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The effect of marker placement around the elbow on calculated elbow extension during bowling in cricket

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ABSTRACT

The elbow extension angle during bowling in cricket may be calculated from the positions of markers attached around the shoulder, elbow and wrist using an automated laboratory based motion analysis system. The effects of two elbow marker sets were compared. In the first a pair of markers was placed medially and laterally close to the condyles while in the second a triad of markers was placed on the back of the upper arm close to the elbow. The root mean square (RMS) difference in elbow extension angle between the two methods at four key instants was 8° for 12 fast bowlers and 4° for 12 spin bowlers. When evaluated against video estimates of the elbow extension angle for the fast bowlers, the elbow extension angle calculated using the pair method had an RMS error of 2° while the triad method had an RMS error of 8°. The corresponding errors for the spin bowlers were 3° and 5° respectively. It is thought that the greater errors associated with the triad is a consequence of soft tissue movement in this dynamic activity. This is consistent with the finding of greater error for the fast bowlers compared with the spin bowlers.

INTRODUCTION

If the elbow extends by more than 15° during a bowling delivery in cricket, the bowling action is considered to be illegal since it includes an element of throwing. The ICC regulations (ICC, 2010) for a legal bowling action currently permit the elbow to extend by up to 15° during the period between the upper arm being horizontal and the instant of ball release (not including any elbow abduction angle changes or elbow hyperextension). If an umpire or match referee in international cricket suspects a bowler of using an illegal bowling action then the International Cricket Council (ICC) will arrange for an independent analysis of the bowler's action to be carried out by an approved human movement specialist under laboratory conditions (ICC, 2010). This will involve the calculation of the elbow extension angle during the bowling action from the locations of retro-reflective markers placed on the bowling arm using an automated motion analysis system.

A protocol was developed by the University of Western Australia (Lloyd, Alderson, & Elliott, 2000) using three markers located centrally on the upper arm and two markers located centrally on the forearm in order to determine the relative orientation of the two arm segments during bowling. While such a protocol involving a centrally located upper arm triad may be appropriate for the analysis of gait in a clinical situation, bowling in cricket is a very dynamic activity in which there is considerable soft tissue movement. As a consequence the protocol was modified by changing from central marker placement in favour of small marker triads positioned on the upper arm near the shoulder and elbow in order to reduce the effect of soft tissue movement on marker movement (Campbell, Alderson, Lloyd, & Elliott, 2009). Eftaxiopoulou, Gupte, Dear and Bull (2013) found that a triad close to the elbow produced more repeatable results than a mid-arm marker triad. Alternative marker placements were described by King and Yeadon (2012) in which pairs of markers

were positioned across the shoulder, elbow and wrist. These upper arm marker placements were chosen in order to be as far away as possible from the soft tissue movement in the central upper arm. As well as changing marker placements, attempts have been made to reduce the effects of soft tissue movement but this approach has had limited success (Zhang, Lloyd, Campbell, & Alderson, 2011).

The original triad based method (Lloyd et al., 2000) was evaluated by Elliott, Alderson and Denver (2007) who placed markers on a robotic arm and found angle errors of 0.6° although this did not account for soft tissue movement. The pairs based method has been quantitatively evaluated by comparing calculated elbow extension angles with those obtained from digitising high speed video images of bowling at ball release when the elbow axis was approximately parallel to the video camera axis (King and Yeadon, 2012). The mean deviation of 12 fast bowling deliveries from the video elbow extension values was $0^\circ \pm 2^\circ$.

For both methods the calculation of the elbow extension angle is dependent on the location of the elbow axis that is calculated using the condyle marker pair (or a reconstructed pair in the case of the triad method). Any misalignment of the calculated elbow axis from this pair of markers with only small separation will result in cross-talk between elbow extension and elbow abduction. By contrast, the directions of the long axes of upper and lower arms are based upon points (joint centre estimates) that have much greater separation and are therefore likely to produce smaller errors in the elbow extension angle. Such errors arising from mislocation of joint centres will be around twice as large for the elbow than for either the shoulder or wrist since an error in elbow centre location will affect the alignment of both the upper arm and forearm. In order to have only one difference between the two marker sets it was decided to restrict this investigation to differences in marker placement at the elbow.

This paper aims to identify the differences in calculated elbow extension angles using pairs of markers at the shoulder and wrist together with (a) a pair of markers near the condyles and (b) a triad of markers on the back of the upper arm close to the elbow to determine the elbow axis. The accuracy of each method will be assessed independently from video images, and possible reasons for the differences and errors will be identified.

METHODS

Twelve elite male fast bowlers (age 18.9 ± 2.5 years; height 1.89 ± 0.08 m; mass 90.5 ± 11.8 kg) and twelve elite male spin bowlers (age 23.6 ± 2.7 years; height 1.78 ± 0.04 m; mass 77.2 ± 9.1 kg) participated in this investigation. All bowlers were members of the England and Wales Cricket Board (ECB) elite squads. All bowlers were deemed fit to bowl by their county or national team physiotherapist. The testing procedures were explained to each bowler and informed consent was obtained in accordance with the guidelines of the university ethics committee. All bowlers conducted a thorough warm-up before data collection.

Nine, 14 mm diameter, spherical reflective markers were attached to the bowling arm using aerosol sports adhesive and double-sided tape along with a piece of reflective tape (≈ 1.5 cm square) attached to one side of the cricket ball. At the wrist a pair of markers were positioned near the styloid processes such that the midpoint of the pair of markers lay on the midline of the lower arm (Figure 1). At the elbow a pair of markers were positioned vertically above the medial and lateral elbow epicondyle bony landmarks (when the arm was horizontal and extended with the

palm of the hand facing upwards) so that the midpoint of the pair of markers lay on the midlines of the upper arm and lower arm (Figure 1). At the shoulder a pair of markers were positioned (anterior and posterior to the shoulder) with the arm overhead so that the line joining these markers intersected the midline of the upper arm (Figure 1). A weighted average of the two shoulder markers was used to identify the midline of the upper arm using a photograph of the bowling arm with the arm overhead for each bowler (King and Yeadon, 2012). A small triad of markers (approximately 60 mm between markers) was positioned on the posterior side of the upper arm close to the elbow (Figure 1). The nine markers on the bowling arm were used to create two marker sets. The first marker set (pair) consisted of the three pairs of markers. The second marker set (triad) used the same pairs of markers at the wrist and shoulder, along with a virtual pair of markers at the elbow. The virtual markers were reconstructed from the triad of markers on the upper arm; the location of the virtual pair of markers relative to the triad was defined in a static calibration trial using the actual marker pair with the arm extended overhead.

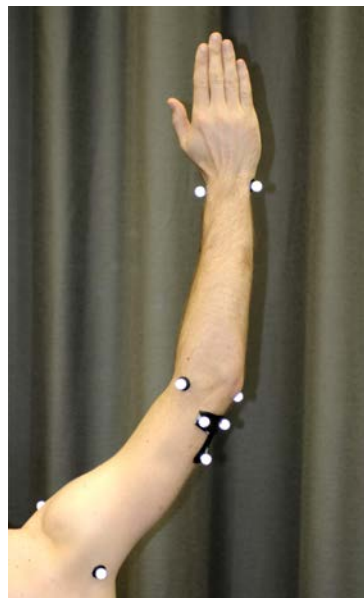


Figure 1. Reflective marker locations.

Each bowler performed six standard deliveries of good length and three bowler calibration trials; these were recorded using an 18 camera (M² M²Cam) Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 300 Hz. The Vicon cameras were positioned around the bowling crease to cover a 7 m × 3 m × 3 m volume that was wand calibrated prior to data collection. In addition high speed video (300 Hz) of the bowling trials was recorded from rear and side views. Data were collected at the England and Wales Cricket Board National Cricket Performance Centre indoor practice facility, allowing all bowlers to use a full length run-up on a standard sized artificial cricket pitch. The three calibration trials comprised: a static “straight arm trial” with the arm overhead, an “elbow flexion trial” where from a straight arm position overhead the arm was flexed at the elbow until the hand touched the top of the head while keeping the upper arm stationary and then extended back to the straight arm position, and a static “ball release trial” where the ball was held in the release position touching the end of the fingertips of the bowling hand (King and Yeadon, 2012). The three calibration trials and one bowling trial (where there was no

marker loss plus video available) were manually labelled and initially processed using the Vicon BodyBuilder software for each bowler.

For each trial both marker sets (pair and triad) were used to calculate the elbow extension angle time history (King and Yeadon, 2012). For both marker sets the lower arm endpoint W was defined as the midpoint of the pair of markers at the wrist and the upper arm endpoint S was defined as a weighted average of the pair of markers at the shoulder (Figure 2). The elbow centre E was defined as the midpoint of the pair of markers at the elbow for the pair method, and the midpoint of the virtual markers for the triad method. The instant of upper arm horizontal was defined as the first time during the delivery when the vertical location of the elbow joint centre was higher than the upper arm endpoint, while the instant of ball release was defined as the first time that the distance between the ball marker and the lower arm endpoint was greater than the measured distance from the static calibration ball release trial.

The lower arm endpoint W , elbow centre E , upper arm endpoint S , and the pair (E_L and E_M) of markers (virtual markers in the case of the triad) across the elbow for two positions of the arm (straight and flexed to 90°), from the elbow flexion calibration trial, were used to define a functional elbow axis E_{axis} (King and Yeadon, 2012). E_{axis} was defined relative to the plane $S_E E_M E_L$ such that the lower arm folds on top of the upper arm when fully flexed (Figure 2). The direction of E_{axis} was determined using the condition that it made equal angles with EW_1 , EW_2 , EW' so that the dot products with these three vectors were equal. The extension angle was defined as the angle between the planes $S_E E_{axis}$ and $W_E E_{axis}$. The elbow abduction angle (or carry angle) was defined as $180^\circ - \text{ang}(WE, E_{axis}) - \text{ang}(SE, E_{axis})$ (King and Yeadon, 2012). The elbow axis E_{axis} (as determined above) was held relative to the upper arm reference plane $S_E E_M E_L$ for the determination of angles from the marker motions. As a consequence the angle between E_{axis} and ES remained constant whereas the angle between E_{axis} and EW could change.

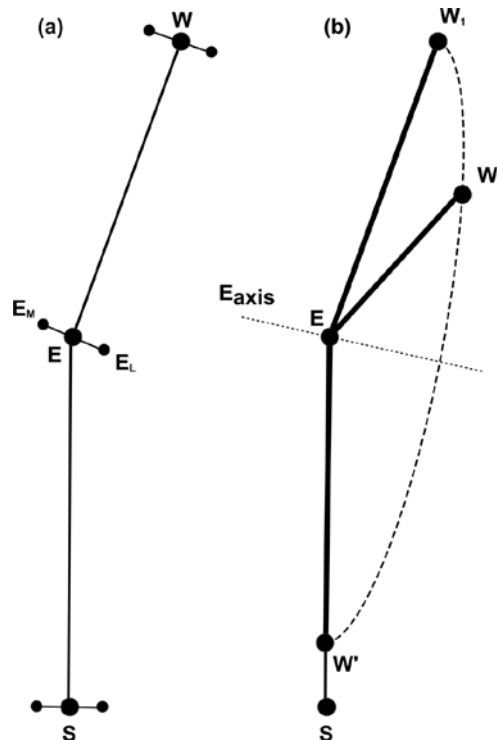


Figure 2. (a) Shoulder, elbow and wrist markers, (b) elbow axis calculation.

For both marker sets the following time histories were calculated for each bowling trial from upper arm horizontal until ball release: the elbow extension angle, the elbow abduction angle, the elbow joint centre (x, y, z) location and the orientation of the upper arm in a global reference frame (somersault, tilt and twist). Somersault was calculated as rotation about a horizontal axis perpendicular to the line of the wickets, tilt was calculated as rotation away from a vertical plane perpendicular to the somersault axis and twist was calculated as rotation about the upper arm long axis. These angles were calculated as sequential rotations with (0, 0, 0) corresponding to upper arm vertically overhead with the condyles pointing across the wicket. For each bowling trial the elbow extension angle was calculated for the instants of upper arm horizontal, ball release and the most flexed and the most extended elbow angles between the times of upper arm being horizontal and ball release. The amount of net elbow extension for each trial was then calculated as the most extended elbow extension angle (up to 180° so that hyperextension was not included) minus the preceding minimum elbow extension angle.

The 300 Hz video recordings were used to estimate elbow extension angles at key instants in the bowling action for each bowler. For the fast bowlers a side camera view was used where possible to estimate the peak elbow extension angle (Figure 3a) and the elbow extension angle at ball release (Figure 3b). For the spin bowlers a side camera view was used where possible to estimate the elbow extension angle at the instant of upper arm horizontal (Figure 3c) and a rear camera view was used to estimate the elbow extension angle at ball release (Figure 3d). Video analysis was only used to calculate the elbow extension angle when the elbow axis was judged visually to be approximately parallel to the video camera axis (King and Yeadon, 2012).

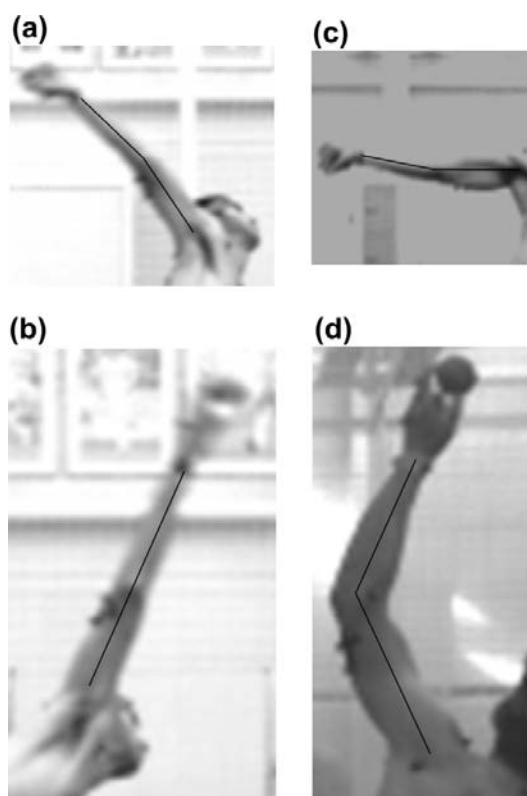


Figure 3. Measurement of elbow extension angles using mid-lines of upper and lower arm for selected video images.

Each identified image was printed out in duplicate for independent angle measurements to be made by the two researchers. On each image the midlines of the upper and lower arm were drawn as in Figure 3. The elbow angle was measured to the nearest degree using a protractor. When both sets of 38 angle measurements had been completed independently the results were averaged, rounding up to the nearest degree. The resulting mean absolute angle change was less than one degree.

The results from the two marker sets were compared by calculating the root mean square (RMS) difference from upper arm horizontal to ball release for: the elbow extension angle, the elbow joint centre (x, y, z) location and the orientation of the upper arm (somersault, tilt and twist). In addition the RMS difference between elbow extension angles measured from video and each marker set were calculated. Although the video estimates were only available at certain times, they were used as criterion values since they were unlikely to be affected by skin and soft tissue movement. In order to quantify marker movement, the distance between the centroid of the marker triad and the midpoint of the elbow pair was calculated during each fast bowling delivery.

One-way repeated measures ANOVAs were used to test for significant ($p \leq 0.05$) differences between the three methods of calculating elbow extension angle for (a) the 12 fast bowlers and (b) the 12 spin bowlers. Where there was a difference post-hoc Bonferroni adjusted paired t-tests were used to investigate further.

RESULTS

The RMS difference in elbow extension angles for the two methods at four key instants (upper arm horizontal, maximum elbow flexion, maximum elbow extension, ball release) was 8° for the fast bowlers and 4° for the spin bowlers (Tables I, II). There were smaller differences (3°) in the net extension angle since hyperextension was not counted in this measure.

Table I. Differences in elbow extension angles [$^\circ$] for the two marker sets at key instants during the bowling action for the 12 fast bowlers

subject	upper arm horizontal	maximum flexion	maximum extension	ball release	net extension
1	2	2	2	2	0
2	17	31	18	16	8
3	6	6	6	5	0
4	2	7	4	3	3
5	4	5	1	5	1
6	11	6	6	10	5
7	4	4	7	7	1
8	1	5	7	5	4
9	2	2	1	0	2
10	1	1	4	6	0
11	3	3	7	3	3
12	2	3	10	7	0
rmsd	6	10	7	7	3

Table II. Differences in elbow extension angles [°] for the two marker sets at key instants during the bowling action for the 12 spin bowlers

subject	upper arm horizontal	maximum flexion	maximum extension	ball release	net extension
1	5	5	7	2	2
2	5	5	3	7	2
3	3	1	5	2	4
4	2	2	5	1	0
5	5	5	3	3	2
6	2	7	6	4	1
7	1	3	7	4	0
8	2	2	3	3	4
9	4	4	3	1	3
10	2	2	2	1	1
11	3	15	11	4	4
12	2	2	1	4	1
rmsd	3	6	5	3	3

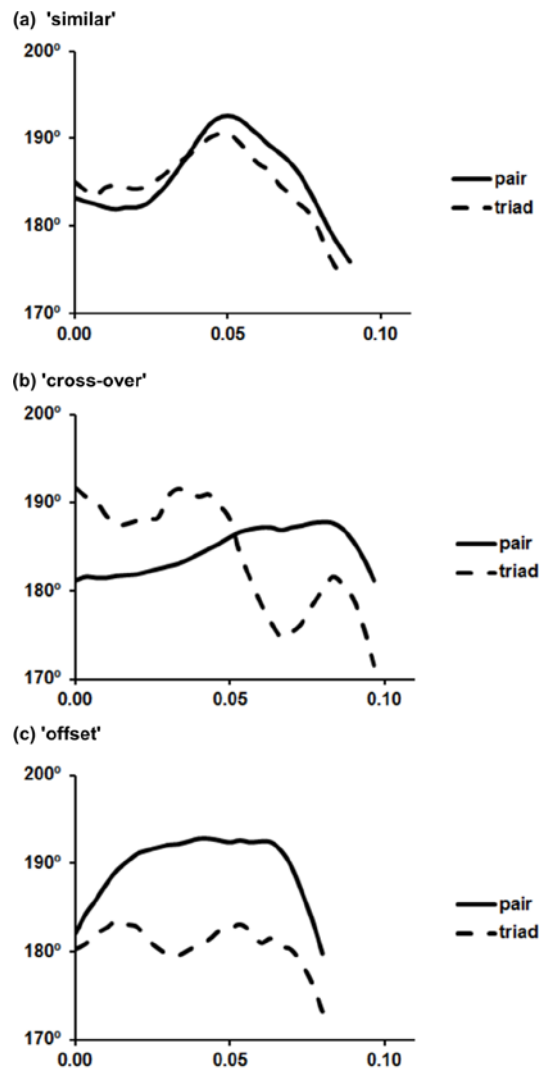


Figure 4. Example time histories of elbow extension angles between upper arm horizontal and ball release for three fast bowlers calculated using the pair method (solid line) and the triad method (dashed line).

The differences in the elbow extension angle time histories calculated from the two marker sets were different from bowler to bowler but they could be divided into three general groups; 'similar', 'offset' and 'cross-over' (Figure 4). For the fast bowlers about 50% were in the offset group and around 25% in each of the other two groups while for the spin bowlers there was a more even split between the three groups. Thus there was no simple systematic difference between the two methods.

For the fast bowlers a one-way repeated measures ANOVA found a significant difference between the three methods of calculating elbow extension angle at the instants shown in Table III. Post-hoc Bonferroni adjusted paired t-tests revealed that the triad method was significantly different from video ($p = 0.001$ with mean 178.8° versus 182.7° , effect size = 0.58) and was significantly different to the pairs method ($p = 0.001$ with mean 178.8° versus 182.4° , effect size = 0.50). For the spin bowlers a repeated measures ANOVA found no significant difference between the methods of calculating elbow extension angle.

The RMS errors from the criterion video estimates of the calculated extension angles were 2° for the pair and 8° for the triad for the fast bowlers and were 3° for the pair and 5° for the triad for the spin bowlers (Tables III, IV). It may be concluded that the triad errors were around four times larger than the pair errors for the fast bowlers (Figure 5).

Table III. Differences between the video estimates of the elbow extension angle and the calculated angles [$^\circ$] using the two marker sets for the 12 fast bowlers

subject	pair differences		triad differences	
	maximum extension	ball release	maximum extension	ball release
1	0	3	2	5
2	-4		23	
3	-3	1	-9	-4
4	4		0	
5	0	-3	5	2
6	0	2	3	11
7	-1	2	6	9
8	4	-2	11	4
9	-2	2	4	2
10	-2	0	2	6
11	1	-1	6	2
12	-2	1	9	8
rmsd	2	2	9	6

Note: missing values are where video recordings were not appropriate to allow angles to be measured.

Table IV. Differences between the video estimates of the elbow extension angle and the calculated angles [°] using the two marker sets for the 12 spin bowlers

subject	pair differences		triad differences	
	upper arm horizontal	ball release	upper arm horizontal	ball release
1	0		-6	
2	-4		-9	
3	2		-1	
4		-2		-1
5		1		5
6	2	3	0	7
7	-1		-1	
8				
9	-5		-9	
10	-1	5	-3	4
11		-4		0
12		3		6
rmsd	3	3	5	5

Note: missing values are where video recordings were not appropriate to allow angles to be measured.

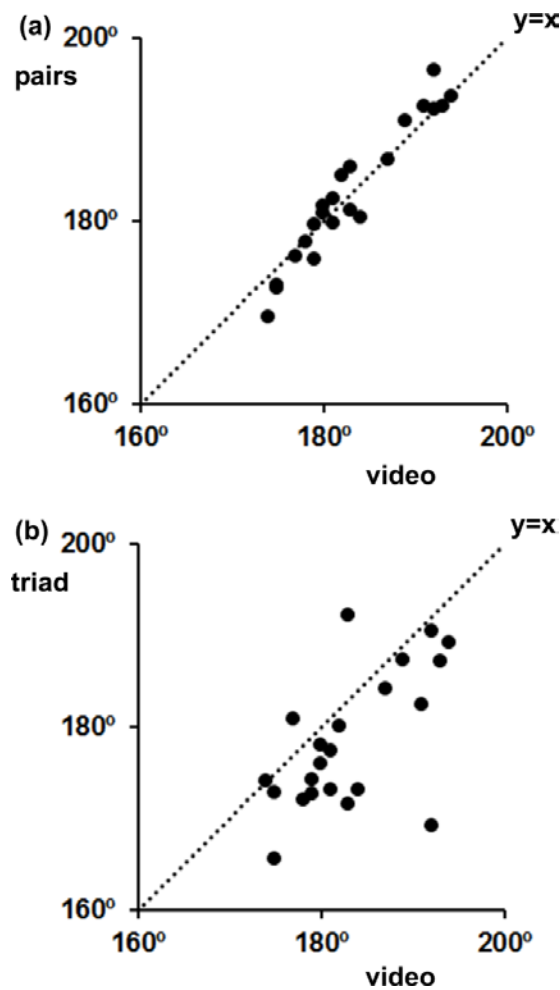


Figure 5. Graphs of calculated elbow extension angles using (a) pairs and (b) triads against the criterion video estimates.

The RMS difference between the elbow extension angle time histories between upper arm horizontal and ball release for the two marker-based methods was 9° for the fast bowlers and 4° for the spin bowlers (Tables V, VI). Generally the RMS differences for somersault and tilt of the upper arm were small (2° and 1°) compared with the RMS differences (16° to 13°) for twist of the upper arm (Tables V, VI). In addition there was 8 to 9 mm RMS difference in the elbow joint centre location between the two methods (Tables V, VI).

Table V. RMS differences in arm kinematics [°] for the time between upper arm horizontal and ball release using the two markers sets for the 12 fast bowlers

subject	elbow extension [°]	somersault [°]	tilt [°]	twist [°]	elbow xyz [mm]
1	2	1	1	11	7
2	23	1	1	47	8
3	6	6	2	9	4
4	5	1	2	12	9
5	4	1	1	5	8
6	8	2	2	14	9
7	7	1	1	5	6
8	5	0	1	2	7
9	3	1	1	4	6
10	6	1	1	8	9
11	5	1	1	11	11
12	9	2	3	6	18
rmsd	9	2	2	16	9

Table VI. RMS differences in arm kinematics for the time between upper arm horizontal and ball release using the two markers sets for the 12 spin bowlers

subject	elbow extension [°]	somersault [°]	tilt [°]	twist [°]	elbow xyz [mm]
1	5	1	2	17	7
2	4	1	1	13	9
3	3	1	1	4	5
4	4	1	1	20	9
5	3	1	1	10	5
6	5	1	1	8	5
7	4	1	1	8	7
8	3	0	1	12	7
9	4	1	1	9	7
10	3	0	0	16	6
11	5	1	3	21	13
12	4	1	1	6	8
rmsd	4	1	1	13	8

The triad centroid to elbow pair distance typically increased during a delivery for the fast bowlers from 10 mm less than the distance in the static calibration trial to around 1 mm more than the static distance (Figure 6). The mean distance during a fast bowling delivery was 5 mm less than the static distance (Table VII).

Table VII. Distance between triad centroid and elbow pair midpoint for the 12 fast bowlers [mm]

subject	static	average	SD	min	max
1	82	76	3	71	82
2	90	83	4	79	89
3	92	89	3	86	95
4	94	91	4	86	99
5	103	97	3	92	105
6	143	137	5	133	150
7	79	76	3	73	80
8	93	93	2	88	95
9	110	102	3	98	110
10	76	70	4	65	77
11	78	73	3	68	78
12	87	80	3	76	85
mean	94	89	3	85	95

Note: static is the distance from static straight arm trial; average, SD, min and max are for the time history of the distance over the period upper arm horizontal to ball release

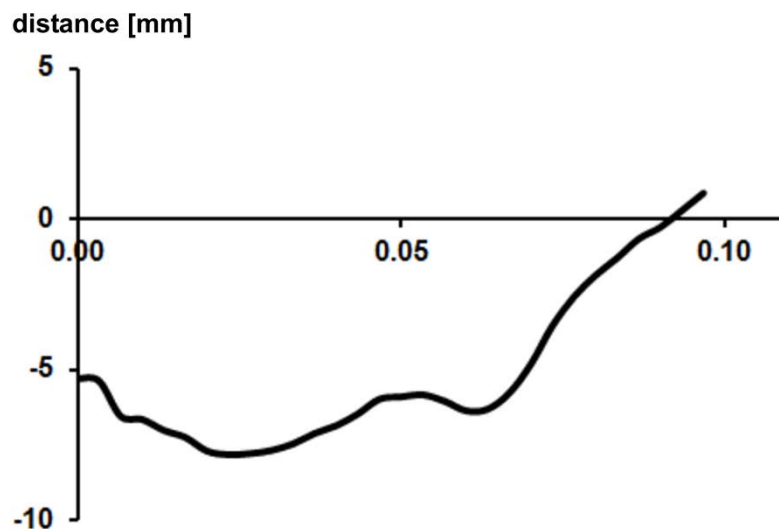


Figure 6. Distance between triad centroid and elbow marker pair during the mean of 12 fast bowling trials. Distance is measured relative to the distance in a static trial and bowling trials have been synchronised at ball release.

DISCUSSION

This study aimed to investigate differences in elbow angles determined from the use of a triad marker set around the elbow versus a pair of markers across the elbow. There were substantial RMS differences in the elbow extension angle time histories that were more pronounced for the fast bowlers (9°) than for the spin bowlers (4°). When compared against an independent criterion angle measure from

video the triad elbow extension angles had greater deviations than the pair elbow extension angles. For the fast bowlers these were 2° (pair) and 8° (triad) while for the spin bowlers the deviations were 3° (pair) and 5° (triad). As a consequence the differences between the two methods can be accounted for by errors arising from the triad method. While the criterion video estimates of arm extension angle may have limited precision they have the advantage of being largely independent of skin and soft tissue movement whereas markers placed on the skin have the potential to suffer from skin and soft tissue movement artefacts.

Besides errors in the orientation angles of the upper arm there were also errors in the elbow joint centre location (Tables V, VI). Each of these will result in errors in calculated elbow extension angles. For the mean carry angle of 15° the RMS difference of 16° twist angle for fast bowlers corresponds to a misalignment of the elbow axis and leads to an elbow extension difference of 4°. For the mean carry angle of 13° the RMS difference of 13° for spin bowlers leads to an elbow extension difference of 2°. The 2° difference in somersault and tilt angles for fast bowlers leads to a difference in elbow centre location of 5 mm and the 1° difference for spin bowlers leads to around half of this. The remainder of the 8-9 mm difference in elbow centre location is a result of the twist angle difference and any linear displacement of the triad (Table VII). The propagated error in elbow extension arising from 8-9 mm elbow centre mislocation is 3° (Appendix). Thus the errors arising from elbow axis and elbow centre mislocations are similar.

The RMS differences in somersault, tilt and twist angles calculated from the pair and triad methods were minimal for somersault and tilt (1° and 2°) and larger (13° and 16°) for twist (Tables V, VI). This suggests that the triad was moving with soft tissue that was rotating about the upper arm long axis. As a consequence the direction of the elbow axis would become tilted and there would be error in the calculated extension angle. The elbow extension differences for spin bowlers are less pronounced as might be expected if the errors are caused by soft tissue movement in this dynamic activity.

Another possibility is that there is a systematic error associated with greater upper arm twist angles since skin movement may lag behind internal rotation and so the triad would not rotate sufficiently around the longitudinal axis. For the spin bowlers the differences in twist angle estimates were just as large as for the fast bowlers but the extension angle errors were smaller. If the error arose from only skin movement it would be expected that the errors for fast and spin bowlers would be similar and so this suggests that the problem may be primarily due to soft tissue movement.

The original protocol developed by the University of Western Australia (Lloyd, et al., 2000) used three markers located centrally on the upper arm and two markers located centrally on the forearm in order to determine the relative orientation of the two arm segments. This choice of marker placement was made since markers placed over joints suffer from skin movement as the joint angle changes (Cappozo, Catani, Leardini, Benedetti & Della Croce, 1996). In bowling, however, the joint angle changes are small (typically less than 15°) and the elbow marker pair were positioned with an extended arm. As a consequence the issue of skin movement for a pair of markers at the elbow is likely to be of minor consequence.

While skin movement arising from joint angle changes may be the over-riding consideration in clinical gait studies, there can be substantial soft tissue movement in dynamic sports activities (Roosen, Pain, & Begon, 2009) that can produce movement

artefacts arising from markers located centrally on a segment. The use of a triad placed away from the elbow joint may be prone to soft tissue artefacts that result in errors in calculated joint centres and axes due to the triad of markers moving relative to the arm (Zhang et al., 2011). Indeed Cutti, Cappello and Davalli (2006) observe that “soft tissue artefact is the dominant error source for upper extremity motion analyses that use skin-mounted markers” while Roosen et al. (2009) state that for athletic human movement “determining the joint centre of the shoulder or elbow with a triad of markers per segment with an accuracy greater than 20 mm is unlikely”. The idea of removing the effects of soft tissue movement using filtering is problematic since there are at least three types of response in fast bowling (Figure 4).

In summary for bowling in cricket the use of a marker pair across the elbow results in a more accurate measure of elbow extension angle than the use of a marker triad on the upper arm near the elbow. The use of marker triads in other dynamic sporting activities such as baseball pitching and javelin throwing are likely to suffer similar problems and alternative marker sets should be sought in order to minimise artefacts arising from soft tissue movement.

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APPENDIX

If the elbow centre E has an error Δh in a direction perpendicular to the arm plane S_E_W (Figure 2) for a fully extended arm with carry angle α , this will be equivalent to a displacement of $\Delta h(1+\cos\alpha) \approx 2\Delta h$ relative to the original arm plane S_E_W. The corresponding change in elbow extension angle will be γ where $\tan\gamma = 2\Delta h / r\cos\alpha$ and r is the forearm length EW.

For a fast bowler with the mean carry angle of 15° and forearm length estimate r of 0.33 m, the standard deviation of elbow position difference 0.09 m gives $\gamma = 3.2^\circ$. For a spin bowler with the mean carry angle of 13° and forearm length r of 0.33 m, the standard deviation of elbow position difference 0.08 m gives $\gamma = 2.8^\circ$.

