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The effect of increased strength on ball release speed and front foot contact-phase technique in elite male cricket fast bowlers

P.J. Felton [a,b], K.J. Shine [b,c], M.R. Yeadon [b] and M.A. King [b]

[a]School of Science and Technology, Nottingham Trent University, Nottingham, UK; [b]School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK; [c]Nottinghamshire County Cricket Club, Nottingham, UK

ABSTRACT

Research on strength in cricket fast bowling has focused on ball release speed over technique. This study investigates how increased strength affects performance and front foot contact-phase technique during fast bowling. A planar, 16-segment, whole-body torque-driven simulation model, customised and evaluated for 10 elite male fast bowlers, was used to optimise the technique for maximum ball release speed under 3 conditions: 1) original strength; 2) 5% increased lower body strength and 3) 5% increased lower body + shoulder strength. As strength increased across conditions, discrete and continuous one-way ANOVA's with post-hoc t-tests, highlighted ball release speed increased (40.7 vs 41.3 vs 41.5 ms^{-1}; $p <$ 0.01), vertical front foot ground reaction impulse decreased ($p < 0.023$) and mid-phase bowling shoulder extensor torque increased (53% to 61%; $p < 0.05$). No significant differences were found in phase time, ground reaction forces, joint kinematics or joint kinetics, although the increased strength techniques exhibited less knee extension, reduced trunk flexion and greater shoulder extension, contrary to expectations. This suggests that increased strength may lead to alterations in the front foot contact technique which allows greater muscular momentum to be generated. Caution is advised when considering using strength interventions to alter the front foot contact-phase technique.

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KEYWORDS
Technique; computer simulation; performance; ball release speed; modelling

Introduction

Cricket, the second most popular sport worldwide, is played between 2 teams consisting of batters and bowlers. Fast bowlers aim to limit runs and take wickets primarily by delivering the ball at high speeds, reducing the batter's time available to react and execute an appropriate shot (Worthington et al., 2013a). As a result, research on fast bowling technique has primarily focused on identifying the link between movement patterns and ball release speed. This has led to a combination of technique parameters during the front foot contact phase (period between front foot contact and ball release) being identified as key to maximising ball release speed. These include a more extended front leg, increased upper trunk flexion, and a greater delay in shoulder extension (circumduction) of both the front and bowling arms (Felton et al., 2023; Worthington et al., 2013a). Although the relationship between fast bowling technique and increased ball release speed has been established, movement patterns are shaped by the interaction of organismic, environmental, and task-related constraints (Newell, 1986) alongside self-organisation processes (Kelso, 1995). One organismic constraint that may impact a fast bowler's ability to achieve these key technique characteristics during the front foot contact phase is strength. For instance, greater strength may assist in maintaining a straighter front leg, increasing upper trunk flexion or delaying bowling arm extension. Despite this, research on the effect of strength on fast bowling movement patterns during the front foot contact phase has received little attention.

Previous research investigating the effect of strength on fast bowling performance has typically focused on its relationship with ball release speed. Results from these studies have varied, with little consensus on strength's direct impact on ball release speed (Ramachandran et al., 2022). One reason may be the varied approaches used to examine the effect of strength. Most studies have used whole-body intervention programmes, rather than targeting specific joints or regions. For instance, despite strength gains, Callaghan, Lockie, et al. (2021) and Hislen et al. (2023), found no increase in ball release speed or bowling arm speed, respectively, following multi-week resistance training. In contrast, Taliep and Maker (2021) and Feros et al. (2020) reported increased ball release speeds after 4-week and 8-week resistance training programmes, although Feros et al. (2020) noted a reduction in bowling accuracy. Research focussing on strength in specific body regions, though more limited, has shown more consistent results, with faster ball release speeds associated with increased lower body strength (Kiely et al., 2021; Letter et al., 2022) and upper body strength (Pyne et al., 2006; Singh et al., 2014). No relationship, however, has been reported to exist between lower body strength and front foot ground reaction forces characteristics (Callaghan, Govus, et al., 2021). Similarly, the relationship between joint torque and ball release speed has scarcely been investigated, although Wormgoor et al. (2010) found that shoulder extension peak torque is correlated with ball release speed, suggesting that stronger shoulder extensors may lead to faster ball release speeds.

CONTACT P.J. Felton paul.felton@ntu.ac.uk School of Science and Technology, Nottingham Trent University, Clifton Lane, Nottingham NG11 8NS, UK

Limited research on the relationship between strength and fast bowling technique may be due to challenges in isolating the effect of strength while controlling other variables. A solution is the use of forward-dynamics musculoskeletal simulation models, which allow the manipulation of individual variables whilst keeping others constant (Yeadon & King, 2017). This method has recently been applied to elite bowlers to identify commonalities in technique when maximising ball release speed during the front foot contact phase, using a novel group-based approach to minimise individual-specific limitations (Felton et al., 2023). This study, therefore, aims to utilise a forward-dynamics musculoskeletal simulation model to investigate how increased strength affects performance and associated front foot contact-phase technique when maximising ball release speed in elite male bowlers.

Materials and methods

Participants

Ten male bowlers (age: 20.7 ± 2.4 years; height: 1.91 ± 0.08 m; mass: 86.9 ± 8.5 kg), all members of the England and Wales Cricket Board (ECB) elite fast bowling group, participated in the study. Ethical approval was granted by Loughborough University's Ethics Committee, and participants provided written informed consent prior to the study commencing.

Simulation model

A 16-segment planar torque-driven computer simulation model previously used to investigate the performance and associated front foot contact-phase technique of cricket fast bowling (Felton et al., 2020, 2023) was adapted to investigate the aim. The model consisted of 14 rigid segments representing the torso + head, 2 upper arms, 2 thighs, 2 shanks, 2 two-segment feet, forearm plus hand (non-bowling arm), forearm (bowling arm), and 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 based on 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, lateral side-flexion was incorporated by adjusting the torso + head segment length using a Fourier series function based on the trunk orientation angle, with inertia parameters adjusted to reflect the change in length (Felton, Yeadon, et al., 2019). The foot–ground interaction was modelled using horizontal and vertical linear spring-dampers at 3 points of contact: heel, metatarsophalangeal joint (MTP) and toe, of the front foot (Felton, Yeadon, et al., 2019). A point mass representing the ball was attached to the end of the bowling hand via a viscoelastic spring to ensure a smooth release (Felton, Yeadon, et al., 2019).

The model was driven by torque generators with contractile and series elastic components to flex and extend the 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. Maximum voluntary torque was defined using a 9-parameter function at each joint, with peak isometric torque incorporated as a scaling factor to allow individual-specific joint angle and joint angular velocity torque profiles to be incorporated (King et al., 2006). Torque generator activation was represented using a quintic function with zero accelerations and velocities at the end points (Yeadon & Hiley, 2000). Activation profiles had a minimum ramp time of 70 ms (Yeadon et al., 2006) and followed 1 of the 4 patterns: ramp up–ramp up; ramp up–ramp down; ramp down–ramp up; ramp down–ramp down (Felton et al., 2023). Passive elastic elements prevented these joints from exceeding anatomical limits (Felton et al., 2020). The non-bowling arm elbow, along with the MTP, ankle and knee joints of the rear leg, were angle-driven, as their movement during the front foot contact phase is not strongly linked to fast bowling performance (Ferdinands et al., 2014).

Input to the simulation model comprised the initial centre of mass position, trunk orientation angle and angular velocity and the angle and angular velocity of each torque-driven joint. Model parameters included the segmental inertia parameters; joint-angle time histories of the angle-driven joints; Fourier series parameters for the massless segment orientations and lengths and for the trunk + head segment length; viscoelastic parameters for wobbling masses and foot–ground interface; torque parameters; and activation profiles for each torque generator (Felton et al., 2020). The model outputs comprised mass centre position, trunk orientation and joint configuration angles, joint torques, ground reaction forces and ball release velocity.

Model customisation and evaluation

For each bowler in the study, the simulation model had been previously customised and evaluated using anthropometric measurements and recorded data of the front foot contact phase of their current fast bowling technique (Felton et al., 2023).

Kinematic and kinetic data for the front foot contact phase were collected at the ECB National Cricket Performance Centre (Loughborough University, UK) using 18 M×13Vicon cameras (OMG Plc, Oxford, UK) sampling at 300 hz, and a Kistler force platform (Type 9287B, Kistler AG, Switzerland) sampling at 1800 hz. Fifty 14 mm retroreflective markers were attached to key bony landmarks on each bowler to determine trunk orientation angle, joint configuration angles and variable segment length and orientation time histories (Felton, Yeadon, et al., 2019). In addition, a 15 × 15 mm reflective patch was attached to the ball to identify the instant of ball release and calculate ball release speed over a period of 10 frames (0.033 s) after release (Worthington et al., 2013a). 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 provide immediate ball release speed and pitch location. The best trial for each bowler (greatest ball velocity, minimal marker loss and front foot force plate impact) was processed to determine the inputs to the simulation model (Felton et al., 2023). Individual-specific inertia parameters were derived using 95 anthropometric measurements taken from each bowler (Yeadon, 1990). These were subsequently used alongside the kinematic data to determine the centre of mass time history (Felton, Lister, et al., 2019). Viscoelastic parameters for the wobbling masses and the foot–ground interface were determined through optimisation using a 16-segment angle-driven model (Felton, Yeadon, et al., 2019). Torque parameters for flexion and extension of the ankle, knee, hip, shoulder and wrist joints were represented by a 9-parameter joint torque function (Yeadon et al., 2006) and scaled for each bowler through optimisation (Felton et al., 2023; King et al., 2009). For the MTP, bowling elbow and bowling shoulder, the flexion and extension torque generators were represented as a constant torque and scaled for each bowler through optimisation (Felton et al., 2020).

The 10 individual-specific simulation models were previously evaluated and deemed to sufficiently reproduce the kinematics (1.9% difference) and ground reaction force (11.3% difference) when compared to each bowler's fastest recorded delivery (Felton et al., 2023).

Optimisations

Three model strength conditions were optimised to explore the effect of increased strength on performance and associated front foot contact-phase technique when maximising ball release speed. Within each condition, all 10 individual-specific simulation models were optimised to maximise an objective score function representing ball release speed. The simulation with the fastest ball release speed was found by varying 112 parameters using a parallelised genetic algorithm (Carroll, 1996) operating on a High-Performance Computing system. The 112 parameters comprised: flexion and extension torque activation parameters across 7 joints (98 parameters); the initial joint angle and angular velocities of 6 joints: front ankle, knee, hip, rear hip, front shoulder and bowling shoulder (12 parameters) and the initial trunk orientation angle and angular velocity (2 parameters). The initial centre of mass position and velocity were taken from each bowler's fastest recorded delivery, with ball release occurring once the bowling arm passed the vertical, and the predicted horizontal ball landing distance on the cricket pitch matched the evaluated simulation (Felton et al., 2023). Exponential penalties were subtracted from the objective function to maintain joint angle time histories within realistic individual-specific limits. Limits were chosen based on each bowler's fastest recorded delivery and expanded to anatomical norms if the range of motion was currently within these boundaries.

The first condition used the original strength of each bowler derived during each model's customisation (0% increase) to determine their potential level of performance and associated technique (initial position and subsequent movement pattern). Previous comparisons of these optimised techniques with each bowler's actual technique (Felton et al., 2023) showed an increase in ball release speed of $4.8 \pm 1.3\ \mathrm{ms}^{-1}$ ($13.5 \pm 4.1\%$). These optimised performances and techniques will be used as the baseline for this study.

The second condition (lower body) increased the original strength of the ankle, knee and hip joint torque generators, keeping the strength of the shoulder, elbow and wrist joints unchanged. This was achieved at each joint by increasing the peak isometric torque parameter value (and associated series elastic stiffness component value), within the 9-parameter function defining maximum voluntary torque by 5% (Allen et al., 2016). This adjustment ensured that the increase in strength was uniformly applied across the joint angle and joint angular velocity torque profiles.

The third condition (lower body + shoulder) increased the original strength of the ankle, knee, hip and shoulder joint torque generators while maintaining the original strength of the elbow and wrist joints. This was achieved at the ankle, knee, hip and front shoulder joints by increasing the peak isometric torque (and the associated series elastic stiffness component) using the same method as the second condition and the bowling shoulder constant torque by 5%. Elbow strength was not increased, as the joint was in hyperextension and outside the active torque range for all bowlers during this phase, and wrist strength was assumed to be sub-maximal during the front foot contact phase prior to ball release.

Each optimisation ran on a High-Performance Computing system using a parallelised genetic algorithm (Carroll, 1996) by varying 112 parameters: flexion and extension torque activation parameters across 7 joints (98 parameters); the initial joint angle and angular velocities of 6 joints: front ankle, knee, hip, rear hip, front shoulder and bowling shoulder (12 parameters) and the initial trunk orientation angle and angular velocity (2 parameters).

Data analysis

Discrete parameters comprising ball release speed and total time of the front foot contact phase were determined for the 3 conditions across the bowlers. Additionally, 6 discrete kinetic parameters associated with performance and injury were calculated and normalised to bodyweight for each condition: peak horizontal and vertical force, average horizontal and vertical loading rate (determined as the peak force divided by the time to peak force) and horizontal 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), 6 joint torque time histories (front ankle, front knee, front hip, rear hip, front shoulder and bowling shoulder) and 2 kinetic time histories (horizontal and vertical ground reaction force), were also determined and time-normalised for the 3 conditions. Data distributions were found to meet the assumption of normality using D'Agostino's K-squared test (D'Agostino et al., 1990). Differences across the 3 conditions for the 10 bowlers were analysed using repeated measures one-way ANOVA's with post-hoc paired t-tests (significance set at 0.05 level) in SPSS v.28 (SPSS Corporation, USA) for the discrete parameters and SPM1D (spm1d.org, T. Pataky) for the continuous parameters. Cohen's d was also calculated to assess the effect size of discrete parameter differences (Cohen, 1988).

Results

The optimised techniques with increased strength (lower body and lower body + shoulder) had significantly faster ball release

Table 1. Descriptive and differential statistics for selected discrete parameters associated with performance and injury during the front foot contact phase of fast bowling for the 10 bowlers.

Parameters	Original strength (mean ±SD)	Increased lower body strength (mean ±SD)	Increased lower body + shoulder strength (mean ±SD)	p
Ball release speed (ms^{-1})	40.7 ± 1.6[a,b]	41.3 ± 1.8 [a,c]	41.5 ± 1.8[b,c]	<0.001
Time (ms)	102 ± 6.0	101 ± 6.2	101 ± 5.8	0.055
Peak horizontal force (BW)	3.94 ± 0.4	3.98 ± 0.5	4.00 ± 0.5	0.458
Peak vertical force (BW)	5.68 ± 0.8	5.68 ± 0.8	5.77 ± 0.9	0.249
Horizontal loading rate (BW·s^{-1})	128.5 ± 45.3	127.0 ± 44.2	130.5 ± 48.5	0.283
Vertical loading rate (BW·s^{-1})	172.6 ± 69.6	188.6 ± 73.5	175.8 ± 73.3	0.415
Horizontal impulse (BW·s)	0.156 ± 0.048	0.157 ± 0.048	0.154 ± 0.046	0.387
Vertical impulse (BW·s)	0.294 ± 0.062[a]	0.292 ± 0.064	0.286 ± 0.061[a]	0.023

[a,b,c]*significant Bonferroni adjusted pairwise comparison (p<0.016).*

speeds compared to the optimised original strength techniques (original vs lower body: 40.7 vs 41.3 ms^{-1}; $p = 0.003$; $d = 0.36$; original vs lower body + shoulder: 40.7 vs 41.5 ms^{-1}; $p < 0.001$; $d = 0.47$; Table 1) and each other (lower body vs lower body + shoulder: 41.3 vs 41.5 ms^{-1}; $p = 0.024$; $d = 0.11$; Table 1). These optimised techniques, however, only produced an average increase in ball release speed of 1.5 ± 1.0% when lower body strength was increased, and 2.0% ± 1.0% when lower body + shoulder strength were increased. No significant differences or non-negligible effect sizes ($d > 0.2$) were observed in the times between front foot contact and ball release (Table 1).

One significant difference was observed in the discrete kinetic parameters, namely lower vertical impulses were associated with increased strength (Table 1). Post-hoc paired t-tests highlighted a significant difference between the optimised original and increased lower body + shoulder strength techniques (0.294 vs 0.286 BW · s; p = 0.028; $d = 0.140$; Table 1) but no difference between the optimised original strength and the increased lower body strength techniques (0.294 vs 0.292 BW · s; p = 0.275; $d = 0.040$; Table 1) or between the optimised increased strength techniques (0.292 vs 0.286 BW · s; p = 0.080; $d = 0.099$; Table 1). In addition, no significantly different

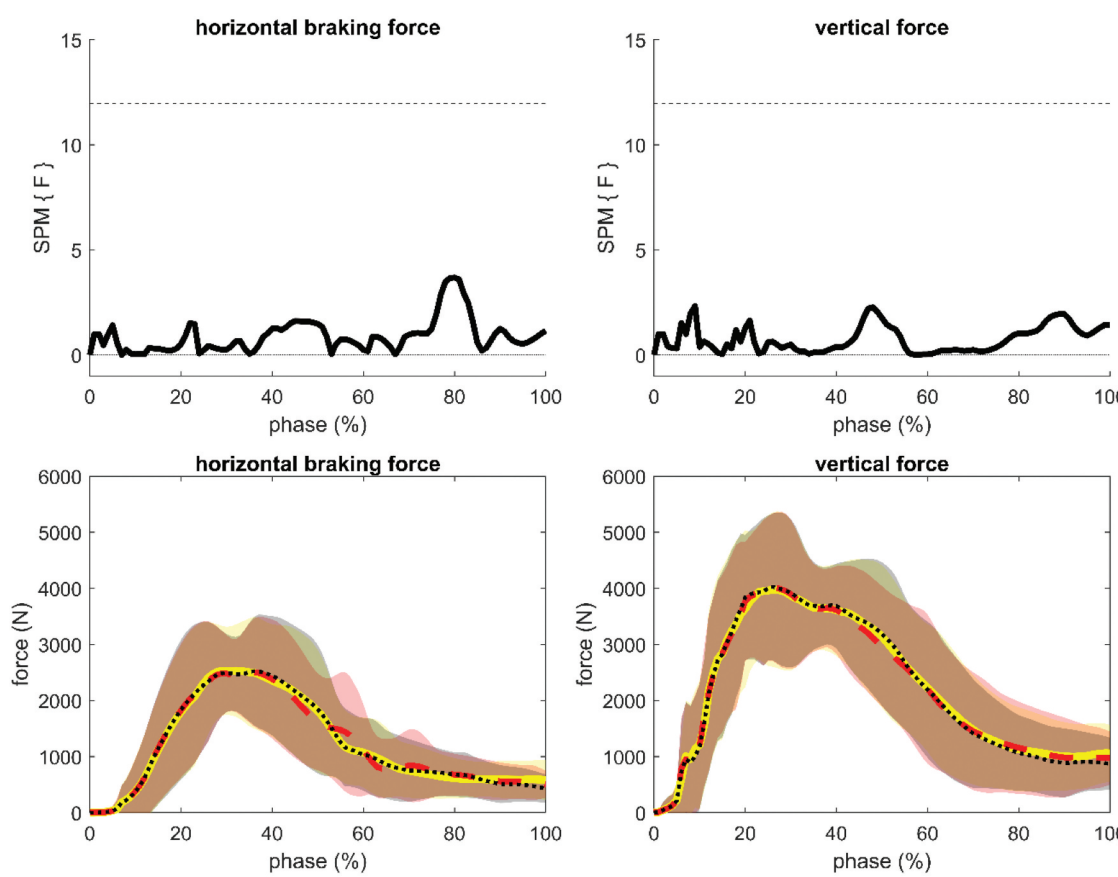

Figure 1. (top) The SPM1D repeated measures ANOVA analysis comparing the horizontal braking and vertical ground reaction force time histories between the optimised original strength, increased lower body strength, and increased lower body + shoulder strength techniques. The grey dashed lines represent the F-value threshold for a significant alpha value of 0.05. (bottom) mean and standard deviations of the horizontal braking and vertical ground reaction force time histories for the optimised original strength (yellow solid line), increased lower body strength (red dashed line), and increased lower body + shoulder strength (black dotted line) techniques. Any statistically significant difference regions ($p < 0.05$) are marked by a grey bar on the horizontal axis.

periods in the horizontal or vertical ground reaction force time histories were identified between the optimised original strength and increased strength techniques (Figure 1).

No joint angle time histories were observed to significantly differ between the optimised original strength and increased strength techniques (Figures 2–4). Significant periods of difference were found in the bowling shoulder joint torque time histories between the optimised original strength and increased strength techniques (Figure 5). Post-hoc paired t-tests highlighted a significant difference between optimised original strength and increased lower body + shoulder strength techniques (Figure 6). The optimised increased lower body + shoulder strength technique employed greater extensor torque compared to the optimised original strength technique in the period between 53% and 61% of the front foot contact phase (Figures 5–7). Although no optimised solutions incurred any range of motion penalties, most of the increased strength optimisations maximised the individualised limit for elbow extension.

Discussion

The optimised techniques demonstrated an average increase in ball release speed of 1.5% (0.6 ms^{-1}) when lower body strength was increased by 5% and 2.0% (0.8 ms^{-1}) when lower body + shoulder strength was increased by 5%, compared to the optimised original strength techniques for the elite bowlers in this study (Table 1). Although lower limb strength has previously been linked to increased ball release speeds in cricket fast bowling (Kiely et al., 2021; Letter et al., 2022), conflicting findings have been reported on the relationship between whole-body strength and ball release speed (Callaghan, Lockie, et al., 2021; Feros et al., 2020; Hislen et al., 2023; Taliep & Maker, 2021). The small effect sizes ($0.2 < d < 0.5$) observed in this study, between the optimised original strength and increased strength ball release speeds, may help explain the inconsistent findings in the previous experimental research. Given that a 5% strength increase in lower body + shoulder strength only led to a 2.0% improvement in ball release speed when controlling for

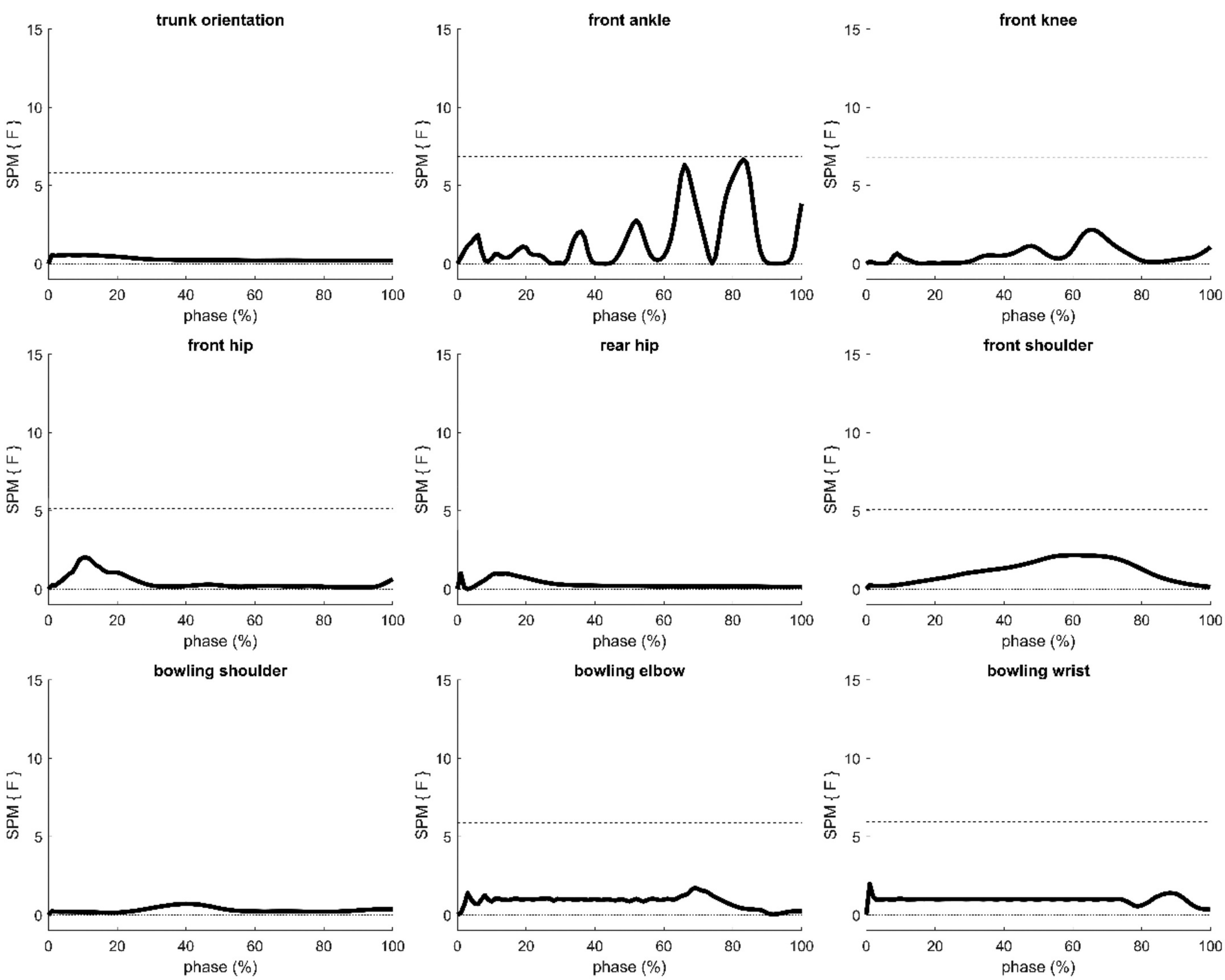

Figure 2. The SPM1D repeated measures ANOVA analysis comparing the kinematic time histories between the optimised original strength, increased lower body strength, and increased lower body + shoulder strength techniques. The grey dashed lines represent the F-value threshold for a significant alpha value of 0.05.

confounding variables, it is likely that studies using short-term whole-body interventions without adequate control of these factors or sufficient statistical power may have struggled to reliably detect this relationship.

Greater bowling shoulder extensor torque was observed in the middle period (53% to 61%) of the front foot contact phase between the optimised original strength and increased lower body + shoulder strength techniques (Figures 5–7). Although research has previously linked increased shoulder strength with greater ball release speeds (Wormgoor et al., 2010), the effect of increased bowling shoulder strength on fast bowling technique was unknown. Although no significant joint angle time history differences were observed, the post-hoc t-scores indicate that bowling shoulder extension was initially delayed for longer before extending further, while trunk flexion was reduced, in the optimised increased lower body + shoulder strength techniques compared to the optimised original strength techniques (Figures 2–4). These findings are contrary to previous research which has associated increased ball release speeds with greater trunk flexion and less bowling shoulder extension (greater delay in arm circumduction) at release (Felton et al., 2023; Worthington et al., 2013a). Ball release speed, however, is dependent on the amount of whole-body momentum available during the front foot contact phase. The amount of whole-body momentum available during this phase is predominately influenced by the initial amount of linear momentum at the front foot contact and the amount of muscular momentum generated between the front foot contact and the ball release. As the amount of whole-body momentum available increases, the time between front foot contact and ball release decreases to less than 100 ms, reducing the amount of additional muscular momentum that can be produced in this phase (Felton, Lister, et al., 2019). As a result, front foot contact-phase technique to maximise ball release speed has been associated with increased initial amounts of linear momentum and a movement pattern which most effectively converts and transfers this momentum through the kinetic chain towards the ball (Felton et al., 2023; Worthington et al., 2013a). In this study, however, the initial amount of linear momentum at the front foot contact was not optimised but kept constant for each bowler based on their fastest delivery. The adaptations observed, therefore, suggest that increases in strength may lead to alterations in the front foot contact technique which allow greater muscular momentum to be generated. These findings, therefore, may challenge coaching assumptions that increased strength is correlated with a more extended front leg, increased trunk flexion, and a greater delay in shoulder extension which have previously been associated with maximising ball release speed.

No lower limb joint angle or joint torque time histories were found to significantly differ between the optimised original strength and the increased lower limb strength techniques during the front foot contact phase (Figures 2–7). It is often proposed that greater lower limb strength allows for increased extension of the front leg. The front knee and hip angle t-scores (Figure 3) suggest that the optimised increased lower limb strength techniques used greater front hip extension but less front knee extension compared to the optimised original strength techniques during the front foot contact phase. Consequently, trunk flexion was reduced, and bowling shoulder extension whilst initially delayed was greater than the optimised original strength techniques at release. These movement adaptations are similar to those observed between the optimised original strength and increased lower body + shoulder strength techniques. It is proposed that increased lower limb strength helps facilitate greater muscular contributions to ball release speed from the upper body by slowing trunk flexion and creating more time for the upper body (shoulder) to work, by utilising less extended front leg kinematics made possible by the increased strength.

Vertical ground reaction impulse was the only discrete kinetic parameter to significantly differ across the 3 conditions. Significantly lower vertical ground reaction impulses were observed in the optimised increased lower body + shoulder strength techniques compared to the original strength techniques (Table 1). However, no differences were observed between the optimised original strength and increased lower body strength techniques or between the optimised increased lower body and lower body + shoulder strength techniques (Table 1). The significant difference observed between the optimised original strength and the increased lower body + shoulder strength techniques is likely attributed to the nearly significant decrease in time between them (Table 1). The less efficient front leg kinematics observed in the optimised increased lower body + shoulder strength techniques less efficiently brakes the centre of mass, shortening the duration from front foot contact to ball release. Whilst the increase in shoulder strength also likely shortens the time taken to extend the bowling shoulder (circumduct the arm) further reducing the time between front foot contact and ball release. Since impulse is a function of time, this likely directly impacts the impulse resulting in the significant difference between the 2 most extreme conditions. No differences were found in the other ground reaction force characteristics, and this aligns with previous experimental research which reported no relationships to exist between lower body strength and front foot ground reaction forces characteristics (Callaghan, Govus, et al., 2021).

The 2.0% increase in ball release speed observed when lower body + shoulder strength were increased by 5% is significantly smaller than the 13.5% increase when the bowlers' current techniques with their original strength were optimised (Felton et al., 2023). This suggests that lower body (ankles, knee and hip) and upper body strength (shoulder) are unlikely to be a major limiting factor on ball release speed and associated front foot contact-phase technique among elite male fast bowlers. Although a 5% strength increase may be considered conservative, it was deemed appropriate given the participants' recent completion of a strength training block as part of the England and Wales Cricket Board's elite fast bowling programme, with a similar intervention previously shown to produce average lower limb strength increases of 9% in elite academy bowlers (Callaghan, Lockie, et al., 2021). While these findings suggest that technique-focused interventions may offer more substantial gains in ball release speed for elite male fast bowlers compared to strength-based approaches, it is unlikely that whole-body strength is unimportant during the

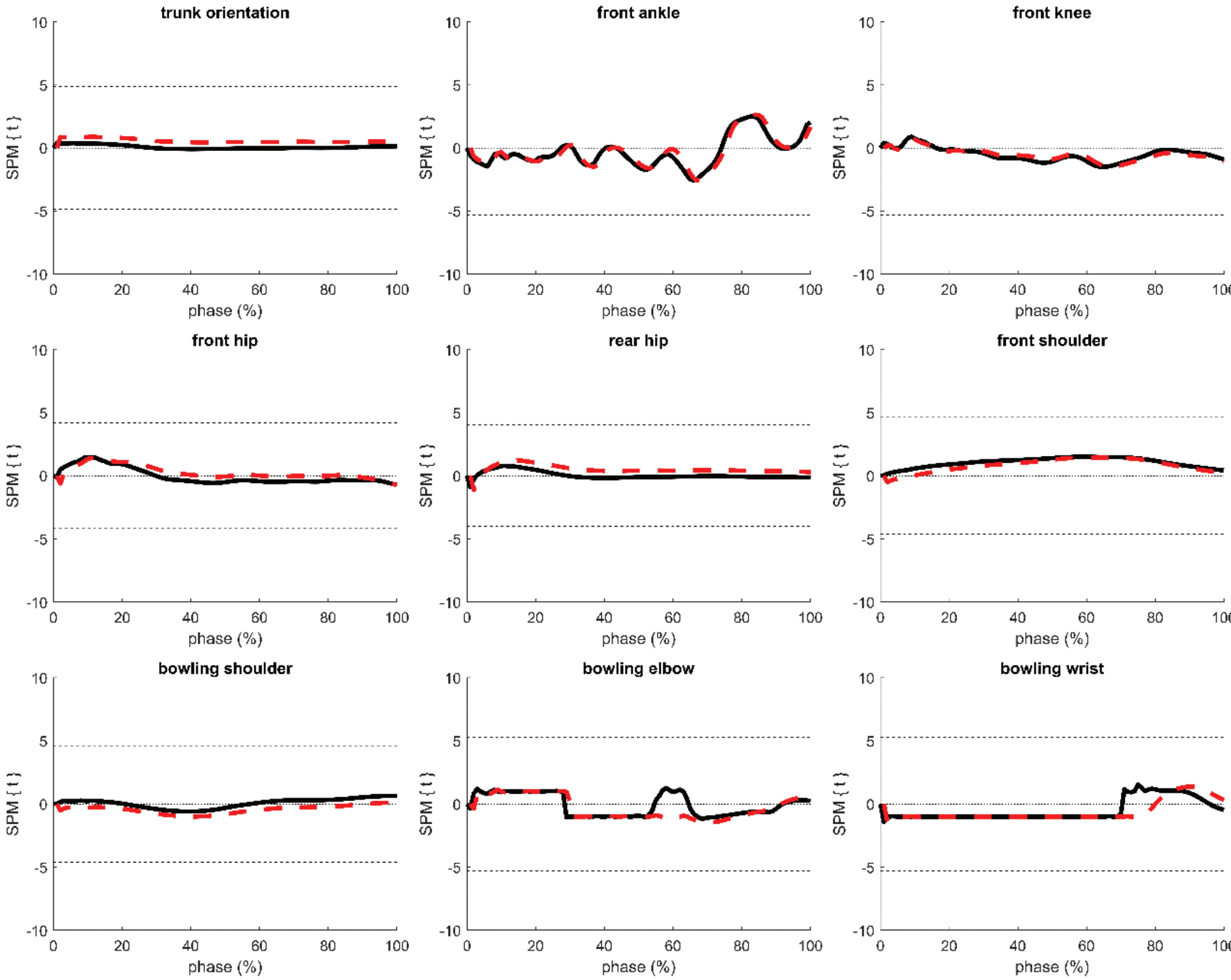

Figure 3. The SPM1D post-hoc paired t-test analysis comparing the difference in the kinematic variables between the original strength and increased lower body strength optimised techniques (black solid line), and the original strength and increased lower body + shoulder strength optimised techniques (red dashed line). The grey dashed lines represent the t-value threshold for a significant alpha value of 0.05. Positive t-values indicate the increased strength optimised techniques have greater extension at that point in the phase compared to the original strength optimised techniques.

fast bowling action. These results likely indicate that this strength and conditioning block adequately prepared the bowlers for the strength requirements of the front foot contact phase of fast bowling. In addition, it is possible that an increase in strength is concurrent with an increase in centre of mass velocity at the front foot contact, which was not altered in this study to ensure the effect of increasing strength on the technique could be identified. Future research exploring the combined effect of increased strength and approach speed could adopt an approach similar to that previously seen in triple jump (Allen et al., 2016). Finally, increased strength may be associated with fast bowling technique characteristics associated with injury risk, as well as being important for successful completion of earlier phases of the fast bowling action which could influence achieving the initial front foot contact position.

No joint angle range of motion penalties were incurred across the 3 conditions in any of the optimised techniques. Nevertheless, increased elbow hyperextension was observed in the optimised increased strength techniques, reaching each bowler's upper limit. While elbow hyperextension during this phase is common, repeated occurrences have been linked to the development of posterior elbow impingement and bone stress injuries (McBride et al., 2021). Coaches often aim to improve bowling arm velocity both via technique and shoulder strength interventions due to the correlation with faster ball release speed (Salter et al., 2007). This study, however, suggests a potential link between increased bowling shoulder angular velocity and greater elbow hyperextension. Although further investigation is required, this potentially implies that interventions focused on increasing shoulder strength and bowling arm

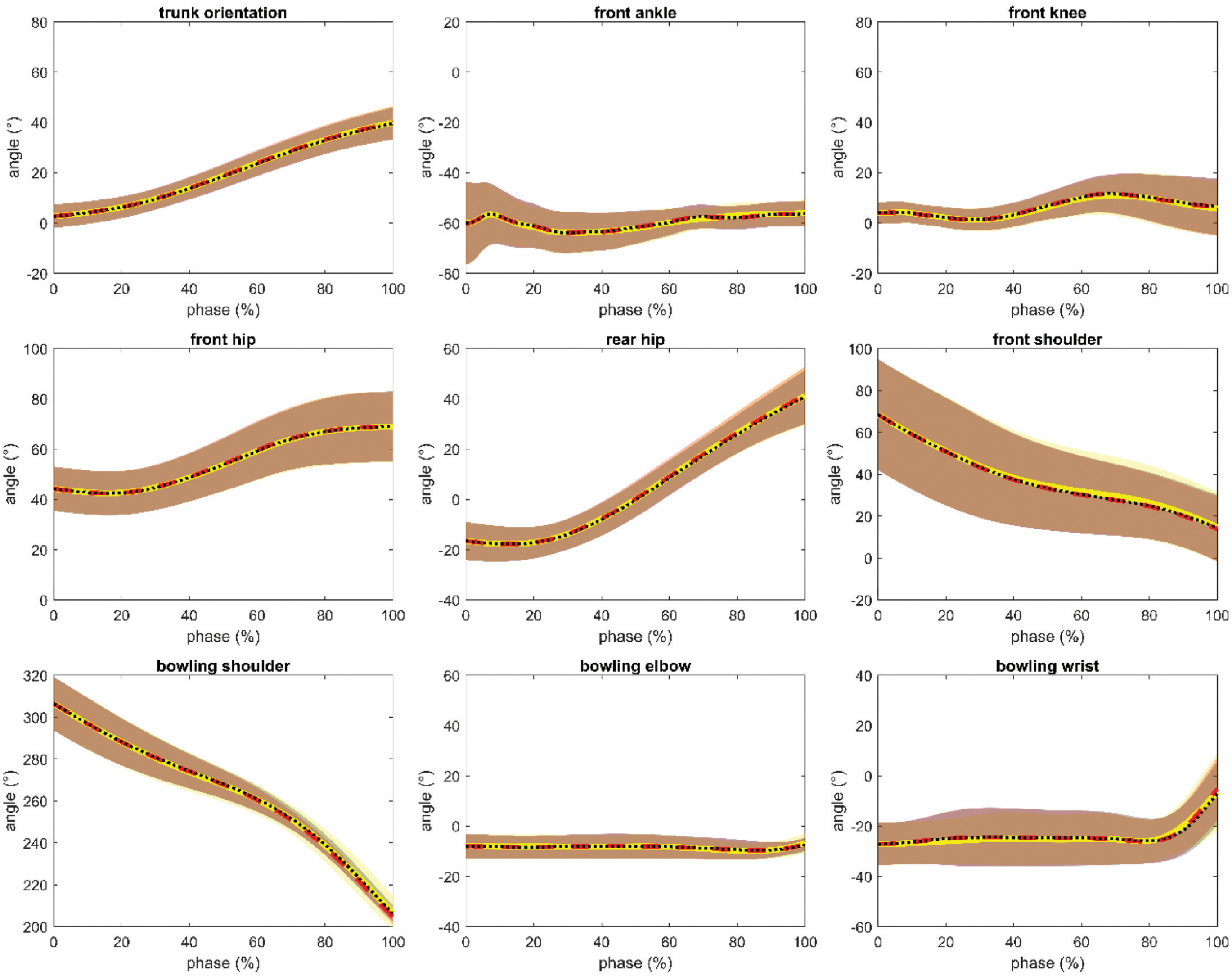

Figure 4. Mean and standard deviations of the kinematic variables for the optimised original strength (yellow solid line), increased lower body strength (red dashed line), and increased lower body + shoulder strength (black dotted line) techniques. The anatomical position of the trunk and the ankle, knee, hips, shoulders, elbow, and wrist joints are defined as 0° (or 360°) with positive increases representing flexion. Any statistically significant difference regions ($p < 0.05$) are marked by a grey bar on the horizontal axis.

velocity could lead to technique adaptations which elevate the risk of posterior elbow impingement and bone stress injuries.

A major strength of this research is the novel approach involving 10 individual forward-dynamic simulation models (Felton et al., 2023). Nevertheless, the statistical power of a sample size of 10 bowlers is limited and may be the reason for a lack of significant kinematic differences observed. 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). Although this study examined the effects of increased strength on fast bowling performance and front foot contact-phase technique, it did not explore the effect of strengthening the bowling wrist joint or investigate the effect of increasing other physical strength qualities. In addition, the research is focussed exclusively on elite male fast bowlers. The findings may differ for adolescent males or elite females, especially given the evidence that suggests gender-related organismic constraints may alter the technique for females compared to male bowlers (Felton, Lister, et al., 2019). Although these findings may transfer, it remains unknown how strength affects fast bowling technique in other populations which have lower levels of baseline strength, and whether strength-based interventions may lead to greater performance gains than technique-focused interventions.

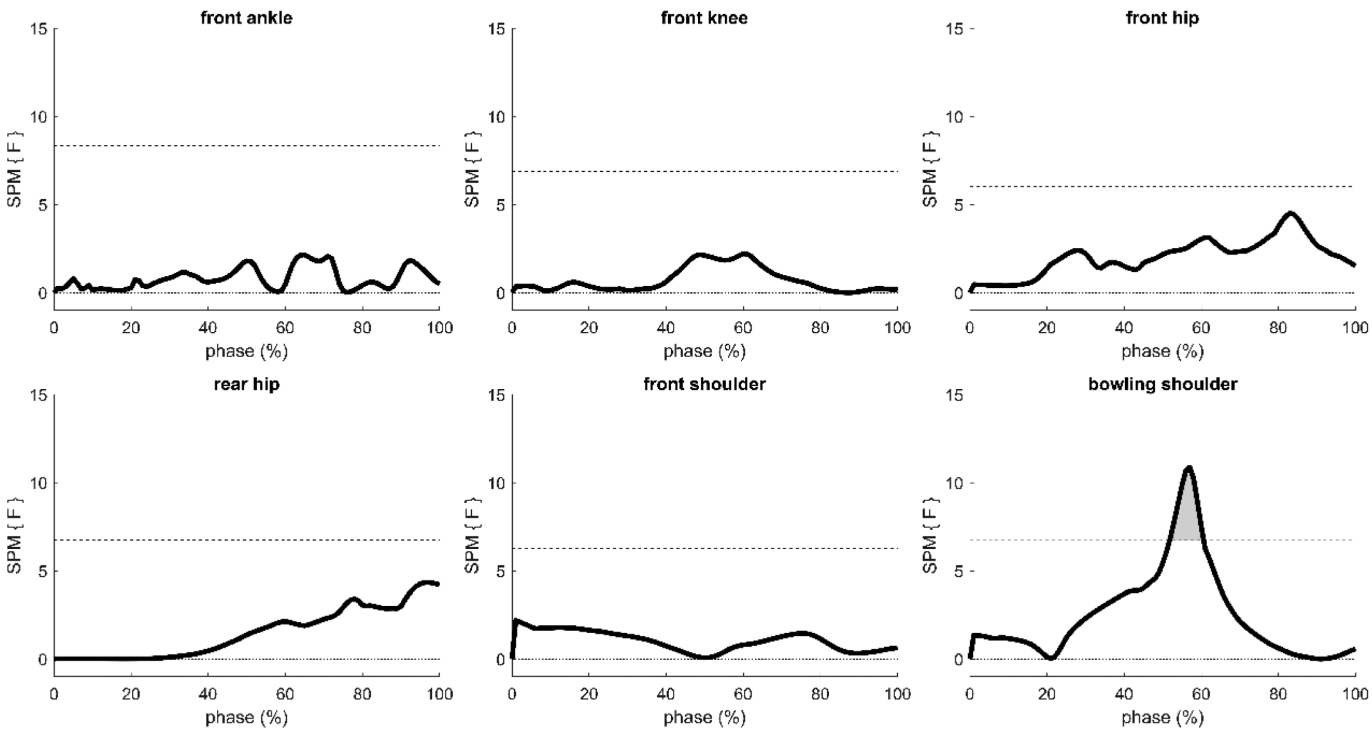

Figure 5. The SPM1D repeated measures ANOVA analysis comparing the joint torque variables between the optimised original strength, increased lower body strength, and increased lower body + shoulder strength techniques. The grey dashed lines represent the t-value threshold for a significant alpha value of 0.05 with the grey shaded regions highlighting periods of significant difference.

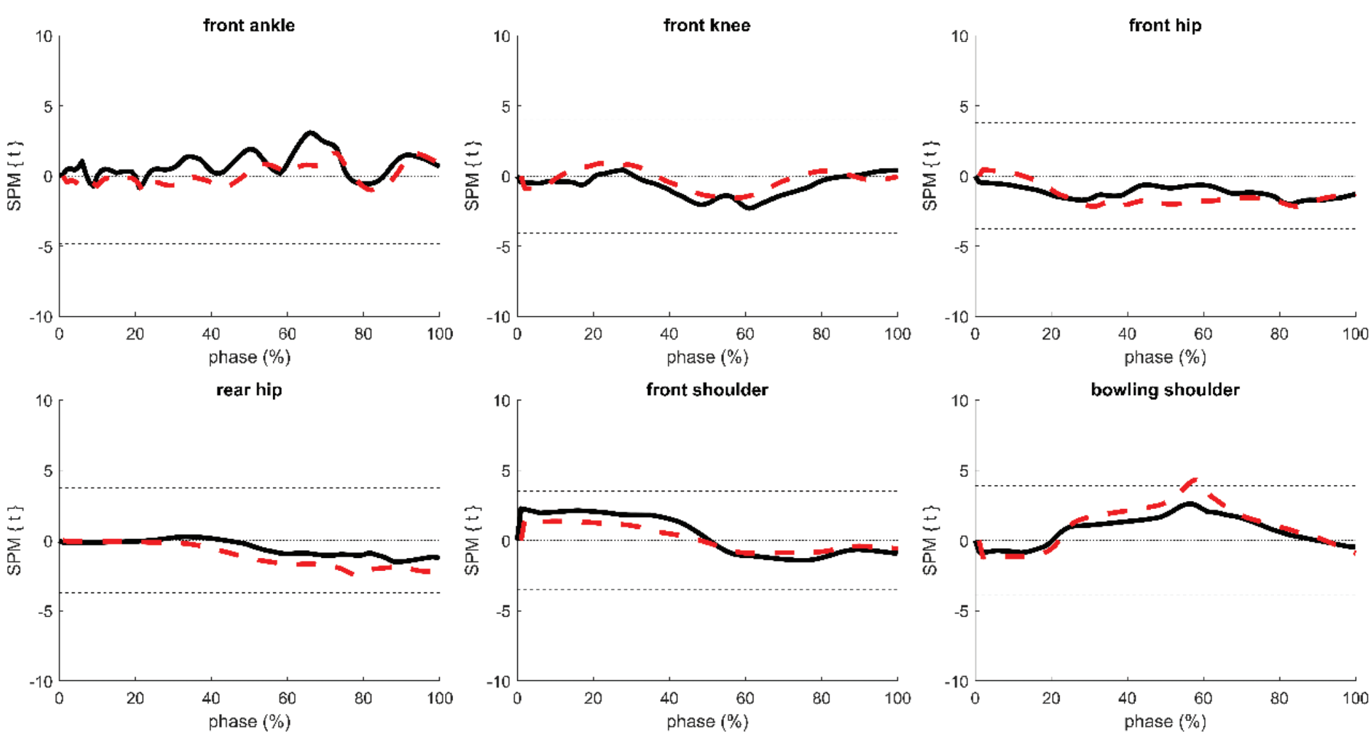

Figure 6. The SPM1D post-hoc paired t-test analysis comparing the difference in the joint torque time histories between the original strength and increased lower body strength optimised techniques (black solid line), and the original strength and increased lower body + shoulder strength optimised techniques (red dashed line). The grey dashed lines represent the t-value threshold for a significant alpha value of 0.05. Positive t-values indicate the increased strength optimised techniques have greater extensor torque at that point in the phase compared to the original strength optimised techniques.

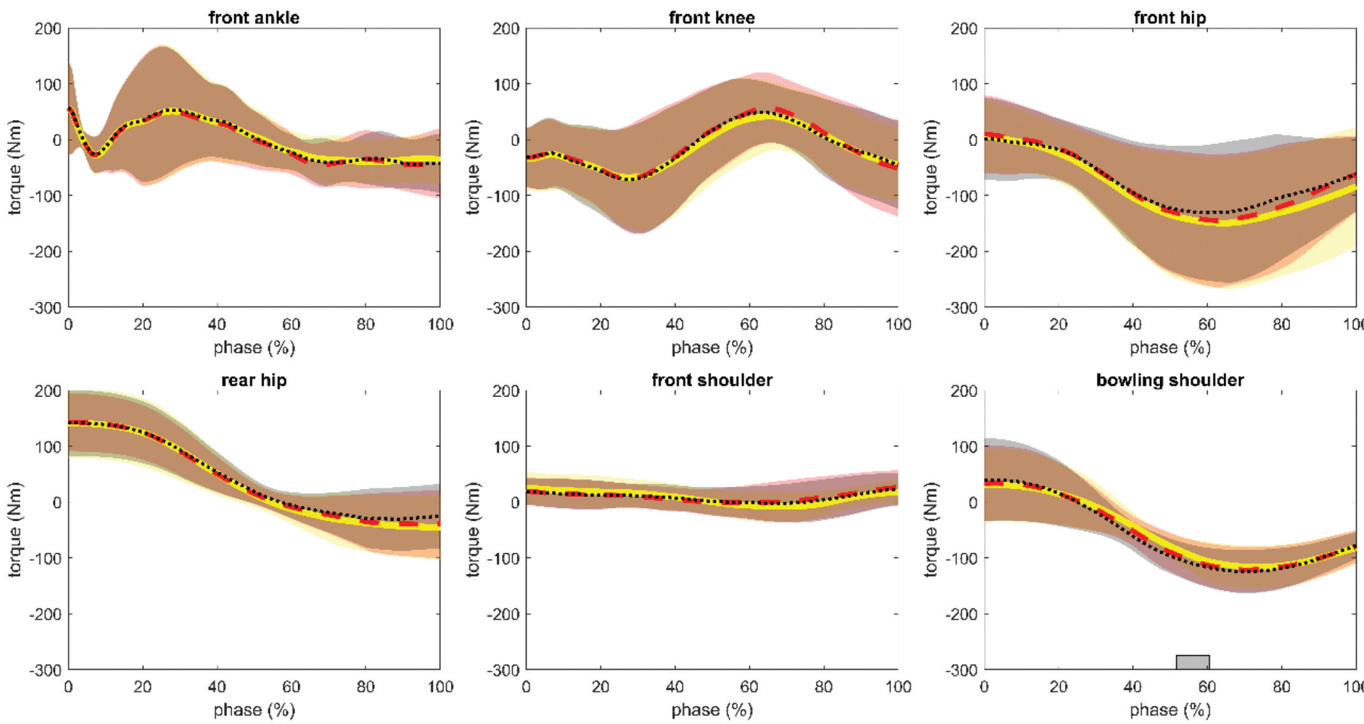

Figure 7. Mean and standard deviations of the joint torque variables for the optimised original strength (yellow solid line), increased lower body strength (red dashed line), and increased lower body + shoulder strength (black dotted line) techniques. Positive torque representing flexion and negative torques extension. Any statistically significant difference regions ($p < 0.05$) are marked by a grey bar on the horizontal axis.

Conclusion

This study has explored the effect of an increase in lower body and lower body + shoulder strength on elite male fast bowling performance and associated front foot contact-phase technique. It has identified that a 5% increase in lower body + shoulder strength (ankle knee, hip and shoulder) resulted in a 2.0% increase in ball release speed. The only significant differences found between the optimised original strength and increased lower body + shoulder strength techniques were in the vertical ground reaction impulse, and in the magnitude of the bowling shoulder torque in the mid-phase of the front foot contact phase. Although non-significant, the optimised increased strength techniques highlighted adaptations compared to the original strength techniques which were contrary to those expected based on previous research. It is suggested that increases in strength may lead to alterations in the front foot contact technique which allow greater muscular contributions to ball release speed to be generated. Caution is, therefore, advised when considering strength interventions as an approach to alter the front foot contact-phase technique.

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ORCID

P.J. Felton http://orcid.org/0000-0001-9211-0319

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