Sports Technology, 2014
http://dx.doi.org/10.1080/19346182.2014.893351

Routledge
Taylor & Francis Group

RESEARCH ARTICLE

The impact of centre of mass kinematics and ground reaction forces on ball release speeds in cricket fast bowling

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(*Received 27 August 2013; accepted 4 February 2014*)

Abstract
The aims of this study were to verify previously reported relationships between whole-body centre of mass kinematics and ball release speed, and establish whether the 'checking of linear motion' or 'hinged-moment' principle is a valid biomechanical principle governing cricket fast bowling. Three-dimensional, full-body kinematic and ground reaction force data were collected from a group of 20 male high-performance English fast bowlers using an 18-camera Vicon® M^2 MCam motion capture system and an interfaced Kistler® 9287B force platform. Ball release speed was found to be moderately correlated with the horizontal velocity of the centre of mass at back foot contact ($r = 0.499$, $p = 0.025$), the average horizontal acceleration of the centre of mass during the front foot contact to ball release phase ($r = -0.544$, $p = 0.013$), the change in horizontal velocity of the centre of mass during the front foot contact to ball release phase ($r = 0.658$, $p = 0.002$), but not the duration of the front foot contact to ball release phase ($r = -0.307$, $p = 0.188$). These results suggest that it is the magnitude of centre of mass velocity reduction during the front foot contact to ball release phase, rather than the duration over which this reduction occurs, that is important in the generation of high ball release speeds. In addition, the resultant ground reaction force vector was found to act in front of the centre of mass for most bowlers during the front foot contact to ball release phase, indicating that the 'checking of linear motion' or 'hinged-moment' principle is unlikely to be a valid biomechanical principle governing cricket fast bowling.

Keywords: *run-up, biomechanics, horizontal velocity, delivery stride, hinged-moment*

Abbreviations: ANOVA, analysis of variance; BFC, back foot contact; BR, ball release; BRS, ball release speed; BW, bodyweight; COM, centre of mass; COP, centre of pressure; FFC, front foot contact; FFF, front foot flat; HMA, hinged-moment angle; RGRF, resultant ground reaction force; RGRFV, resultant ground reaction force vector

1. Introduction

The run-up is widely considered to be an important component of successful fast bowling in cricket. Many coaching texts (e.g. Bradman, 1958; Lillee, 1977; Pont, 2006) emphasise the need for a smooth and rhythmical run-up so that the bowler arrives at the delivery stride well balanced and correctly orientated to enable him or her to release the ball at high speed and with great accuracy. The run-up has also received coverage in the scientific literature but most empirical studies that have considered this aspect of fast bowling have been limited in scope and have typically only reported run-up speed during the pre-delivery stride or at BFC (see abbreviations) and its relationship to BRS (Duffield, Carney, & Karppinen, 2009; Glazier, Paradisis, & Cooper, 2000; Stockill & Bartlett, 1992). All of these studies reported moderate to strong correlations between run-up speed and BRS ($r = 0.55–0.73$), although a limited calibration volume in the study of Stockill and Bartlett (1992) and small sample size of nine and six bowlers in the studies of Glazier et al. (2000) and Duffield et al. (2009), respectively, suggest that these results should be interpreted with caution.

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Recently, Ferdinands, Marshall, and Kersting (2010) analysed 34 fast bowlers to establish the relationship between whole-body COM kinematics during the delivery stride and BRS. As in previous studies, they reported a strong correlation between COM velocity at BFC and BRS ($r = 0.58$, $p < 0.001$). When the study sample was divided into sub-groups according to BRS, bowlers in the fast and medium-fast groups were shown to have faster COM velocities at BFC ($5.46 \pm 0.43\,\mathrm{m \cdot s^{-1}}$ and $5.58 \pm 0.29\,\mathrm{m \cdot s^{-1}}$, respectively) than bowlers in the medium group ($5.18 \pm 0.61\,\mathrm{m \cdot s^{-1}}$) and significantly ($p < 0.05$) faster COM velocities than bowlers in the slow-medium group ($4.62 \pm 0.67\,\mathrm{m \cdot s^{-1}}$). Perhaps the most notable finding of this study, however, was that average COM acceleration during the period between BFC and FFC and between FFC and BR both had significant ($p < 0.02$) moderate to strong correlations with BRS ($r = -0.62$ and $r = -0.42$, respectively). Furthermore, stepwise multiple linear regression indicated that COM deceleration over the delivery stride phase was the strongest predictor of BRS in the two fastest sub-groups. However, despite collecting ground reaction force data and full-body kinematics, potential biomechanical mechanisms responsible for COM deceleration were not explored.

One theoretical principle that has yet to be validated in cricket fast bowling, which may be instrumental in COM deceleration and the transfer of energy and momentum to the bowler's upper extremities, is the 'checking of linear motion' or 'hinged-moment' principle (Dyson, 1978). This little-known biomechanical principle suggests that ground reaction forces generated during the FFC-BR phase can be used to decelerate the lower body whilst causing the trunk and bowling arm to accelerate around the front leg and foot (Bartlett, 2000). For this principle to be valid, however, Alexander (1992) argued that the RGRFV should act behind the bowler's COM, not in front of, or through, it, presumably to produce the torque required to induce forward rotation about the COM. Of the few studies that have reported ground reaction forces in cricket fast bowling (e.g. Elliott & Foster, 1984; Elliott, Foster, & Gray, 1986; Hurrion, Dyson, & Hale, 2000; Mason, Weissensteiner, & Spence, 1989; Portus, Mason, Elliott, Pfitzner, & Done, 2004), none has described how the magnitude and direction of the RGRFV changes during the delivery stride or how COM kinematics are related to these changes.

The main aim of the current study was to establish whether the significant negative relationship between COM acceleration during the delivery stride and BRS previously reported by Ferdinands et al. (2010) could be replicated in a group of high-performance fast bowlers who produced higher BRSs and, if so, how COM deceleration was influenced by various lower extremity kinematic and kinetic (ground reaction force) variables derived from the lower extremities. A further aim of this study was to establish whether there is a relationship between the magnitude and direction of the RGRFV and COM kinematics during the delivery stride, thereby enabling the validity of the 'checking of linear motion' or 'hinged-moment' principle in cricket fast bowling to be determined.

2. Method

2.1 Participants

Twenty high-performance male fast bowlers (mean ± SD: age = 20.1 ± 2.6 years; height = 1.88 ± 0.08 m; body mass = 81.5 ± 7.1 kg) were selected to participate in this study. All bowlers had either represented England at senior or under-19 level or were a professional first-class cricketer with the potential to play for the senior England team within 3 to 5 years. All bowlers were injury-free and had been involved in regular match-play or practice leading up to data collection. Prior to data collection, all bowlers were briefed about the testing procedures, which had previously been approved by the Loughborough University Ethical Advisory Committee, and informed consent forms were signed. Each bowler was instructed to undertake a thorough warm-up prior to data collection.

2.2 Data collection

All data were collected at the England and Wales Cricket Board National Cricket Performance Centre based at Loughborough University. The dimensions of this purpose-built indoor cricket facility were sufficient to enable each bowler to use their normal, full length, run-up and bowl test deliveries on a standard size cricket pitch. Each bowler was fitted with 47 × 14 mm retro-reflective markers, which were temporarily adhered to prominent anatomical landmarks (Figure 1) and used to estimate joint centres of rotation as well as enabling the position and orientation of body segments to be calculated. An additional marker, a 15 × 15 mm patch of 3M Scotch-Lite reflective tape, was attached to the ball to enable the instant of BR and BRS to be calculated. Ninety-five anthropometric measurements, as described by Yeadon (1990), were also taken from each bowler to calculate personalised inertia parameters and whole-body COM.

Six maximum-effort deliveries of 'good length' (i.e. deliveries that either hit, or just passed over, the top of the off stump) were then captured for each bowler using an 18-camera Vicon® M^2 MCam motion capture system (OMG Plc, Oxford, UK)

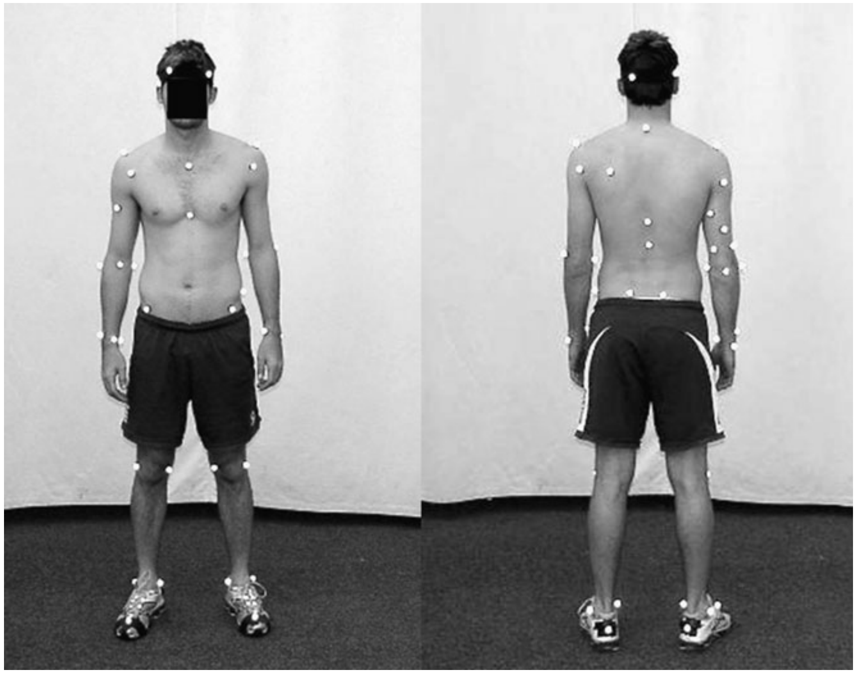

Figure 1. A bowler fitted with a full-body marker-set consisting of 47 × 14 mm retro-reflective markers.

operating at 300 Hz. The cameras were positioned such that they yielded a capture volume of approximately 7 × 3 × 3 m (63 m^3). A Kistler® 9287B force platform(Kistler Instruments AG, Winterthur, Switzerland), measuring 900 × 600 mm and operating at 1008 Hz, was used to collect ground reaction force data during the FFC phase. The force platform was mounted in a recessed pit located beneath the location of FFC and was covered with a layer of artificial grass that was 25 mm in thickness.

2.3 Data processing

The three fastest deliveries with acceptable marker visibility for each bowler were manually labelled and processed using Vicon® Workstation software (OMG Plc, Oxford, UK). The ankle, knee, shoulder, elbow and wrist joint centres of rotation were calculated as the mid-point between two markers positioned either side of the respective joints. The hip joint centres were calculated from markers placed over the left and right anterior superior iliac spine and the left and right posterior superior iliac spine (Davis, Ounpuu, Tyburski, & Gage, 1991). Lower and upper trunk motions were defined using the four markers on the pelvis in addition to markers placed over the cephalad and caudad ends of the sternum and the spinous processes of L1, T10 and C7.

The instants of BFC, FFC and FFF were identified using the motions of the markers on the foot (Figure 2). Ground contact was defined as the first frame in which the foot's motion was visually observed to change due to contact with the ground. FFF corresponded to the first frame in which the forefoot was on the ground. BR was identified using the time-history of the distance between the ball

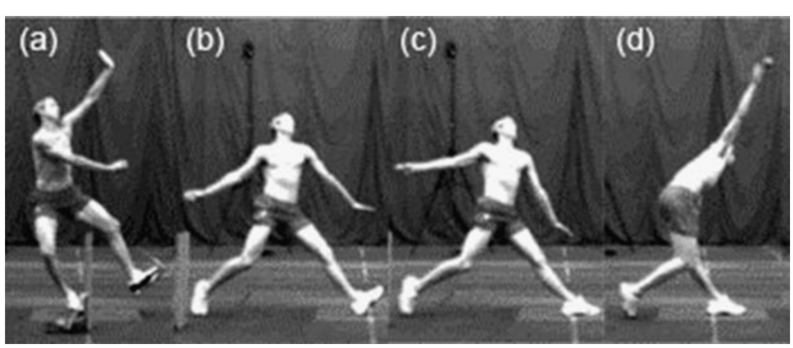

Figure 2. Key instants during the delivery stride: (a) BFC, (b) FFC, (c) FFF and (d) BR. The delivery stride (BFC-BR) was sub-divided into two phases: the BFC-FFC phase and the FFC-BR phase.

marker and the mid-point of a pair of markers placed over the wrist. The frame corresponding to BR was defined as the first frame in which this distance increased by more than 20 mm relative to the distance in the previous frame. All marker trajectories were filtered using a recursive fourth-order low-pass Butterworth filter with a cut-off frequency of 30 Hz determined using the residual analysis method described by Winter (2009). COM kinematics for both the BFC-FFC and FFC-BR phases for each bowler were interpolated using a cubic spline and time normalised to 101 data points so that the start and end of each phase were represented as 0% and 100%, respectively.

Local reference frames were defined comprising a three-dimensional full-body 18-segment representation of a bowler (head and neck; upper trunk; lower trunk; pelvis; 2 × upper-arm; 2 × lower-arm; 2 × hand; 2 × upper-leg; 2 × lower-leg; and 2 × two-segment foot). These reference frames were defined using three markers on the segment itself, allowing segment orientations and joint angles to be calculated. A global coordinate system was defined with the y-axis pointing down the pitch (towards the batsman), the x-axis pointing to the right and the z-axis representing the upwards vertical. Ground reaction force data remained unfiltered and the coordinate axes of the force platform were coincident with the global coordinate system.

2.4 Data analysis

The following kinematic variables were calculated for each bowler and their correlations with BRS assessed (all velocity and acceleration variables were measured with respect to the global y-axis):

- Horizontal velocity of the COM at BFC
- Horizontal velocity of the COM at FFC
- Horizontal velocity of the COM at BR
- Average horizontal COM acceleration during the BFC-FFC phase
- Average horizontal COM acceleration during the FFC-BR phase
- Change in horizontal velocity of the COM during the BFC-FFC phase
- Change in horizontal velocity of the COM during the FFC-BR phase
- Duration of the BFC-FFC phase
- Duration of the FFC-BR phase

To establish whether the 'checking of linear motion' or 'hinged-moment' principle is a valid biomechanical principle governing cricket fast bowling, the HMA, defined as the angle between the RGRFV and the vector adjoining the COP and the COM during the FFC-BR phase, was calculated (Figure 3). A positive HMA indicated that the RGRFV was acting in front of the COM whereas a negative HMA indicated that the RGRFV was acting behind the COM.

All statistical analyses were performed using Statistical Package for the Social Sciences v.17 (SPSS® Corporation, Chicago, USA). The variation observed in each parameter from the three trials was assessed using an ANOVA. For the parameters calculated in this study there was an intra-class correlation coefficient of 0.74–0.97 (mean 0.91) using the method of Donner and Koval (1980). As there was good between-trial repeatability for all parameters (Norton et al., 2000), the three trials analysed were averaged to provide representative data for each bowler. Relationships between kinematic variables and BRS were formally assessed using two-tailed Pearson's product-moment correlation coefficients, which were deemed to be significant at $p < 0.05$. The underpinning assumptions of this statistical test were assessed and no evidence was found to indicate that they had been violated.

3. Results

The range of BRSs obtained from the sample of 20 high-performance fast bowlers was 32.8–39.7 m·s^{-1} (mean ± SD: 34.9 ± 1.7 m·s^{-1}). Means, SDs and ranges for selected COM kinematic variables are presented in Table I along with Pearson's product-moment correlation coefficients (r-values) and probability statistics (p-values).

Ensemble mean ± SD time-normalised plots for the horizontal velocity of the COM, the HMA and the RGRF during the FFC-BR phase across the 20 bowlers, are shown in Figure 4. The minimum mean HMA (3.4°) and maximum mean RGRF (6.40 BWs) occurred almost simultaneously at 26% and 29% of the FFC-BR phase, respectively.

In total, 9 of the 20 bowlers analysed exhibited negative HMAs and the percentage of the FFC-BR phase during which the RGRFV was acting behind the COM ranged from 2%–23% (mean ± SD: 7.9 ± 6.9%). Of these nine bowlers, only three had maximum negative HMAs exceeding −2°. Figure 5 shows synchronous HMA and RGRF time-normalised plots over the FFC-BR phase for these three bowlers. The RGRF that coincided with the maximum negative HMA for each bowler, when expressed as a percentage of the maximum ground reaction force during the FFC-BR phase, was 36.3% (top), 49.6% (middle) and 70.2% (bottom).

4. Discussion

The aims of the current study were to verify previously reported relationships between COM kinematics and BRS, as well as establish whether

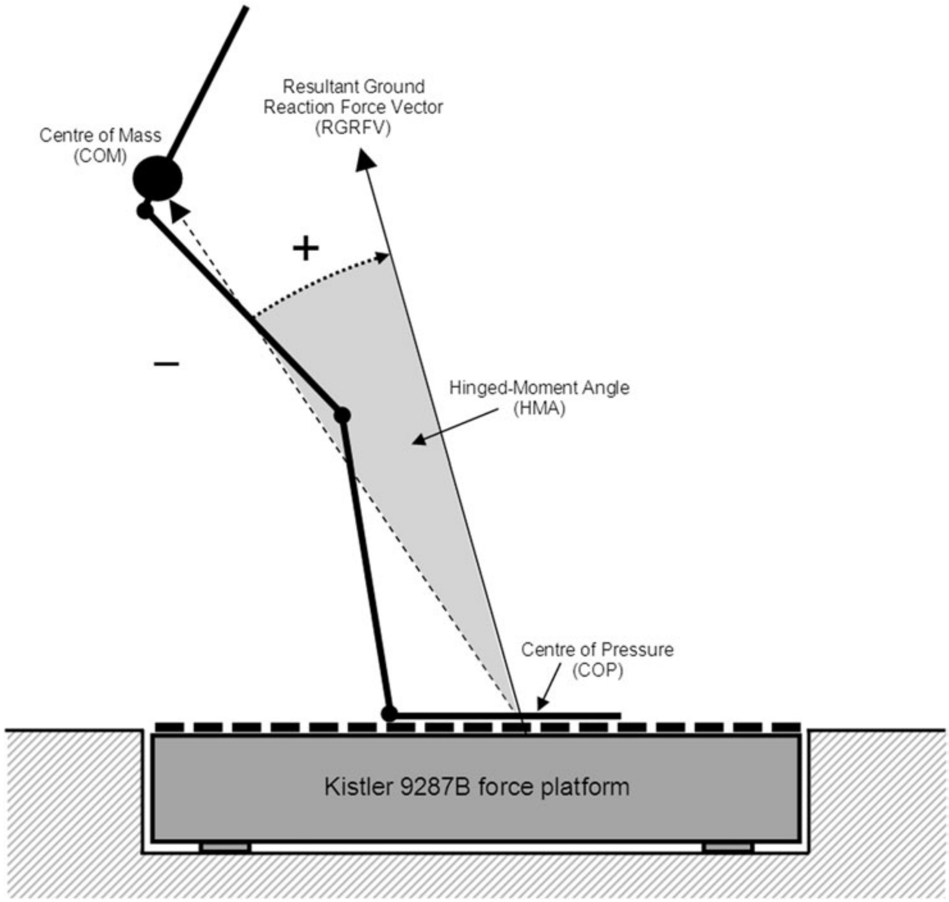

Figure 3. The hinged-moment angle (HMA).

the 'checking of linear motion' or 'hinged-moment' principle is a valid biomechanical principle governing cricket fast bowling. Findings relating to each of these aims are considered in Sections 4.1 and 4.2, respectively.

4.1 Relationships between centre of mass kinematics and ball release speed

The majority of the findings in the current study support those previously reported in the literature. The horizontal velocity of the COM at BFC was found to be significantly correlated with BRS, thus corroborating the results of Stockill and Bartlett (1992), Glazier et al. (2000) and Ferdinands et al. (2010). Furthermore, the horizontal velocity of the COM at FFC was significantly correlated to BRS as also shown by Ferdinands et al. (2010). No significant relationship was found between BRS and the horizontal velocity of the COM at BR, which was consistent with the findings of Burden and Bartlett (1990) and Ferdinands et al. (2010).

Table I. COM kinematic variables and their relationship to BRS.

Variable	Range	Mean ± SD	r	p
Horizontal velocity of the COM at BFC ($m \cdot s^{-1}$)	4.77 to 6.76	5.79 ± 0.58	0.499	0.025
Horizontal velocity of the COM at FFC ($m \cdot s^{-1}$)	4.35 to 6.25	5.20 ± 0.54	0.508	0.022
Horizontal velocity of the COM at BR ($m \cdot s^{-1}$)	2.94 to 4.50	3.69 ± 0.40	0.075	0.754
Average horizontal COM acceleration during the BFC-FFC phase ($m \cdot s^{-2}$)	−0.97 to −6.21	−3.01 ± 1.40	−0.181	0.444
Average horizontal COM acceleration during the FFC-BR phase ($m \cdot s^{-2}$)	−7.21 to −55.18	−34.78 ± 14.12	−0.544	0.013
Change in horizontal velocity of the COM during the BFC-FFC phase ($m \cdot s^{-1}$)	−0.17 to −1.28	0.60 ± 0.27	0.102	0.668
Percentage change in horizontal velocity of the COM during the BFC-FFC phase (%)	−3.5 to −21.5	10.2 ± 4.3	–	–
Change in horizontal velocity of the COM during the FFC-BR phase ($m \cdot s^{-1}$)	−0.74 to −2.22	1.51 ± 0.37	0.658	0.002
Percentage change in horizontal velocity of the COM during the FFC-BR (%)	−16.9 to −37.5	28.8 ± 5.9	–	–
Duration of the BFC-FFC phase (s)	0.12 to 0.24	0.19 ± 0.032	0.184	0.437
Duration of the FFC-BR phase (s)	0.08 to 0.12	0.10 ± 0.011	−0.307	0.188

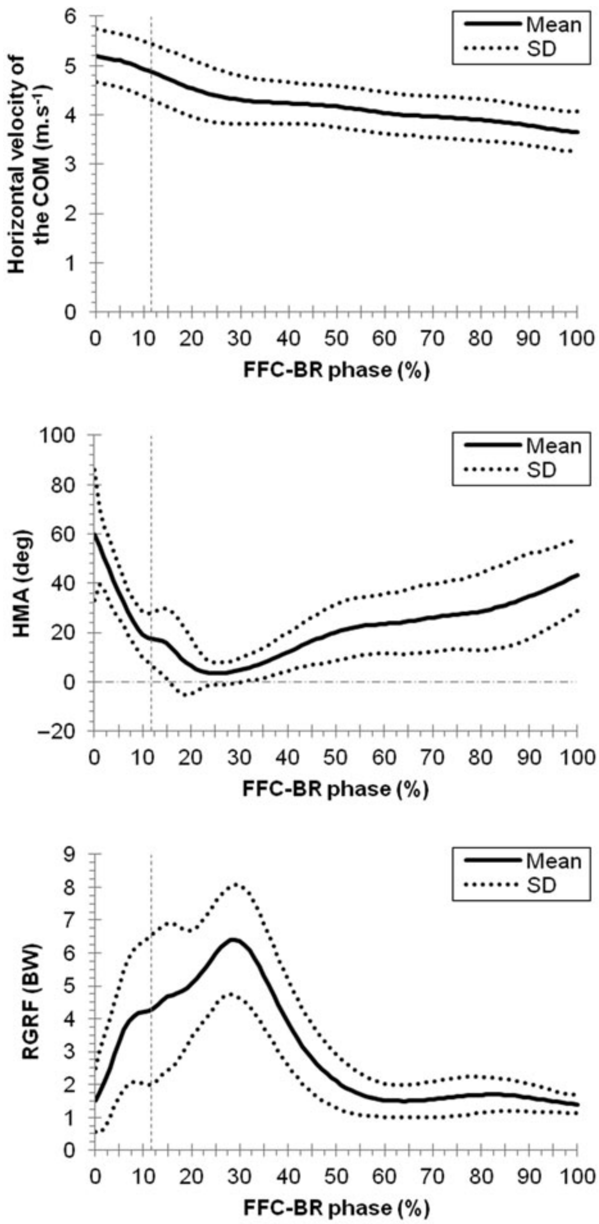

Figure 4. Ensemble mean ± SD of the horizontal velocity of the COM (top), HMA (middle) and RGRF (bottom) during the FFC-BR phase across the 20 bowlers (zero reference line = horizontal dash dot line; FFF = vertical dash line).

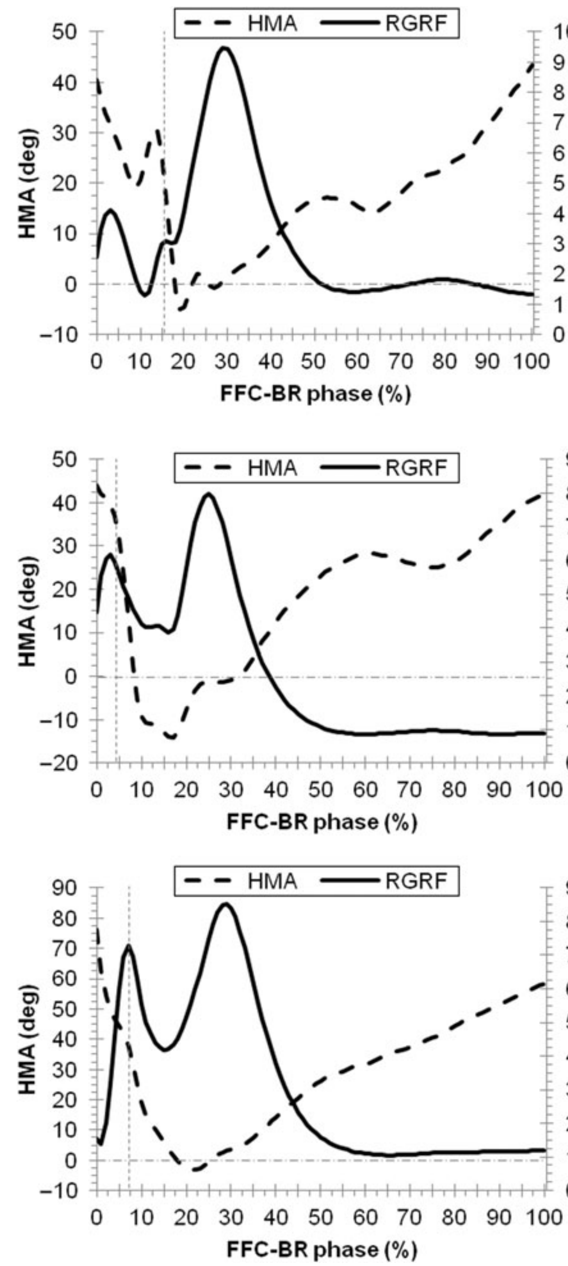

Figure 5. HMAs and RGRFs during the FFC-BR phase for the three bowlers who exhibited maximum negative HMAs exceeding −2° (zero reference line = horizontal dash dot line; FFF = vertical dash line).

In contrast to the results of Ferdinands et al. (2010), no significant negative relationship was found between BRS and average horizontal COM acceleration during the BFC-FFC phase. However, there was a significant negative relationship between BRS and average horizontal COM acceleration during the FFC-BR phase. These findings suggest that the FFC-BR phase is the most important phase of delivery stride and as such the mechanics of the front leg and the geometry of ground reaction forces need to be closely considered. Further analysis revealed a significant relationship between BRS and the change in the horizontal velocity of the COM during the FFC-BR phase but not between BRS and the duration of the FFC-BR phase. These results suggest that it is the magnitude of COM velocity reduction during the FFC-BR phase, rather than the duration over which this reduction occurs, that is important in the generation of high BRSs.

In the study of Ferdinands et al. (2010), 9 bowlers were classified as fast ($>33.3\,\mathrm{m\cdot s^{-1}}$), 10 as medium-fast ($31.9-33.3\,\mathrm{m\cdot s^{-1}}$), 8 as medium ($30.6-31.9\,\mathrm{m\cdot s^{-1}}$) and 7 as slow-medium

($< 30.6\,\mathrm{m \cdot s^{-1}}$). Interestingly, when Ferdinands et al. (2010) systematically removed the slowest groups (i.e. slow-medium, slow-medium and medium, etc.) from their sample, the strength of the negative correlation between BRS and average horizontal COM acceleration, especially over the FFC-BR phase, tended to diminish and become non-significant. The results of the current study, which were derived from 17 fast bowlers and only 3 medium-fast bowlers, according to the criteria of Ferdinands et al. (2010), suggest that the negative relationship between BRS and average horizontal COM acceleration over the FFC-BR phase is robust at higher BRSs and that the non-significant results of Ferdinands et al. (2010) may be attributable to a sampling artefact (i.e. the narrower range and smaller variability of BRSs in that study could have contributed to the non-significant negative correlations that were reported).

4.2 Changes in the hinged-moment angle during the front foot contact to ball release phase

For the ‘checking of linear motion’ or ‘hinged-moment’ principle to be a valid biomechanical principle governing cricket fast bowling, the RGRFV should act behind the bowler’s COM, not in front or through it (Alexander, 1992). The ensemble mean profile (Figure 4) indicates that, on average, this sample of fast bowlers did not exhibit a negative HMA during the FFC-BR phase, although peak RGRF and minimum HMA did occur almost simultaneously. When individual bowlers were analysed, 9 of the 20 bowlers exhibited a negative HMA but the percentage of the FFC-BR phase during which the RGRFV acted behind the COM was comparatively short for most bowlers. Furthermore, of these nine bowlers, only three bowlers exhibited a maximum negative HMA exceeding $-2°$. Interestingly, for these three bowlers, the magnitude of the RGRF coinciding with the maximum negative HMA was generally small relative to, and non-coincident with, the peak RGRF recorded during the FFC-BR phase (Figure 5). When considered together, these findings suggest the ‘hinged-moment’ principle is unlikely to be a valid biomechanical principle governing cricket fast bowling. These results also appear to corroborate with those of other force platform studies of biomechanically similar sports actions, such as javelin throwing (e.g. Deporte & van Gheluwe, 1988), which have indicated that the RGRFV tends to act in front of the COM during periods of the delivery stride where ground reaction forces are at their largest. However, these studies are extremely limited in number and further research is required to verify these conclusions.

5. Conclusion

This study found that BRS was linearly related to the horizontal velocity of the COM at both BFC and FFC, the average horizontal deceleration of the COM during the FFC-BR phase and the change of horizontal velocity during the FFC-BR phase, but not the duration of the FFC-BR phase for this group of high-performance fast bowlers. These results suggest it is the magnitude of COM velocity reduction during the FFC-BR phase, rather than the duration over which this reduction occurs, that is important in the generation of high BRSs. Although little evidence was found to support the ‘checking of linear motion’ or ‘hinged-moment’ principle as a valid biomechanical principle governing cricket fast bowling, this study represents one of the few cricket-related biomechanical studies that is underpinned by strong theoretical rationale and it is recommended that future research on performance aspects of cricket fast bowling follows this lead (see Glazier & Wheat, 2014, for a commentary on this state-of-affairs). Future research could focus on examining the relationship between the geometry of the ground reaction forces and the transfer of energy and momentum along the kinematic chain. To increase the practical application of this work, it is recommended that more individual-based research designs are adopted since findings derived from group-based research designs may not necessarily apply to individual fast bowlers (see Bouffard, 1993).

Acknowledgements

This study was partly funded by the England and Wales Cricket Board.

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