Maximal voluntary joint torque data for flexion and extension was obtained using a Con-Trex MJ isovelocity dynamometer (Felton et al., 2020), and scaled to each individual (King et al., 2009). The MTP, bowling elbow, and bowling shoulder joint torque generators for flexion and extension were combined as a net torque and represented as a constant torque since it was not possible to test the joint range using an isovelocity dynamometer (Felton et al., 2020).

Each simulation model was evaluated to assess how accurately it could match the bowler's recorded performance for the delivery with the fastest ball speed (Felton et al., 2020). The closest simulation of the recorded performance was found by varying 107 parameters via genetic algorithm (Carroll, 1996) to minimise an objective score function representing the difference between a simulation and the recorded kinematics and kinetics of the performance (Felton et al., 2020). The 107 parameters comprised: 8 parameters varying the passive torque elements, 10 parameters scaling the joint torque functions to the individual, 88 parameters varying the torque generator activation timing and one parameter varying the timing of release.

2.4. Model optimisation

The initial position at front foot contact and the subsequent technique were optimised to maximise ball release speed for each simulation model. A parallelised genetic algorithm (Carroll, 1996) operating on the High-Performance Computing system at Loughborough University was used to vary 112 parameters: flexion and extension torque activation parameters across seven joints (98 parameters); the initial joint angle and angular velocities of six joints: front ankle, knee, hip, rear hip, front shoulder, and bowling shoulder (12 parameters); and the initial trunk

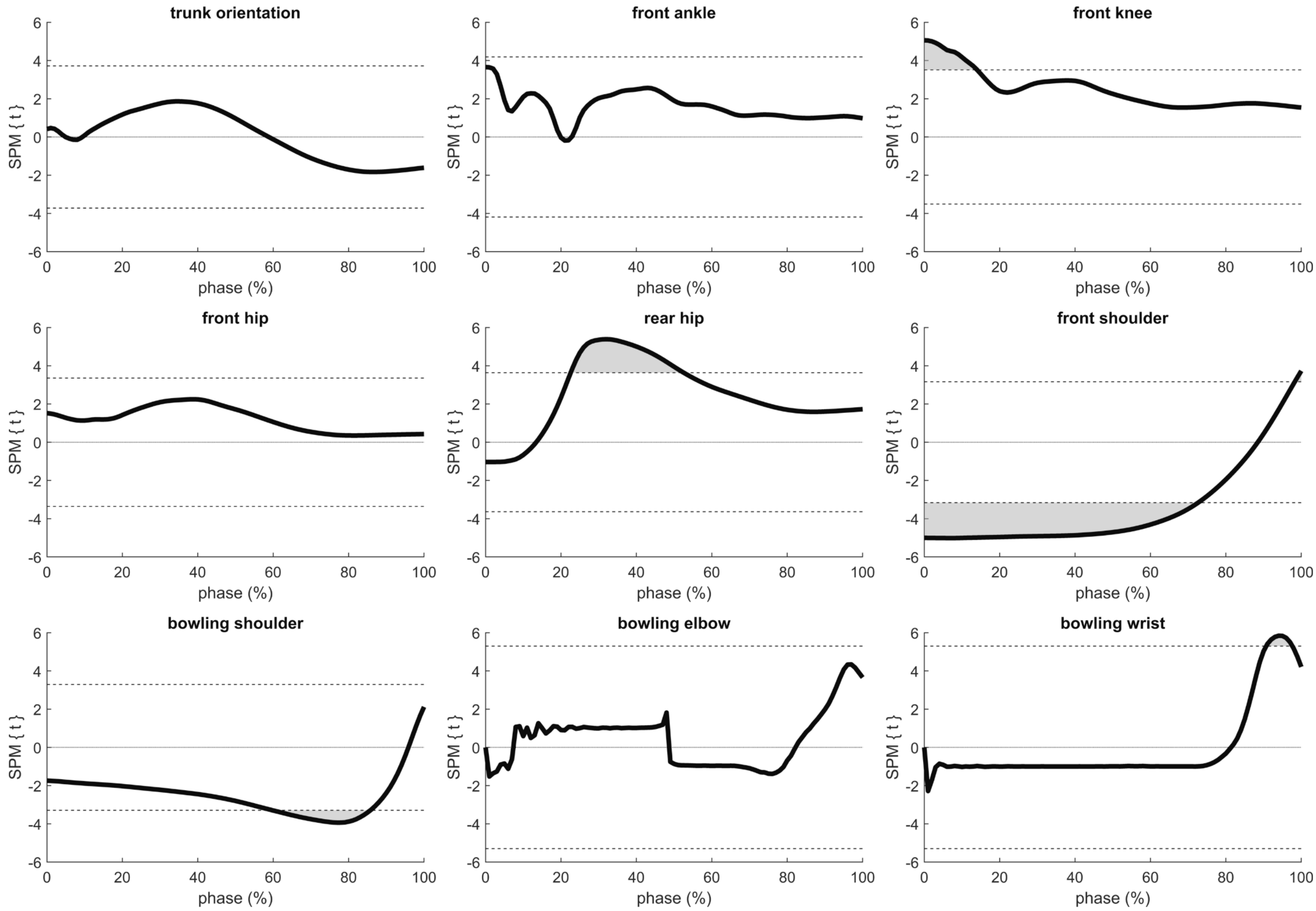

Fig. 4. The SPM1D paired *t*-test analysis comparing the kinematic variables between the current technique and optimised technique. The grey dashed lines represent the t-value threshold for a significant alpha value of 0.05. Positive t-values indicate the optimised technique has greater extension at that point in the phase compared to the current technique.

orientation angle and angular velocity (2 parameters). Initial centre of mass position and velocity was taken from the current performance and ball release occurred when the bowling arm had passed the vertical and the predicted horizontal ball landing distance on the cricket pitch was equal to the evaluated simulation. Penalties were imposed if any of the joints exceeded anatomical limits and to prevent excess wobbling mass movement and compression at the ground.

2.5. Data analysis

Discrete parameters comprising ball release speed and total time of the front foot contact phase were determined for both the current technique (evaluated simulation) and optimised technique (optimised simulation) for all bowlers. In addition, six discrete kinetic parameters previously linked to performance and injury were also determined and normalised to bodyweight for each technique: peak horizontal braking and vertical force; average horizontal braking and vertical loading rate (determined as the peak force divided by the time to peak force); and horizontal braking and vertical impulse (Worthington et al., 2013b). Nine kinematic angle time histories: trunk orientation, front ankle, front knee, front hip, rear hip, front shoulder, bowling shoulder, bowling elbow, and bowling wrist; six joint torque time histories: front ankle, front knee, front hip, rear hip, front shoulder, and bowling shoulder; and two kinetic time histories: horizontal braking and vertical ground reaction force; were also determined and time normalised for the current and optimised technique for all bowlers. These data distributions were found to satisfy the assumption of normality using D'Agostino's K-squared test (D'agostino et al., 1990). To compare the differences between the current and optimised technique, paired t-tests with an alpha significance value of 0.05 were performed in SPSS v.26 (SPSS Corporation, USA) for the discrete parameters, and using SPM1D (spm1d.org, T. Pataky) for the continuous parameters. Cohen's d was also calculated to determine the effect size (ES) of the difference (Cohen, 1988).

3. Results

3.1. Model evaluation

The ten individual-specific torque-driven simulation models closely matched the recorded performances with a mean objective difference score function of 5.0% (SD: ±0.8; Range: 4.0–6.5). This consisted of a mean kinematic difference score of 1.9% (SD: ±0.5; Range: 0.9–2.7) and force difference score of 11.3% (SD: ±1.9; Range: 9.2–15.0). Every model was deemed to sufficiently reproduce the kinematics and kinetics of each respective fast-bowling action and was put forward for optimisation.

3.2. Current vs optimised technique

The optimised techniques significantly increased ball release speed by 4.8 ± 1.3 ms^{-1} (13.5 ± 4.1%) and ranged between 37.8 and 42.9 ms^{-1} (Table 1). No change was observed in the time between front foot contact and ball release (Table 1). Two significant differences with moderate effect sizes (ES > 0.5) were observed in the kinetic parameters

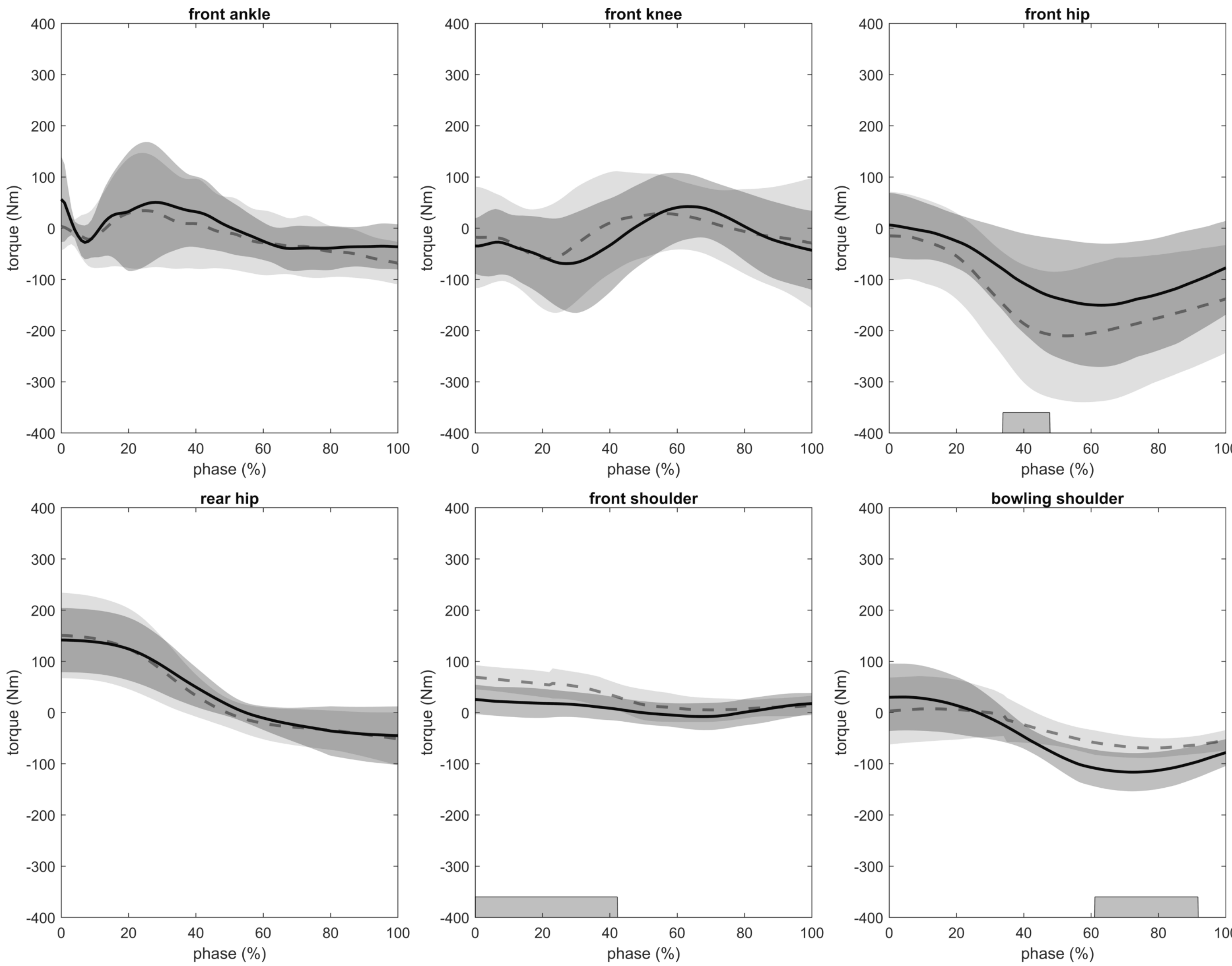

Fig. 5. Mean and standard deviation of the joint torque variables for the current techniques (grey dashed line) and optimised techniques (black solid line). Positive torques representing flexion and negative torques extension. The statistically significant difference regions ($p < 0.05$) are marked for each variable by the grey bar on the horizontal axis.

(Table 1). The optimised techniques demonstrated significantly lower average horizontal braking and vertical loading rates compared to the current techniques. Despite this, no significantly different periods between the ground reaction time histories were observed (Fig. 1).

Four joint angle time histories and three joint torque time histories were found to have periods which differed significantly between the current and optimised techniques (Figs. 2-6). The optimised techniques adopted more extended front knee angles and more flexed front shoulder positions at front foot contact. During the movement the optimised techniques utilised a more extended front leg throughout (Figs. 2-4), as well as delayed onset and increased magnitude of the motion of the trunk, rear leg and both arms towards the target (Figs. 2-4). Lower front hip extensor and front shoulder flexor torques, as well as greater bowling shoulder extensor torques were also evident (Figs. 5-6).

4. Discussion

The optimised techniques for the elite male bowlers in this study demonstrated an average increase in ball release speed of 13.5% (4.8 ms^{-1}), as well as lower peak ground reaction forces and loading rates. Common differences in the optimal initial body position included more extended front knees, and greater flexion of the front and bowling arm shoulders (Fig. 2). In the subsequent technique delays to the onset of trunk flexion, front arm and bowling arm shoulder extension and wrist flexion were common. This led to lower front hip extensor and front shoulder flexor torques, but greater bowling shoulder extensor torques being evident (Fig. 5).

Greater extension of the front knee was observed in all optimised techniques compared to the current techniques (Figs. 2-4) corroborating studies linking this with increased ball release speed (Felton et al., 2020; Worthington et al., 2013a). This technique brakes the lower half of the body more efficiently and converts whole-body linear momentum (from the run-up) into angular momentum. The significant differences between the ground reaction force characteristics (Table 1; Fig. 1) also supports previous research indicating that straighter front leg kinematics lowers horizontal braking and vertical peak forces and loading rates (King et al., 2016; Worthington et al., 2013b). No differences in impulse were found, however, highlighting that previously found group-based associations may be due to conflicting uncontrollable variables across a group (King et al., 2016). Although more extended front knee kinematics was evident for all optimised techniques, there were no significant differences in the knee joint torque time history (Fig. 5). In addition, not all optimised techniques utilised a straight (braced) front knee throughout (Fig. 2). This may highlight factors beyond those varied within this study influence front knee kinematics (e.g. centre of mass velocity at front foot contact). A greater understanding of the factors

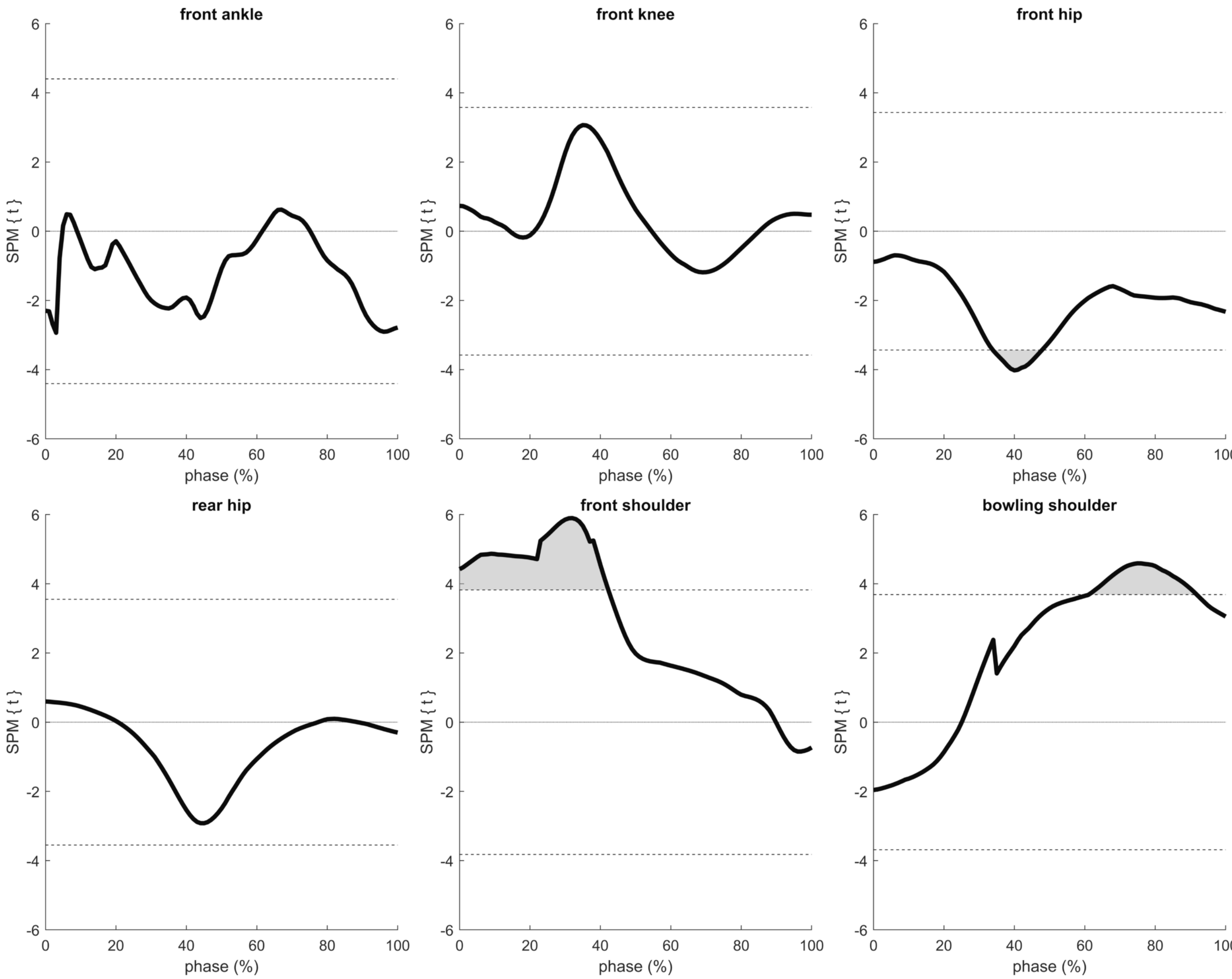

Fig. 6. The SPM1D paired *t*-test analysis comparing the joint torque variables between the current technique and optimised technique. The grey dashed lines represent the t-value threshold for a significant alpha value of 0.05. Positive t-values indicate the torque in the optimised technique is lower at that point in the phase compared to the current technique.

limiting knee extension, and the effect this has on fast bowling technique may provide further insights.

Shoulder extension (arm circumduction) and subsequent wrist flexion was delayed in the optimised technique (Figs. 2-4). More delayed arm circumduction has previously been associated with increased ball release speeds (Tyson, 1976; Worthington et al., 2013a). A more delayed bowling arm permits greater amounts of trunk flexion, whilst still allowing the arm to deliver the ball towards the intended target (Felton et al., 2020). Previous studies have therefore also linked increased trunk flexion with faster ball release speeds (Elliott et al., 1986; Portus et al., 2004; Worthington et al., 2013a). The trunk orientation t-scores indicate that trunk flexion while initially delayed, is subsequently greater in the optimised techniques (Fig. 4) and was achieved by utilising lower front hip extensor torques (Fig. 5). The increase in bowling shoulder extensor torque (Fig. 5), provides further evidence that increased trunk flexion and the timing of bowling arm circumduction are related in how they affect ball release speed. Future research could investigate how whole body momentum at front foot contact, range of motion, strength and anthropometric constraints affect this relationship.

The front shoulder is initially more flexed in the optimised techniques (Fig. 2). The adoption of this position resulted in lower front shoulder flexor torques in the first half of the movement pattern (Fig. 5). From this position, greater and faster extension occurred in the optimised techniques compared to the current techniques (Figs. 2-4). This may explain literature linking increased ball release speeds with higher front arm velocities (Davis and Blanksby, 1976; Salter et al., 2007). A more flexed initial front shoulder position likely aids the delay of the bowling shoulder by helping to align the shoulder girdle and stabilise the upper body. This position, however, increases the rotational inertia of the upper body about the transverse axis. To reduce this and aid trunk flexion, the front arm needs to accelerate downwards to align the front arm with the torso. Although front arm technique is considered by coaches to be an essential part of the coordinated sequence of fast bowling (Ferdinands, 2015), this is the first study to highlight this movement. Further investigation is required to understand the relationship between front arm kinematics and kinetics, ball release speed and other parts of the fast bowling technique.

Rear hip flexion was also delayed in the optimised techniques compared to the current techniques (Figs. 2-4). The function of rear hip flexion within the fast bowling action is uncertain. Coaches advocate its role, but previous research suggests bowlers do not actively drive the leg though (Ferdinands et al., 2014). Rear hip flexion possibly brings the rear leg segments closer to the rotation axis of the torso reducing the moment of inertia of the body about the front hip and helping to increase trunk flexion (Felton et al., 2020). It is possible therefore, that delaying rear hip flexion may delay upper trunk flexion occurring until after front foot contact, providing a more efficient transfer of momentum through the kinetic chain. It may also help maintain linear momentum and aid pelvic stability which have been linked to lumbar bone stress injuries in fast bowling (Alway et al., 2021). The delay observed in this study is likely due to timing changes in the proximal to distal sequencing within the kinetic chain due to the straighter front leg kinematics employed as there were no significant differences evident in the rear hip torque (Fig. 5). Future research should focus on understanding how rear leg kinematics and kinetics affect fast bowling performance, especially in earlier phases of the fast bowling action.

A major strength of this research is the novel approach involving ten individual optimisation studies. Nevertheless, the statistical power of a sample size of ten bowlers is limited despite a ten-fold increase on any previous theoretical approach. Further methodological limitations include the planar modelling approach which limits the investigation of the non-planar rotations of the torso and pelvis, and the optimisation procedure where the optimised solution was found for a single set of activation parameters which may not be robust to perturbations (Felton et al., 2020). In addition, the front MTP, bowling elbow, and bowling wrist joint torques were not investigated, as the torque generator contribution was either minimal (front MTP and bowling elbow) or constrained to match their current performance (bowling wrist). Despite this, optimised ball release speeds (37.8 to 42.9 ms^{-1}) were considered realistic based on previous research (Worthington et al., 2013a) and the maximum match recorded ball release speed (44.7 ms^{-1}). Although this study has identified the common characteristics exhibited for the initial body position at front foot contact and subsequent technique when optimising for ball release speed in elite male fast bowling, the ability of an individual to adopt these depends on their organismic constraints (e.g. range of motion, strength, and anthropometric constraints) and self-organisational processes (e.g. movement variability and intrinsic dynamics). For example, there is evidence that gender-related organismic constraints may alter optimal technique for females compared to male bowlers (Felton et al., 2019a). Future research could therefore focus on investigating how organismic constraints and self-organisational processes affect fast bowling technique. In particular to understand what limits individual bowlers adopting optimal technique, how this changes the understanding of optimal technique for an individual, and what is the quantifiable effect these constraints have on ball release speed.

5. Conclusion

This study has resolved the controversy on whether individual and group optimisation studies of fast bowling reflect underlying commonalities. It has identified the common characteristics exhibited for the initial body position at front foot contact and subsequent technique when optimising for ball release speed in elite male fast bowling. At front foot contact the optimised techniques employed more extended front legs, as well as more flexion of the front and bowling arm shoulders compared to the current techniques. Delays to the onset of trunk flexion, front arm and bowling arm shoulder extension, and wrist flexion, were also common in the subsequent movement during the front foot contact phase. This led to lower front hip extensor and front shoulder flexor torques, but greater bowling shoulder extensor torques. The optimised techniques were also observed to lower peak ground reaction forces and loading rates. The knowledge developed from this research is useful holistically for coach development, talent identification, and coaching practice, however caution is required during application to consider bowlers individual organismic and self-organisational constraints. The individual optimisations which incorporate some of these constraints for the bowlers participating in this study, have been used indicatively to support applied coaching.

CRediT authorship contribution statement

P.J.Felton: Conceptualisation, Data curation, Writing - original draft, Writing - review and editing, Vizualisation, Investigation, Validation, Formal analysis, Methodology, Project administration. **K.J. Shine:** Conceptualization, Funding acquisition, Data curation, Supervision. **M.R. Yeadon:** Conceptualization, Writing - review & editing, Formal Analysis, Methodology, Supervision. **M.A. King:** Conceptualization, Funding acquisition, Writing - review & editing, Formal Analysis, Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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