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REVIEW ARTICLE

An Integrated Approach to the Biomechanics and Motor Control of Cricket Fast Bowling Techniques

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Abstract To date, scientific investigations into the biomechanical aspects of cricket fast bowling techniques have predominantly focused on identifying the mechanical factors that may predispose fast bowlers to lower back injury with a relative paucity of research being conducted on the technical features that underpin proficient fast bowling performance. In this review paper, we critique the scientific literature examining fast bowling performance. We argue that, although many published investigations have provided some useful insights into the biomechanical factors that contribute to a high ball release speed and, to a lesser extent, bowling accuracy, this research has not made a substantive contribution to knowledge enhancement and has only had a very minor influence on coaching practice. To significantly enhance understanding of cricket fast bowling techniques and, therefore, have greater impact on practice, we recommend that future scientific research adopts an interdisciplinary focus, integrating biomechanical measurements with the analytical tools and concepts of dynamical systems motor control theory. The use of qualitative (topological) analysis techniques, in particular, promises to increase understanding of the coordinative movement patterns that define 'technique' in cricket fast bowling and potentially help distinguish between functional and dysfunctional aspects of technique for individual fast bowlers.

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1 Introduction

The fast bowler is generally considered to be one of the most important members of a cricket team and potentially one of the most influential in determining the outcome of a match. However, they have also been shown to be at the greatest risk of injury [1], with their lower trunk being most susceptible to both traumatic and overuse injury [2], forcing them to endure more time away from the game than any other category of player [3]. The realisation of these factors has led to the formation of specialist fast bowling academies in various countries around the world (e.g. the MRF Pace Foundation in Chennai, India) to promote and encourage the use of safe and effective fast bowling techniques among aspiring young fast bowlers. Most test-playing nations now also employ the services of a full-time fast bowling coach to assist in refining the techniques and enhancing tactical awareness of young fast bowlers who are being expedited into the international game with limited or no experience of first-class cricket.

Despite the increased interest in fast bowling from a coaching perspective, scientific research into this important facet of the game has been much slower to develop. Since the pioneering investigations into the biomechanics of fast bowling techniques by researchers at the University of Western Australia approximately a quarter of a century ago [4–6], progress has been limited to a relatively small, but steadily increasing, number of studies published in scholarly journals[1]. Many of these investigations have attempted

[1] There have also been four World Congresses on Science and Medicine in Cricket that coincided with the 1999 [7], 2003 [8], 2007 [9] and 2011 [10] 50-over Cricket World Cups in England, South Africa, West Indies and India, respectively, and three conferences organised by Cricket Australia in 2007 [11], 2010 [12] and 2012 (no proceedings available).

to build upon research by Elliott and colleagues [13–15] and establish causative associations between bowling technique and lower back injuries. Indeed, recent research has indicated that a combination of contralateral side flexion and ipsilateral axial rotation of the lumbar spine, not necessarily counter-rotation of the thorax as previously thought, is likely to be instrumental in the development of lumbar bone stress injury and intervertebral disc derangement [16–18].

The number of scientific studies focusing on the factors that contribute to proficient fast bowling performance has also been limited. Although many of the investigations published in the literature have provided some useful insights into the biomechanical factors that contribute to a high ball release speed and, to a much lesser extent, bowling accuracy (e.g. [15, 19–23]), it could be argued that this research has not substantially enhanced knowledge and has only had a very minor impact on coaching practice. In many respects, these investigations have suffered from the same issues that have plagued performance-oriented sports biomechanics research, more generally, for the past three decades—that is, they have seldom moved beyond the descriptive phase to a more analytical one, they have typically not made reference to motor control theory, the universal principles of biomechanics, or the fundamental laws of physics and biology that govern them, and they have tended to be outcome focused rather than process focused (e.g. [24–27]).

In this review paper, we critique the scientific literature on fast bowling performance. We build a case for an integrated approach to the biomechanics and motor control of cricket fast bowling performance based on the analytical tools and concepts of dynamical systems theory. It is argued that this approach has the potential to provide more information that is directly relevant to the coaching of cricket fast bowling techniques than traditional biomechanical paradigms that have previously been used, with limited success, to gain understanding of the performance aspects of cricket fast bowling techniques. Similar approaches have been adopted previously to enhance understanding of the coordinative movement patterns that define technique in swimming [28], hockey [29], basketball [30] and javelin throwing [31], amongst others.

2 Review of the Literature on the Biomechanical Aspects of Cricket Fast Bowling Performance

As noted in Sect. 1 and previous literature reviews on cricket fast bowling [32, 33], there has been a relative paucity of scientific investigations into the factors that underpin proficient fast bowling performance (i.e. ball release speed and accuracy). Much of the early research on fast bowling performance was based on the observation and expert evaluation of ciné film footage [34–36] and descriptive kinematic and force platform analyses [4, 37, 38] of successful fast bowlers. Latterly, surface electromyography was used to determine the sequential and temporal patterning of muscle activity in collegiate fast bowlers [39]. Subsequent empirical studies attempted to establish statistical associations among kinematic variables, anthropometric parameters, physical capacities and ball release speed [15, 19, 21, 22, 40–43]. More computationally complex approaches, such as inverse dynamics analyses [44, 45], forward dynamics simulations [46] and energetic analyses [47], have also been used to examine the forces and torques, and energy transfers, that contribute to the generation of ball release speed.

There have been fewer studies that have focused on bowling accuracy. Devlin and colleagues [48] reported that moderate exercise-induced hypohydration impaired bowling accuracy but not ball release speed in sub-elite standard fast–medium cricket bowlers. Taliep and colleagues [49] found that there was no change in bowling accuracy over the course of a 12-over bowling spell but there was a decrease in ball release speed, particularly after the sixth over. Petersen and colleagues [50] showed that training with overweight and underweight cricket balls over a 10-week period decreased bowling accuracy but only slightly increased ball release speed. Duffield and colleagues [51] observed no decrease in ball release speed or bowling accuracy during two 6-over bowling spells interspersed by a 45-min period of light physical activity. Phillips and colleagues [52] revealed that national and emerging fast bowlers were better able to bowl to different targets, with greater consistency, and at greater speeds than junior fast bowlers. None of these studies, however, analysed the coordinative movement patterns responsible for producing these outcomes or how different task (e.g. weighted balls) and organismic (e.g. fatigue) constraints might have influenced those coordinative movement patterns.

In the following sub-sections of this article, key findings from the literature examining inter-relationships between aspects of fast bowling techniques, ball release speed and bowling accuracy during the run-up and pre-delivery stride (Sect. 2.1), delivery stride (Sect. 2.2) and follow-through (Sect. 2.3) are consolidated and evaluated. As this review is primarily concerned with the kinematic, kinetic and energetic aspects of fast bowling technique, discussion of the role of anthropometric and strength variables on ball release speed is limited.

2.1 Run-Up and Pre-Delivery Stride

The run-up is defined as the phase between the start of the bowler’s approach run to the moment of take-off for the pre-delivery stride. The pre-delivery stride, also known as the bound in the cricket coaching literature, is defined as the phase between the end of the run-up and the moment of back foot impact at the start of the delivery stride. The run-up and pre-delivery stride combined are typically 15–30 m in length [53], although it has been suggested that a 14-pace run-up is sufficient to release the ball at 37 m/s [35]. Most studies have used the horizontal velocity of the centre of mass or hip joint centre at back foot impact as a measure of run-up speed. Typical run-up speeds reported in the literature range from 4.0 to 6.0 m/s, although the 'optimum' run-up speed appears to be bowler specific and somewhat dependent on the type of bowling action adopted (see Fig. 1 for definitions of bowling action types). For example, there is some, albeit very limited, evidence to suggest that side-on bowlers may have a slower run-up than front-on, and possibly mixed, action bowlers to enable them to change orientation more easily during their pre-delivery stride [4, 34, 55].

There has been a lack of consensus in the literature regarding the relationship between run-up speed and ball release speed. However, many studies appear to suggest that fast bowlers with higher run-up speeds tend to produce higher ball release speeds [19, 41–43, 55]. Burden and Bartlett [40] reported a weak correlation between run-up speed and ball release speed ($r = 0.21$, $P > 0.05$) but run-up speed in that study was measured at the point of release, not at back foot impact as is customary, which is likely to account for some of the unusually low run-up speeds [mean ± standard deviation (SD) 3.42 ± 0.76 m/s] reported. The most comprehensive analysis of the run-up and its contribution to ball release speed, to date, was provided by Ferdinands and colleagues [55]. In that study, 34 premier-grade fast bowlers were divided into four groups based on their ball release speed. The horizontal velocity of the centre of mass at back foot impact in the fast (mean ± SD 5.46 ± 0.43 m/s) and medium–fast (mean ± SD 5.58 ± 0.29 m/s) groups was found to be faster than the medium group (mean ± SD 5.18 ± 0.61 m/s) and significantly faster ($P < 0.05$) than the slow–medium group (mean ± SD 4.62 ± 0.67 m/s). When the sample was pooled together, a strong positive relationship ($r = 0.58$, $P < 0.001$) was found between centre of mass velocity at back foot impact and ball release speed.

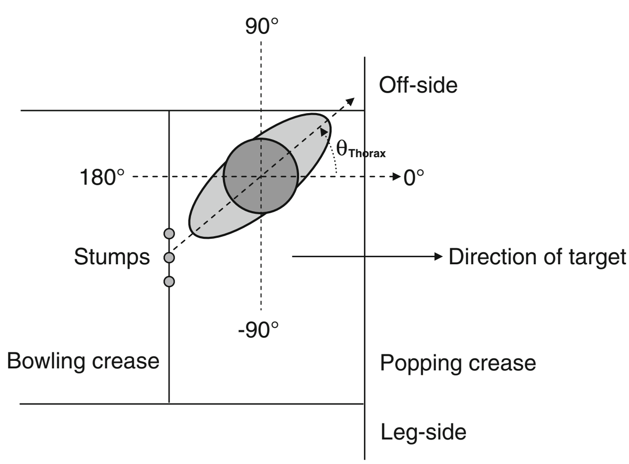

Fig. 1 The bowling action classification system described by Ferdinands and colleagues [54]. Side-on bowlers were defined as having a thorax alignment of less than 25° at back foot impact and thorax counter-rotation of less than 30° during the delivery stride. Semi-open bowlers were defined as having a thorax alignment of equal to, or greater than, 25° but less than 50° at back foot impact and thorax counter-rotation of less than 30° during the delivery stride. Front-on bowlers were defined as having a thorax alignment of equal to, or greater than, 50° at back foot impact and thorax counter-rotation of less than 30° during the delivery stride. Mixed bowlers were defined as having a pelvis–thorax separation angle of greater than 30° at back foot impact or thorax counter-rotation of greater than 30° during the delivery stride [Figure adapted from Ferdinands et al. [54] Reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.informaworld.com)]

Another noteworthy recent study on the run-up was provided by Renshaw and Davids [56]. They examined how step length was visually regulated to avoid bowling illegal deliveries—so-called 'no-balls'—when the bowler's front foot at delivery fails to land behind the front or popping crease. Using an approach adopted previously by Montagne and colleagues [57] to analyse the run-up phase of the long jump, Renshaw and Davids [56] found that, despite inconsistencies in the initiation point of their run-ups (range 0.20–0.97 m), skilled fast bowlers exhibited remarkably low levels of variability in final foot placement (range 0.08–0.16 m) over multiple deliveries. They also showed that adjustments to step length were made as and when required throughout the run-up, although there was a tendency for these adjustments to be more marked at the beginning and towards the end of the run-up. These findings were used to support the proposition that fast bowlers use a prospective control strategy, facilitated by a continuous perception–action coupling, to regulate their run-ups. This work represents an important departure from traditional monodisciplinary approaches that have dominated biomechanics research on fast bowling and demonstrates how integrating biomechanical measurements and motor control theory can enhance knowledge that is directly relevant to coaching practice (see Renshaw and Davids [58] for a summary of practical implications of this work).

2.2 Delivery Stride

The delivery stride has typically been defined as the phase between back foot impact and ball release. At ~70 % of this phase, front-foot impact occurs and it is during the remaining ~30 % of the delivery stride where the majority of energy and momentum required for a high ball release speed is generated and transferred to the ball. In the following sub-sections, we summarise the key aspects of technique during the delivery stride that lead to a high ball release speed and bowling accuracy.

2.2.1 Pelvis and Thorax Orientation and Interaction

In many biomechanical studies of fast bowling, particularly those considering technique from an injury as well as a performance perspective, the orientation of the pelvis and thorax at various key moments during, and their interaction throughout, the delivery stride have been reported. There has been some suggestion that side-on bowlers tend to rely on pelvis and thorax rotation in the transverse plane to generate ball release speed, whereas front-on bowlers appear to use more of the linear velocity generated during the run-up [4]. However, there is little evidence to suggest that the side-on action is superior to the front-on action in terms of generating ball release speed, although several studies [15, 23, 36, 37] have shown that a greater range of motion of the pelvis and thorax in the transverse plane is related to the production of greater ball release speeds. This finding may explain why some fast bowlers realign or counter-rotate their thorax to a more side-on position during the delivery stride—that is, so that they can move their thorax through a larger arc leading up to ball release[2].

The pelvis–thorax separation angle—defined as the angle between the vector adjoining the hip joint centres and the vector adjoining the shoulder joint centres—has also been reported in some investigations [15, 19, 22, 47]. Portus and colleagues [15] found a moderate correlation ($r = 0.34$, $P < 0.05$) between the timing of maximum pelvis–thorax separation angle and ball release speed—that is, the maximum pelvis–thorax separation angle tended to occur after front-foot impact and closer to ball release in faster bowlers. In contrast, Ferdinands and colleagues [47] reported no significant correlation between either maximum pelvis–thorax separation angle and ball release speed or the timing of maximum pelvis–thorax separation angle and ball release speed. Furthermore, there was no significant correlation between maximum pelvis–thorax separation velocity and ball release speed. However, maximum negative pelvic–thorax separation acceleration was found to be negatively correlated with ball release speed ($r = -0.47$, $P < 0.01$). It was suggested that, as the rapid reduction of pelvis–thorax separation velocity occurred through eccentric contraction of the trunk rotators caused by the pelvis beginning to rotate forwards, the elastic energy generated could be used to enhance concentric contraction, leading to an increase in the angular velocities of the thorax and more distal body segments in the upper extremity linked segment system.

There has also been some attempt to relate pelvis and thorax orientation during the delivery stride to bowling accuracy. Portus and colleagues [20] reported a significant inverse relationship ($r = -0.542$, $P = 0.045$) between total accuracy scores and counter-rotation of the thorax during overs 5 and 8 of an 8-over bowling spell, although the strength of this relationship reduced and became non-significant ($r = -0.469$; $P = 0.071$) when analysed over the duration of the bowling spell. This study also reported that the amount of thorax counter-rotation for front-on fast bowlers increased significantly over the bowling spell. From these results, it may be tentatively concluded that the mixed bowling action produces less accurate deliveries than front-on and side-on bowling actions, although as front-on bowlers appear to increase the amount of thorax counter-rotation over the course of a bowling spell, they may also become increasingly less accurate. Caution should be applied when interpreting the results of this study, however, as there was only a comparatively small number of bowlers in the side-on ($n = 1$), front-on ($n = 5$) and mixed ($n = 8$) groups, and only the sixth delivery of overs 2, 5 and 8 (i.e. 3 of 48 deliveries) was selected for kinematic analysis.

2.2.2 Front Leg Action

The action of the front leg between front-foot impact and ball release has received considerable research attention in the literature. From a purely mechanical standpoint, the 'optimum' front leg action is considered to be one that lands extended or slightly flexed, followed by a period of flexion to absorb shock, before vigorously extending up to the point of ball release to provide an effective lever for the upper body to rotate around [32, 37, 59]. Apart from a few notable exceptions [19, 20], most studies appear to support the view that bowling with a straight, or even hyper-extended, front leg at ball release can lead to greater ball release speeds [15, 21, 23, 36, 40, 41, 43], although there has been some conjecture about whether landing with a straight front leg at front-foot impact produces higher ground reaction forces and loading rates than a flexed front leg [4, 6, 15, 38]. A recent study by Worthington and colleagues [60], however, has indicated that the type of front leg action adopted—flexor, extender, flexor-extender or constant brace—has little effect on ground reaction forces. Rather, the magnitude and direction of ground

[2] Based on the findings of recent studies on high-performance fast bowlers from Australia [15], England [16] and New Zealand [54], pure front-on or side-on bowling actions (i.e. actions with no thorax counter-rotation) appear to be rare. Indeed, for the majority of this population of fast bowlers, some degree of thorax counter-rotation during the delivery stride, often beyond the 30° limit typically deemed to be 'safe', appears to be the norm.

reaction forces appears to be more influenced by the foot angle—defined as the angle between the vector adjoining the ankle and metatarsophalangeal joint centres and the horizontal plane—and plant angle—defined as the angle between the vector adjoining the hip and ankle joint centres and the vertical plane—at front-foot impact.

2.2.3 Non-Bowling Arm Action

From very early on, the action of the front arm was identified in the literature as being a key component of the fast bowling technique. Although no data were provided, Davis and Blanksby [36] observed that faster bowlers tended to adduct the non-bowling arm later and more rapidly than slower bowlers. They proposed that the bowling and non-bowling arms form a cooperative force-couple whereby the vigorous downward thrusting of the non-bowling arm can lead to increased angular velocity of the bowling arm. They also suggested that this forceful motion of the non-bowling arm can facilitate rotation and lateral flexion of the trunk, which can further increase the angular velocity of the bowling arm. Elliott and Foster [4] further highlighted the important role of the non-bowling arm in proficient fast bowling but suggested its contribution may be dependent on the type of action being adopted. They showed that front-on bowlers tended to have lower non-bowling arm vertical velocities (−2.4 m/s) than side-on bowlers (−3.2 m/s), although sample sizes were extremely limited in that study (three and two international fast bowlers, respectively). These findings were further supported by Elliott and colleagues [37], who reported that a group of 15 high-performance fast bowlers, with mainly front-on bowling actions, had similarly low non-bowling arm vertical velocities (−2.8 ± 0.8 m/s).

Since these early studies, there have been surprisingly few other investigations that have considered the action of the non-bowling arm. Salter and colleagues [22] reported that the vertical velocity of the non-bowling elbow was moderately correlated with ball release speed ($r = 0.42$, $P < 0.05$) in their individual-based analysis but did not include it as an independent variable in their group-based analysis. Wormgoor and colleagues [23] reported the angular velocity of the non-bowling arm but did not attempt to relate it to ball release speed. Ferdinands and colleagues [47] observed that the timing of maximum front-arm angular velocity occurred significantly earlier than peak trunk flexion and peak bowling arm angular velocity. They speculated that the front arm may be instrumental in facilitating trunk flexion and enhancing bowling arm angular velocity, although it was recommended that further studies using inverse dynamics analyses were necessary to confirm any causative relationship.

2.2.4 Sequencing and Timing of Body Segment Motions

An important line of enquiry for fast bowling research is the sequencing and timing of body segment motions but surprisingly few investigations have focused on this aspect of technique. Early research examining segmental sequencing was typically based on the analysis of peak resultant velocities [37] and peak horizontal velocities [19, 40, 41, 61] of key joints in the upper extremity linked segment system or kinematic chain. These studies generally demonstrated a proximal-to-distal increase in peak velocity of joint centres of the right hip, shoulder, wrist and fingers (for right-handed bowlers) as the moment of ball release approached. Furthermore, comparisons of elite fast and collegiate fast–medium bowlers by Burden and Bartlett [41] showed that, not only did faster bowlers tend to have higher joint centre velocities than slower bowlers, these differences tended to become more pronounced as joint centres become progressively more distal. Stockill and Bartlett [61] also found that the temporal occurrence of peak horizontal velocities of joint centres for international senior fast bowlers was consistently closer to ball release than for international junior fast bowlers. However, when expressed as a percentage of delivery stride duration, these temporal differences disappeared.

Recent investigations have adopted more sophisticated approaches to examining segmental sequencing. Based on 3D segment coordinate systems, Zhang and colleagues [62] calculated the angular velocities of the pelvis, torso, thorax, and upper and lower bowling arm during the performance of three different types of deliveries: maximum effort deliveries, normal deliveries and maximum lower trunk flexion deliveries. They found that a proximal-to-distal sequence of body segment motion existed for all bowlers for all types of delivery. Other differences in segmental motions between delivery types were also observed, such as the timing of peak rotations in relation to ball release, but none of these were shown to be statistically significant. Average ball release speed was shown to be greater for maximum lower trunk flexion deliveries but there was also a slight concomitant reduction in accuracy for this type of delivery compared to the other two types.

Ferdinands and colleagues [47] also examined angular velocities of body segments but extended their analysis to include kinetic energy transfer. They found that there was a significantly distinct temporal sequencing of peak linear and rotational kinetic energy and peak angular velocities, which adhered to a general proximal-to-distal order. However, several anomalies in segmental sequencing were observed, including the almost simultaneous peaking of forearm and hand rotational kinetic energies and some overlapping of pelvis and thorax angular velocities. No significant correlations were found between the timings of peak angular velocities of the pelvis and thorax and ball release speed, although significant moderate to strong correlations were identified between maximum angular velocities of pelvic flexion ($r = 0.56$; $P < 0.001$), pelvic rotation ($r = 0.57$; $P < 0.001$) and thoracic rotation ($r = 0.46$; $P < 0.01$) and ball release speed. Other significant correlations were found between the timing of peak kinetic energies and ball release speed, including, most notably, maximum linear thoracic kinetic energy, maximum forearm rotation, maximum linear hand and maximum hand rotation energies.

2.2.5 Body Segment Contributions to Ball Release Speed

The contribution of different body segments to ball release speed has also received limited coverage in the literature. Davis and Blanksby [35] used physical restraints to systematically immobilise the pelvis, thorax and wrist, and compared the ball release speed delivered under these conditions to the ball release speed delivered under normal unrestrained conditions. The differences, expressed as a percentage of the latter, were then used to approximate the respective contribution of each of the immobilised body segments to ball release speed. They calculated that the run-up contributed 19 % to the ballrelease speed, leg action and hip rotation 23 %, trunk flexion and shoulder girdle rotation 11 %, arm action 42 % and hand flexion 5 %. These findings, however, need to be treated with caution since the joint immobilization or restraint paradigm adopted presupposes that the restriction of one or more joints will not alter the coordinated action of the unaffected body segments, which is, at best, a tenuous assumption [63].

Other studies have used different methods to quantify the contribution of body segments to ball release speed. Elliott and colleagues [37] simply calculated the difference between peak resultant velocities of adjacent joint centres in the link segment system and expressed this difference as a percentage of the ball release speed. They reported that the run-up and pelvis rotation contributed 15 % of ball release speed, trunk flexion and thorax rotation 13 %, arm circumduction 50 %, and hand and finger flexion 22 %. Glazier and colleagues [19] adopted a similar approach but used peak horizontal velocities, instead of peak resultant velocities, of joint centres. They calculated that the run-up contributed 16 % of ball release speed, pelvis rotation 2 %, trunk flexion and thorax rotation 6 %, arm circumduction 62 %, and hand and finger flexion 14 %. More recently, Zhang and colleagues [62] used a velocity decomposition method, previously introduced by Sprigings and colleagues [64], to quantify body segment contributions for maximum-effort deliveries, normal deliveries and maximum lower trunk flexion deliveries. They calculated that the run-up contributed 8 %, pelvis rotation 12 %, thorax rotation and trunk flexion 29 %, arm circumduction 48 %, and forearm rotation and hand action 3 %. Despite some variation across the three conditions, body segment contributions were shown to remain relatively consistent.

Although the findings of Elliott and colleagues [37] and Glazier and colleagues [19] were broadly similar, they were somewhat different to those of Davis and Blanksby [35] and Zhang and colleagues [62], presumably due to the method of calculation rather than any systematic differences in bowling technique between study samples. In all four studies, however, the action of the bowling arm was consistently shown to be the most significant contributor to ball release speed. This finding can be explained by the fact that linear speed is a product of radial length and angular velocity and that the bowling arm represents the longest lever in the upper extremity link segment system.

2.3 Follow-Through

Most biomechanical analyses of fast bowling cease at, or immediately after, ball release. Accordingly, very little, if any, research has focused on the follow-through phase of the fast bowling action, which is typically defined as the period from ball release to one to three strides post-release. The follow-through has no bearing on ball release speed, although it may have implications for performance, in terms of avoiding encroaching on the protected area of the pitch, and injury, in the case of decelerating too abruptly.

3 Current Issues and Recommendations for Future Research on the Biomechanics of Cricket Fast Bowling Techniques

The empirical investigations reviewed in Sect. 2 provide some useful insights into the biomechanical factors that contribute to proficient fast bowling performance. However, it could be argued that this research has not substantially enhanced knowledge and has only had a very minor impact on coaching practice. In the following subsections, we offer some recommendations for future research that could help to improve biomechanical knowledge of fast bowling techniques, thereby enhancing the practical application of this work.

3.1 Greater Emphasis on Analysing 'Technique' Through the Use of Qualitative (Topological) Analysis Techniques

Paradoxically, sport biomechanists have not typically analysed 'technique'—defined by Lees [65] as the "… relative position and orientation of body segments as they change during the performance of a sport task to perform that task effectively" (p. 814)—in cricket fast bowling. Rather, they have tended to focus on isolated time-discrete kinematic variables (e.g. linear and angular displacements and velocities of body segments and joints) at key moments (e.g. maxima, minima, back foot impact, front-foot impact, ball release, etc.) during the delivery stride that are thought to be related to performance outcome. Consequently, researchers have been able to identify what time-discrete kinematic variables—typically known in the sports biomechanics literature as performance parameters [65]—are related, for instance, to ball release speed, but not what aspects of 'technique' underpin these performance parameters. A good example of this anomaly was evident in the study of Burden and Bartlett [40]. They reported that a strong linear relationship existed between the peak linear speed of the right hip joint centre and ball release speed but information about how the front leg and pelvis should interact to maximise this apparently important performance parameter for specific fast bowlers was not provided. In other words, this approach typically indicates *what* performance parameters are important but not *how* target values for these performance parameters are generated. The lack of information about inter-segmental interactions or coupling relationships that define 'technique' takes on even greater significance when one considers empirical evidence suggesting that coaches rely primarily on relative, rather than absolute, motion information when making subjective judgements about sports motions [66, 67].

One method of increasing understanding of the coordinative movement patterns adopted by fast bowlers is to apply various qualitative analytical techniques to time–continuous kinematic datasets. By qualitative, we do not mean the observation and subjective evaluation of movement sequences as is traditionally meant in sports biomechanics [68] and applied to cricket fast bowling by Hurrion and Harmer [69], but rather the study of geometric properties of movement as disclosed, for example, by the application of topological dynamics [70, 71]. Qualitative (topological) techniques form the basis for many of the coordination measures, such as continuous relative phase and vector coding (see Wheat and Glazier [72] for a review), that have been developed and applied in human movement science over the past few decades. In our view, sports biomechanists examining cricket fast bowling techniques would benefit from applying these qualitative techniques, particularly if they could be combined with kinetic and energetic analyses, such as those used by Ferdinands and colleagues [47], to establish which coordination patterns produce the most efficient transfer of kinetic energy and momentum along the kinematic chain for specific fast bowlers. Given that current biomechanical modelling approaches cannot identify individual-specific optimal sports techniques [73], this approach may help to distinguish between those aspects of technique that lead to successful performance outcomes, and those aspects that do not, for specific fast bowlers.

3.2 Need for Idiographic Rather than Nomothetic Research Designs

Traditionally, cross-sectional, group-based (nomothetic) research designs have been used in studies of cricket fast bowling, as they have been in performance-oriented sports biomechanics research more generally, largely because the aim of many investigations has been to make generalisable statements about the wider population of cricket fast bowlers. Two basic research designs have typically been adopted—the correlation approach and the contrast approach [74]. In the former, associations between the performance criterion (dependent variable) and the underlying performance parameters (independent variables) derived from a single homogenous group of fast bowlers are formally examined using relationship statistics (e.g. interclass correlation, regression). Conversely, in the latter, differences in the mean values of key performance parameters derived from two or more heterogeneous groups of fast bowlers are formally compared using mean difference statistics (e.g. *t* test, ANOVA). The majority of scientific investigations into fast bowling performance have used the correlation approach [15, 19, 21–23, 43, 47] and, in almost all of these studies, a single 'representative' or 'best' trial performed by each participant has typically been analysed.

Despite the widespread use of cross-sectional, group-based research designs in performance-oriented sports biomechanics research, they do have some limitations that restrict the application of their results in a practical context. First, the strategy of pooling performance parameter data to analyse central tendencies and dispersions often masks individual differences [75]. By using pooled group data, the focus is on establishing the 'average' response for the 'average' individual, which has the effect of de-emphasising the individual performer [76]. Second, the results they yield cannot necessarily be extrapolated to specific individuals of the study sample or to the population that they purportedly represent [77]. For example, taking the results of the aforementioned study by Burden and Bartlett [40], which were derived from a single group of elite fast bowlers, one may be tempted to conclude that a key coaching point for fast bowlers seeking to improve their performance would be to try to maximise the peak linear speed of the right hip joint centre given its direct relationship with ball release speed. However, in addition to not being able to specify how this outcome might be achieved, it is highly likely that any attempt to maximise the peak linear speed of the right hip joint centre will disrupt the coupling relationship between the pelvis and thorax segments, leading to an inefficient transfer of energy and momentum along the kinematic chain and, in all likelihood, a reduction in ball release speed and bowling accuracy.

To establish individual-specific coordination solutions that lead to high ball release speeds and increased accuracy, sports biomechanists analysing cricket fast bowling techniques should consider implementing more longitudinal, individual-based (idiographic) research designs [75, 76, 78]. This approach has not featured prominently in sports biomechanics literature to date mainly because of issues relating to a lack of generalisability, but as Bates and colleagues [78] pointed out, "It is important to note that single-subject analysis does not imply 'case study' investigation. Rather, it is an experimental technique that invokes an in-depth examination of individuals in order to better understand what unique movement characteristics, if any, they have in common" (p. 5). In other words, just because multiple trials performed by an individual fast bowler are analysed, it does not mean that they cannot or should not be compared with multiple trials performed by other fast bowlers. Indeed, Reboussin and Morgan [79] argued that many investigations described as single-subject analyses are, in actual fact, multiple single-subject analyses. By enabling commonalities and differences to be established both within and between subjects over repeated trials, multiple single-subject research designs can overcome some of the criticisms regarding generalisability often directed at single-subject research designs. New approaches, such as coordination profiling [80], which integrates qualitative (topological) analytical techniques with multiple single-subject designs, appear to hold much promise for enhancing knowledge of cricket fast bowling techniques.

3.3 Empirical Work Requires a Theoretical Basis

A criticism often directed at performance-related sports biomechanics research is that it has traditionally been descriptive rather than analytical, largely because it has lacked a theoretical basis [27, 81]. Indeed, this accusation could be directed, with some justification, at biomechanical investigations of cricket fast bowling techniques. Although fleeting reference has been made in the fast bowling literature to various 'biomechanical principles of movement' (e.g. proximal-to-distal sequencing, utilisation of elastic energy, maximisation of acceleration path, etc.), which are based on simple mechanical relationships, multi-segment interactions, and the structural and functional characteristics of the neuromuscular system (see Lees [65] for a summary), sustained systematic investigation of their role in proficient fast bowling performance has been rare.

Recently, Chow and Knudson [82] recommended that deterministic models, which are putatively based on the well-established principles of Newtonian mechanics, could provide a strong theoretical basis for future performance-related sports biomechanics research and help avoid the selection of arbitrary and meaningless performance parameters. However, despite being widely promoted in key biomechanics textbooks (e.g. Hay and Reid [83] and Bartlett and Bussey [84]) and various review articles (e.g. Yeadon and Challis [85] and Lees [86]) over the past three decades, the use of deterministic models has not been widespread and they have yet to feature in the scientific literature on cricket fast bowling. An example of a deterministic model as applied to cricket fast bowling is shown in Fig. 2.

One of the reasons why deterministic models have not been widely used, which has also greatly restricted their application in a practical context, is that they typically specify performance parameters that provide little information about 'technique'. That is, they are able to identify factors that are relevant to performance but not necessarily aspects of technique (i.e. coordinative movement patterns) relevant to those factors [65]. It could be argued, as Glazier and Robins [87] did, that deterministic models may have contributed, at least in part, to the lack of advancement in performance-oriented sports biomechanics as they have encouraged sports biomechanists to go in search of independent variables that are statistically associated with the performance outcome rather than attending to the more important task of establishing the causative mechanisms and processes that produce these variables. In principle, a range of different, but equally functional, coordinative movement patterns could be used to produce similar performance parameter values, both within and between fast bowlers. In this regard, then, although the relationships between performance parameters on adjacent levels of the model are determinate, the manner in which body segments interact to produce these performance parameter values may be profoundly indeterminate.

Over the past decade, dynamical systems theory has received increased exposure in the sport and human movement science literature and has been proposed as a viable theoretical framework for applied sports biomechanics research [88–90]. A key proposition of dynamical systems theory is that coordinative movement patterns are an emergent property of ubiquitous self-organising processes and the confluence of interacting organismic, environmental and task constraints [91]. Accordingly, any variability in technique within and between fast bowlers should not, by default, be deemed as error or noise but instead be viewed as a potentially functional adaptation to internal and external constraints. For this reason, the 'one-size-fits-all' or 'common optimal movement pattern'

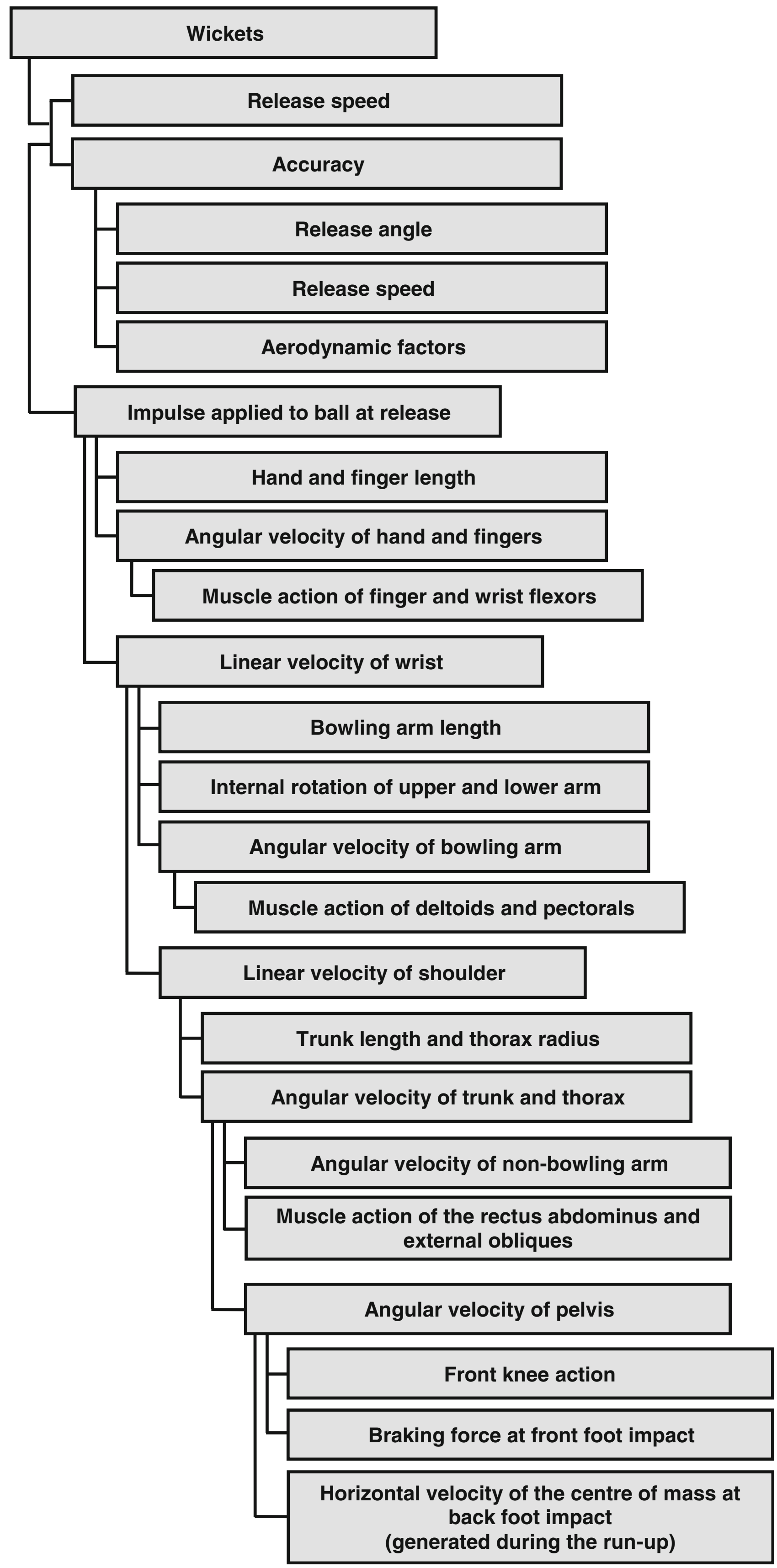

Fig. 2 A deterministic model of cricket fast bowling. The performance criterion (i.e. the result or outcome of performance) is identified at the top of the model and the performance parameters (i.e. the mechanical factors) that determine the performance outcome are listed below it. The performance parameter on each tier of the model should be completely determined by the performance parameters listed below it. Although this model does not strictly conform to the criteria set out by Hay and Reid [83] for constructing hierarchical performance models, it does provide an indication of the mechanical factors that are likely to be related to performance in cricket fast bowling

approach advocated by many practitioners and coaching texts should be abandoned in favour of encouraging fast bowlers to develop their own individual-specific movement solutions [92]. If this perspective is to be accepted, however, a key challenge for applied sports biomechanists is diagnosing and remediating faults in the techniques of specific fast bowlers—a task made more complicated by virtue of there being no template or criterion technique to make direct comparisons against. Indeed, it could be argued that this is *the* main challenge for applied sport biomechanists working to improve the techniques of high-performance athletes. The analytical techniques, research designs and theoretical framework outlined in this section may help sports biomechanists meet this challenge.

4 Conclusion

In this paper, a state-of-the-art review of the scientific literature on the biomechanical aspects of fast bowling performance is provided and several issues restricting the practical application of extant research are highlighted. The almost exclusive use of cross-sectional, group-based research designs, where the emphasis has been on the pooling of performance parameter data to analyse differences and relationships in key performance parameters, has tended to mask differences between individual fast bowlers. The obscuring of individual differences is an important issue that requires attention given that individuality of fast bowling techniques has become a 'hot topic' amongst coaches recently [93, 94]. Moreover, the emphasis on the quantitative analysis of time-discrete performance parameters has generally precluded insights from being made into the qualitative aspects of 'technique' (i.e. coordinative movement patterns). Further research is required to understand the causative mechanisms and processes producing these performance parameter measures for individual fast bowlers, but if this aim is to be realised, the reductionist, nomothetic (group-based), product-oriented approach habitually used in sports biomechanics needs to be superseded by a more appropriate research strategy. The holistic, idiographic (individual-based), process-oriented approach (e.g. coordination profiling) advocated by proponents of dynamical systems theory appears to be particularly well-suited to this research endeavour and promises much in terms of enhancing knowledge of cricket fast bowling techniques and increasing the impact of this research work on practice.

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