The effect of elbow hyperextension on ball speed in cricket fast bowling

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ABSTRACT

This study investigates how elbow hyperextension affects ball release speed in fast bowling. A two-segment planar computer simulation model comprising an upper arm and forearm + hand was customised to an elite fast bowler. A constant torque was applied at the shoulder and elbow hyperextension was represented using a damped linear torsional spring at the elbow. The magnitude of the constant shoulder torque and the torsional spring parameters were determined by concurrently matching three performances. Close agreement was found between the simulations and the performances with an average difference of 3.8%. The simulation model with these parameter values was then evaluated using one additional performance. Optimising ball speed by varying the torsional spring parameters found that elbow hyperextension increased ball release speed. Perturbing the elbow torsional spring stiffness indicated that the increase in ball release speed was governed by the magnitude of peak elbow hyperextension and the amount that the elbow recoils back towards a straight arm after reaching peak elbow hyperextension. This finding provides a clear understanding that a bowler who hyperextends at the elbow and recoils optimally will have an increase in ball speed compared to a similar bowler who cannot hyperextend. A fast bowler with 20° of elbow hyperextension and an optimal level of recoil will have increased ball speeds of around 5% over a bowler without hyperextension.

Keywords: simulation, modelling, pace bowler, ball velocity

INTRODUCTION

Fast bowling is a dynamic activity within cricket where the bowler utilises the speed at which they are able to deliver the ball towards the batsman. The fastest bowlers are capable of delivering the ball in excess of 40 m/s (90 mph) (Worthington et al., 2013). The bowling action can be thought of as a series of segmental movements which ends with the forward rotation of the bowling arm (Bartlett et al., 1996). Previous research has suggested that the action of the bowling arm during this delivery period (the phase between the upper arm being horizontal and ball release) is the most important aspect for ball release speed with contributions of 40-50% to the final ball release speed coming from the angular displacement of the bowling arm (Davis and Blanksby, 1976; Elliott et al., 1986). There is still a lack of understanding however, regarding the effect of the elbow joint angle time history on ball release speed.

Research investigating the effect of elbow extension on ball release speed has been motivated by a law governing bowling in cricket which prohibits elbow extension exceeding 15° between the upper arm reaching horizontal and ball release (ICC, 2015). During these investigations elbow hyperextension has been witnessed during the bowling action in the joint angle-time history (Ferdinands and Kersting, 2004; Portus et al., 2006; King and Yeadon, 2012). Elbow hyperextension occurs when the joint angle exceeds a straight position (180°) which is considered to be the anatomical range of motion (Alter, 2004). Elbow extension is usually limited by the tension in the anterior joint capsule and flexor muscles and to some extent in the anterior parts of the collateral ligament (Palastanga et al., 2002). It is speculated that during fast bowling the load on the elbow can cause elbow hyperextension to occur (Ferdinands and Kersting, 2004; Portus et al., 2006) with peak hyperextension

angles reported in excess of 20° (King and Yeadon, 2012). The results of these investigations into the effect of elbow extension on ball speed suggest that there appears to be a relationship between elbow extension and ball release speed (Portus et al., 2006; Roca et al., 2006). Further research by Middleton et al. (2015) has suggested however, that increased joint extension does not necessarily result in increased wrist velocity but those bowlers who flex their elbow joint immediately prior to ball release gain an advantage in increased ball release velocity. A linear relationship was also found when investigating how a flexion-extension offset from a straight arm affects wrist velocity with a hyperextended arm being slowest and a flexed arm fastest. Non-constant elbow hyperextension time histories however, were not investigated.

In order to investigate the effect of elbow hyperextension on ball release speed a theoretical approach can be used. Two forward dynamic simulation models have previously been developed for cricket bowling (Ferdinands et al., 2008; Middleton et al., 2015). Ferdinands et al. (2008) developed a preliminary model which required kinetic inputs derived from inverse dynamics which could be manipulated to elicit kinematic effects. Middleton et al. (2015) developed a 3D model which required the joint angle-time histories to be input. The elbow joint-angle time history was manipulated to investigate the effect differing joint angle-time histories had on wrist speed. The validity of the results in this model were compromised however, since the manipulations of the input variables did not take into consideration the mechanical properties of muscles.

Although, elbow hyperextension is exempt from counting towards the 15° extension limit since it is considered to be an involuntary movement caused by the load on the elbow during the bowling action (ICC, 2015) there is still a lack of understanding of the effect of elbow hyperextension on ball release speed as previous research has not distinguished between extension and hyperextension. The aim of this study was to determine the effect of elbow hyperextension on ball speed in fast bowling through the use of a subject-specific simulation model.

METHODS

A four stage theoretical process was used to investigate the effect of elbow hyperextension on ball release speed in fast bowling (King and Yeadon, 2013). The model was developed, customised to an elite bowler, evaluated by comparison with the elite bowlers performance and then used to investigate the effect of elbow hyperextension on ball release speed.

Data collection

Performance data were collected from a member of the England and Wales Cricket Board (ECB) elite fast bowling group (age 19 years; height 1.80 m; mass 82.4 kg) at the National Cricket Performance Centre in accordance with Loughborough Universities Ethical Advisory Committee guidelines. Four maximal ball speed bowling trials of a good length were recorded using an 18 camera (MX13) Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 300 Hz on a standard length indoor cricket pitch. Three pairs of 14 mm retro-reflective markers were attached across the wrist, elbow and shoulder joints on the bowling arm such that their mid-points coincided with the joint centres (King and Yeadon, 2012) and a reflective patch (approximately 15 x 15 mm) was attached to the ball to enable ball release velocity and the instant of ball release to be determined.

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Data processing

The four trials were manually labelled and initially processed using the Vicon Nexus software with all trials tracked without any marker loss. All marker trajectories were then filtered using a recursive fourth-order low-pass Butterworth filter with a cut-off frequency of 30 Hz determined using a residual analysis (Winter, 1990). The three-dimensional wrist, elbow, and shoulder joint centre-time histories were calculated from the pairs of markers across the wrist, elbow and shoulder. The projection of the joint centres on the sagittal plane (vertical plane parallel to a line joining the two middle stumps together) was then used to determine the orientation angle (the angle of the upper arm in the sagittal plane relative to the downwards vertical) and the elbow joint angle (Figure 1). A quadratic function was fitted to the time history of the horizontal and vertical displacement of the shoulder joint centre in the sagittal plane so that derivatives could be derived.

Ball release was determined as the first frame where the distance between the ball marker and wrist joint centre had increased more than 5 cm (Worthington et al, 2013). The coordinates of the reflective tape on the ball in the sagittal plane were used to calculate the ball release velocity as the average resultant velocity calculated over the first five frames after ball release. The average percentage increase between wrist and ball speed at ball release across the four trials was also calculated in order to establish the general increase in ball speed due to wrist flexion for the participant used in this study.

Simulation model

A two-segment planar simulation model of the bowling arm delivery period of fast bowling (Figure 1) was constructed using AutolevTM (Kane and Levinson, 1985). The two-segments represented the upper arm and lower arm + hand segments. A ball was included at the end of the forearm + hand segment.
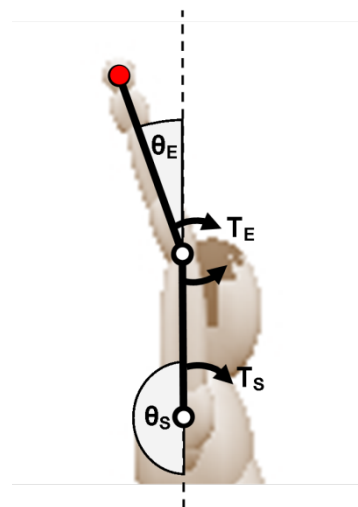

Figure 1. Two-segment simulation model of the bowling arm. The torque generator Ts, opens the shoulder joint angle θs, and a torsional spring T_E, allows hyperextension of the elbow ($\theta_E > 0$).

A constant torque generator was employed at the shoulder T_S, which opened (extended) the shoulder joint angle θ_s. The shoulder joint centre was driven horizontally using the displacement time history from the performance data. The

vertical displacement of the shoulder joint centre was ignored since the performance data showed minimal movement (< 0.025 m) throughout the delivery period.

The torque at the elbow was modelled as a damped linear torsional spring which only acted when the elbow was in hyperextension (Lundon, 2007):

$$T_E = \begin{cases} -k_E\theta_E - c_E\dot{\theta}_E, & \theta_E \geq 0 \\ 0, & \theta_E < 0 \end{cases}$$

where θ_E is the elbow joint angle, $\dot{\theta}_E$ is the elbow joint angular velocity, k_E is the torsional spring stiffness and c_E is the torsional spring damping.

Ball release was defined to have occurred once the upper arm had passed the vertical and the calculated horizontal projectile distance travelled by the ball to the predicted landing site matched the performance data. This was in order to ensure the outcome of each simulation delivered a ball which landed in the same place and was therefore comparable.

Input to the simulation model comprised the magnitude of the constant shoulder torque T_S, the torsional spring parameters k_E and c_E, the horizontal shoulder joint centre displacement time history, the segmental inertial parameters and the initial orientation and angular velocity of the upper arm and lower arm + hand segments. The output from the simulation model comprised the shoulder and elbow joint angle time histories as well as the tangential velocity of the wrist, which was converted to ball speed using the average percentage increase from the performance data in order to incorporate the effect of wrist flexion.

In order to quantify the effect of elbow hyperextension on ball release speed compared to a straight arm, a one-segment planar simulation model was also constructed. The one-segment model had the same inputs and outputs as the two-segment model but the elbow joint was omitted and the single segment represented the upper arm + forearm + hand.

Parameter determination

The segmental inertia parameters were calculated using the inertia model of Yeadon (1990) from ninety-five anthropometric measurements taken from the elite fast bowler. A common set of parameters consisting of the magnitude of the constant shoulder torque T_S, and the torsional spring parameters at the elbow k_E and c_E, were determined concurrently for three maximal speed bowling performances using the Simulated Annealing algorithm to minimise an objective function (Corana et al., 1987). The objective function was the average of a cost function defined as a root mean square (RMS) score of the absolute differences between the simulation and recorded performance for four variables: ball release speed, total time of simulation, maximum elbow hyperextension angle and elbow extension angle at ball release. Each difference score was weighted equally and 1° difference was considered to be equivalent to 1% difference (Yeadon and King, 2002).

Evaluation of the model

The robustness of the matching set of parameters was evaluated using a fourth performance by the bowler, where the matching parameters were fixed and a single simulation run (King and Yeadon, 2013). The trial with the best match was then selected to provide the initial inputs to the simulation model for all subsequent simulations.

Simulations investigating the effect of elbow hyperextension on ball release speed

Initially to quantify the effect of elbow hyperextension on ball release speed, the ball speed for the best matched simulation was compared to the ball speed for a simulation with the one-segment model where the same matched inputs were used. Secondly, to quantify the maximum effect of elbow hyperextension on ball release speed, an optimisation was run where the torsional spring parameters k_E and c_E, were varied using the Simulated Annealing algorithm (Corana et al., 1987) in order to maximise ball release speed. A penalty was imposed if peak elbow hyperextension exceeded an upper bound of 25° based on previous research (King and Yeadon, 2012). Thirdly to investigate the relationship between the magnitude of elbow hyperextension and ball release speed simulations were required with different elbow hyperextension angle-time histories. To achieve this, the elbow torsional spring stiffness k_E, was perturbed to give a wide range of realistic elbow hyperextension time histories whilst the elbow torsional spring damping term c_E, was set to the optimised value. The time where elbow hyperextension would start to occur within the delivery period was also varied. In order to do this, the first part of the delivery period was simulated using the one-segment model before switching to the two-segment model at different times in the delivery period with the output from the one-segment model input to the two-segment model. Penalties were included to prevent unrealistic elbow hyperextension angle time histories where all simulations included in the final analysis incurred no penalties.

RESULTS

The simulation model closely matched the movement of the bowling arm during the delivery period with overall difference values of 4.4%, 4.5% and 2.5% for the three matched trials (Figure 2). An evaluation simulation, in which a fourth bowling trial was simulated using the matched parameters, returned a RMS difference function value of 4.4% (Table 1).

Table 1. The initial conditions, matching parameters and RMS differences for the matching and evaluation simulations

	Initial conditions				Matching parameters				Matched RMS differences				
	θ_S (°)	θ_E (°)	θ'_S (°s^{-1})	θ'_E (°s^{-1})	ball speed (mph)	peak θ_E (°)	θ_E at BR (°)	time (s)	ball speed (%)	peak θ_E (°)	θ_E at BR (°)	time (%)	Overall RMS
M$_1$	109	4.3	1272	379	86.1	13.5	11.3	0.07	5.0	0.1	0.4	7.6	4.5
M$_2$	93	0.5	1261	144	86.3	13.9	11.9	0.07	1.1	0.0	1.1	8.6	4.4
M$_3$	93	0.1	1250	164	86.8	14.0	12.3	0.06	2.2	0.2	1.4	4.3	2.5
E	99	0.0	1187	203	86.9	14.3	12.9	0.06	4.2	0.5	2.5	7.4	4.4

Abbreviations: match M$_i$; evaluation E; shoulder angle θ_S; elbow angle θ_E
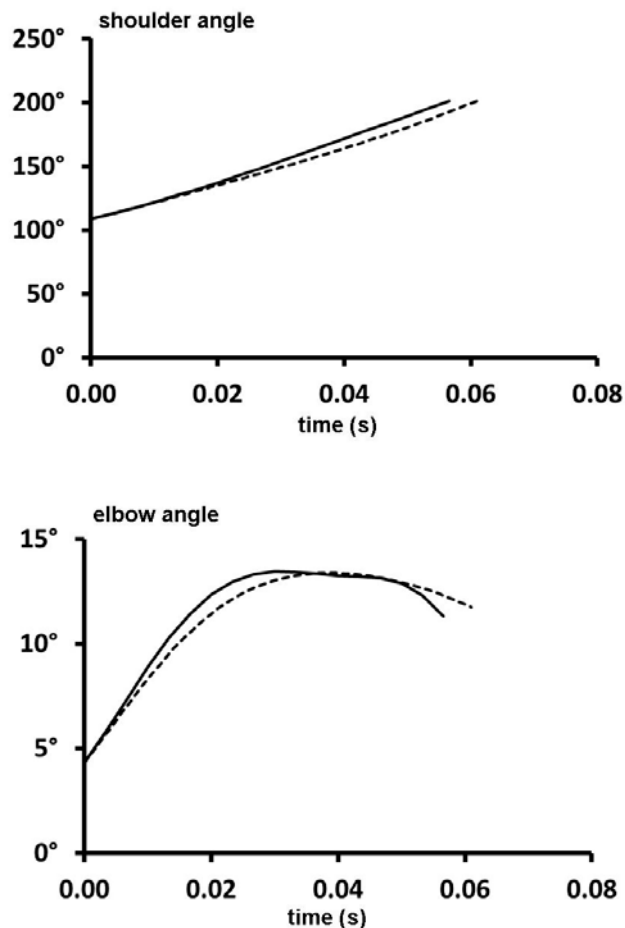
Figure 2. Comparison of key kinematic variables during the bowling delivery period for Match 1; solid line – actual, dashed line – simulation.

The best match (M3) simulated ball release speed to be 85.8 mph (38.1 m/s). When the initial conditions for this match were input into the one-segment model, ball release speed was simulated to be 82.5 mph (36.7 m/s). This indicated that the bowler's elbow hyperextension caused an increase in ball release speed of 4% (Table 1).

Optimising ball release speed by varying the torsional spring parameters found a solution with a peak elbow hyperextension of 25° (upper limit) and 5° of recoil. This optimal simulation had a ball release speed of 86.6 mph (38.5 m/s). This equated to an increase of 5% compared to bowling with a straight arm (Table 1). In the optimum solution the damping parameter was equal to zero.

Perturbing the spring stiffness and varying the start time of elbow hyperextension resulted in seven thousand simulations with different elbow hyperextension characteristics. These simulations were classified into one of two categories depending on their elbow angle time history: "Recoiling"- the elbow hyperextends and is recoiling at the instance of ball release or "At peak" – the elbow hyperextends and is at peak hyperextension at ball release. In both these categories the ball release speed was faster than bowling with a straight arm (Figure 3). Further investigation of the simulations in the recoiling category indicated that an optimal amount of recoil exists in order to maximise ball release speed for each amount of peak elbow hyperextension (Figure 4). For both the 'recoiling' and 'at peak' groups proximal to distal sequencing was evident with the peak upper arm angular velocity occurring prior to the lower arm peak angular velocity at ball release.
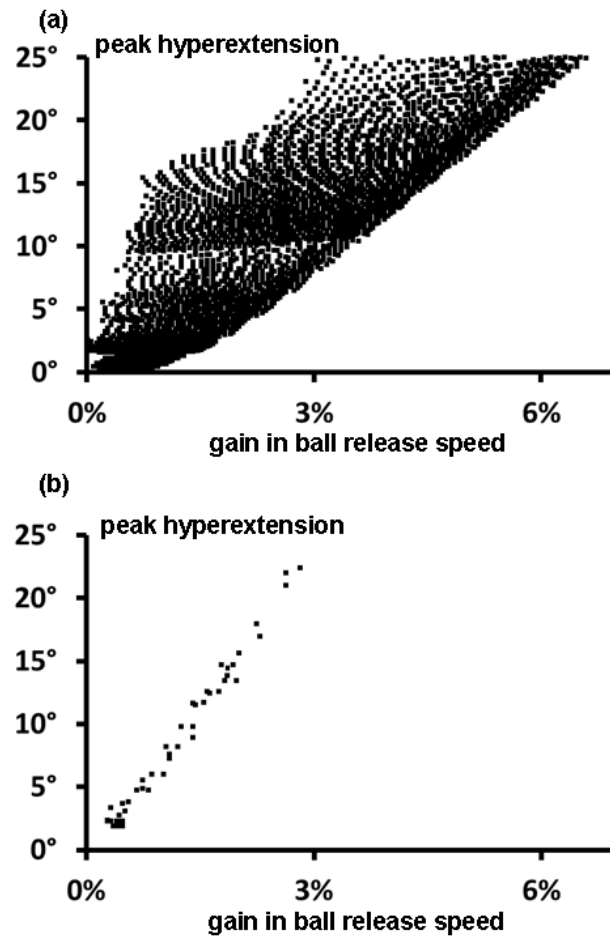
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Figure 3. The relationship between peak elbow hyperextension and gain in ball speed (compared to a straight arm) for (a) "Recoiling" and (b) "At peak" categories.
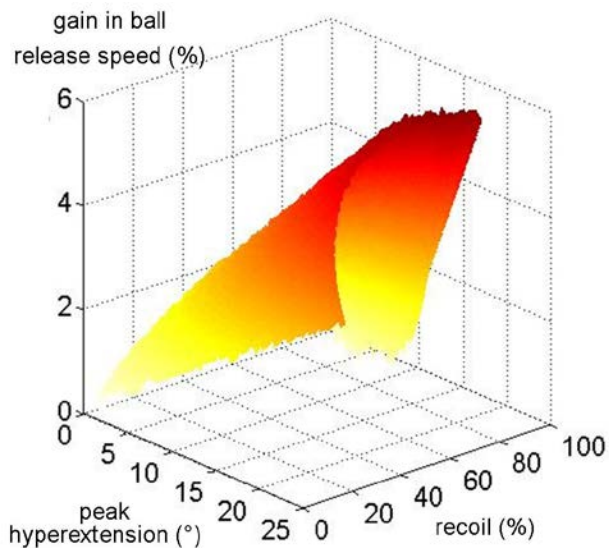

Figure 4. The percentage gain in ball speed (compared to a straight arm) as a function of peak elbow hyperextension and recoil percentage.

The relationship between the optimal recoil percentage and peak elbow hyperextension to maximise ball speed was found to be inversely hyperbolic (R^2 = 0.7) (Figure 5). Rapid growth in the optimal recoil percentage only occurred when the peak hyperextension was less than 1°.   Therefore, for the majority of

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hyperextensions seen within fast bowling (> 1°) the optimal recoil lies between 30% and 60% of the theoretical maximum, becoming closer to 60% the closer the peak hyperextension approaches 1°. The initial exponential phase (<1°) provides a 1% gain in ball release speed and thereafter each 1° of hyperextension leads to a gain in ball speed of 0.2% (Figure 6).
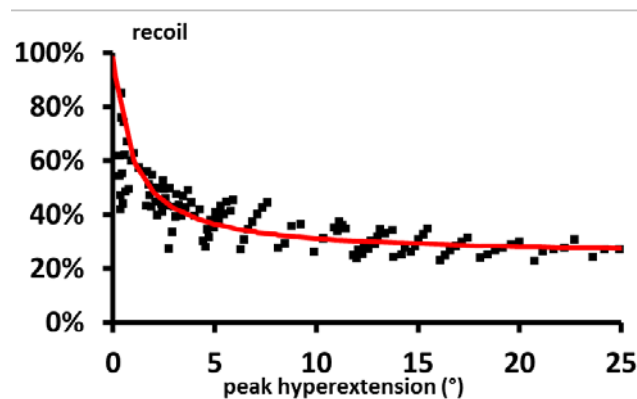

Figure 5. The relationship between recoil percentage and peak elbow hyperextension for the fastest simulation for each torsional spring stiffness.
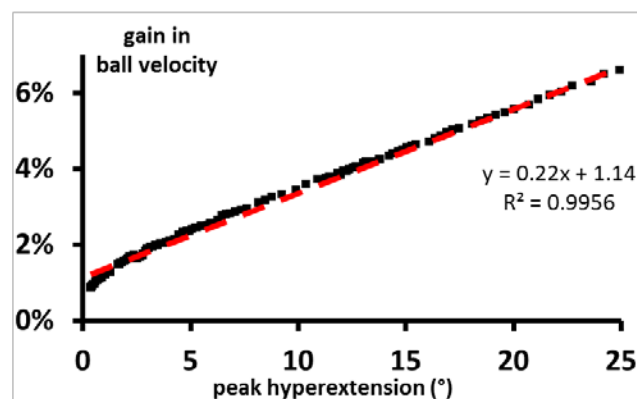

Figure 6. The relationship between peak elbow hyperextension and percentage gain in ball speed when optimal recoil occurs.

DISCUSSION

The ball release speed of the bowler in this study was increased by 4% due to elbow hyperextension when compared to a straight arm. Optimising ball speed by varying the two parameters which govern the laxity of the elbow joint showed that a larger peak elbow hyperextension was better with the arm starting to recoil before ball release. Perturbing the stiffness of the spring governing the amount of elbow hyperextension possible within the simulation model found that any amount of elbow hyperextension increases ball release speed during fast bowling although the increase is governed by the magnitude of peak elbow hyperextension and the amount the elbow recoils. To optimise the increase in ball speed the larger amount of elbow hyperextension the better so long as the elbow recoil percentage is optimal. The optimal recoil percentage to maximise the ball release speed for each peak elbow hyperextension has an inverse hyperbolic relationship.

The increase in ball speed caused by elbow hyperextension is a consequence of two mechanisms within the bowling delivery. Firstly, the simulations where the elbow reaches peak hyperextension at ball release reveal that in order to satisfy the ball release criteria (i.e. release the ball towards the same landing point) the shoulder

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release angle has to increase as the elbow hyperextension increases. This allows the shoulder torque to be applied over a longer period which increases the work done by the shoulder. As a result the upper arm has a faster angular velocity at ball release and as a consequence a faster ball speed (Figure 7). Secondly, in the simulations where the elbow is recoiling at ball release the angular velocities of the elbow and shoulder act in the same direction and as a consequence ball speed is increased. These two mechanisms work against one another; as the elbow recoils the increase in work done at ball release due to the first mechanism is reduced (Figure 8). This creates a trade-off between the two and an optimal recoil percentage exists for each peak elbow hyperextension in order to maximise the gain in ball speed (Figure 4).
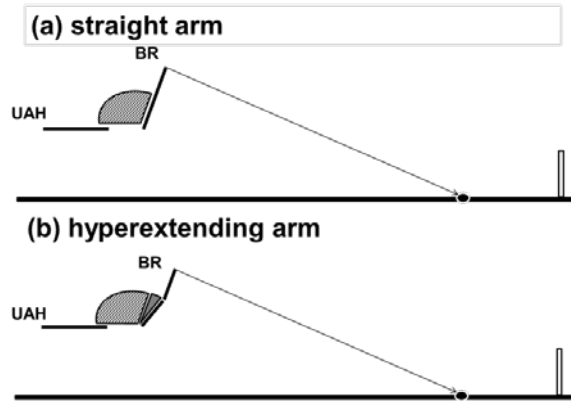

Figure 7. The work done at the shoulder between upper arm horizontal (UAH) and ball release (BR) for: (a) a straight arm (b) a hyperextending elbow.
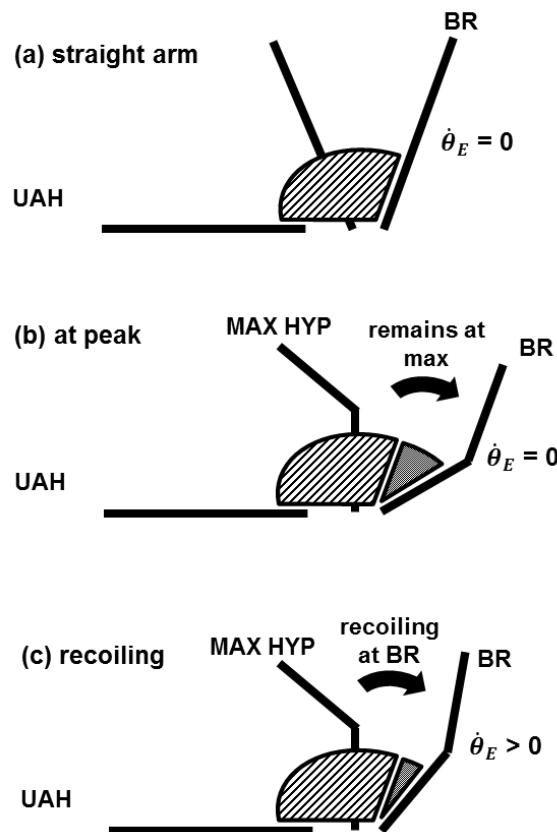

Figure 8. The work done at the shoulder between upper arm horizontal (UAH) and ball release (BR) and the angular velocity of the elbow at BR for: (a) a straight arm (b) at peak (c) recoiling elbow time histories.

The increase in ball speed of non-recoiling elbow hyperextensions over a straight arm disagrees with the results found by Middleton et al. (2015) which indicated that an elbow with a fixed offset in hyperextension bowled slower than a straight arm. It is proposed that an increase in ball speed is always possible with a flexion/extension and/or abduction/adduction offset as long as the orientation of the upper arm increases the ability for the shoulder to do work as suggested by Marshall and Ferdinands (2003). Previous research investigating the effect of flexion or extension of the elbow from upper arm horizontal to ball release has found differing results where both flexion (Middleton et al., 2015) and extension (Portus et al., 2006; Roca et al., 2006) have been shown to increase ball speed. The results in this study show that a greater increase in ball speed is caused by the recoil (mechanism 2) than extension to peak hyperextension (mechanism 1) which agrees with Middleton et al. (2015). In reality however, it is probable that the increase in ball speed caused by the second mechanism can be achieved by either flexion or extension depending on the orientation of the upper arm. If the flexion-extension axis is orientated such that flexion is away from the target and extension is towards then the first mechanism explained in this study is caused by flexion and the second mechanism by extension. If however, the flexion-extension axis is aligned so that extension is away from the target and flexion is towards then the roles are reversed and the first mechanism is caused by extension and the second by flexion. The main application of this work is to give a clear understanding of how movements at the elbow effect ball release speed in fast bowling and the potential advantage individuals with the ability to hyperextend at the elbow have over those bowlers who cannot hyperextend.

Although, this two-dimensional planar simulation model can offer an explanation as to how the kinematics of the elbow joint can affect the mechanical system and increase ball speed, it is not exempt from limitations. The elbow joint is a complex three-dimensional system which has been generalised in two-dimensions within this study. The degrees of freedom which have been omitted would reduce the length of the forearm + hand and upper arm segments if the upper arm was rotated away from the plane and/or an abduction-adduction angle existed. This would create a trade-off between the increase in angular velocity due to the reduced inertia of the arm and the decrease in the linear velocity of the wrist towards the target. It is speculated that a three-dimensional model would follow the same mechanics as the two-dimensional model where the optimal solution maximises the ability for work to be done at the shoulder before the joint moves back towards the target to optimise the trade-off between the two mechanisms. This suggests bowlers with large abduction angles and more movement towards the target using flexion or extension are likely to benefit with increased ball speeds compared to those with straighter arms.

In the future, the model could be developed to investigate whether the mechanics discussed in this study also hold true for flexion and extension by adding an active torque generator at the elbow, as well as increasing the complexity of the shoulder torque profile. A hand segment could also be introduced to directly investigate the effects of the wrist joint on elbow hyperextension and ball speed. Close agreement however, was found between the matching simulations and the recorded performances indicating the model was capable of reproducing the relevant parts of the bowling action for this study. In addition the effect of varying the shoulder displacement profiles could also be investigated to determine whether braking of the shoulder joint centre increases elbow hyperextension and/or changes the optimal amount of recoil.

In summary, a two-dimensional simulation model capable of recreating the kinematics of the bowling arm delivery period in fast bowling showed that elbow

hyperextension along with optimal recoil increased ball release speed. Although it may be possible for bowlers who do not hyperextend to bowl faster than those who hyperextend due to other technique or strength parameters, a bowler who can hyperextend at the elbow and recoil optimally will have an increase in ball speed compared to a similar bowler who cannot hyperextend. For example, a bowler with an optimal recoil peak hyperextension of 20° will experience an increase in ball speed of 5% over a bowler with a straight arm. At an elite level, in which fast bowlers are seen to bowl in excess of 90 mph (40 m/s), this equates to an increase of 5 mph (2.2 m/s), which is a substantial increase in performance.

ACKNOWLEDGEMENTS

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