Biomechanical, anthropometric, and isokinetic strength characteristics of elite finger and wrist-spin cricket bowlers: A developmental and performance perspective

Wayne Spratford, BEd., BSc. (Hons)

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Supervision Team
Associate Professor Jacqueline Alderson
Emeritus Professor Bruce Elliott
Dr Nicholas Brown
Dr Marc Portus
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Finally to my family, my three beautiful children, Kiana, Charli and Isaac, I thank you for inspiring me every day to be better. To my beautiful wife Loy, I love you more than words can say and I dedicate this thesis to you.
Statement of Candidate Contribution

The outline and experimental design of the studies contained in this thesis were developed and planned by Wayne Spratford (the candidate) in consultation with supervisors; Associate Professor Jacqueline Alderson, Professor Bruce Elliott, Dr Nicholas Brown and Dr Marc Portus. The candidate was responsible for the organisation, implementation of data collection, data processing, analysis and original drafting of all chapters contained within the thesis. Cricket Australia assisted with participant recruitment. The supervisors provided guidance on data and statistical analysis, feedback on drafts of all chapters contained within the thesis, and final approval of all chapters.
Overview of the Thesis

Spin bowling can be classified into two main categories, with bowlers either having a finger-spin (FS) or wrist-spin (WS) action, a definition referring to the body endpoint segment motion primarily responsible for placing revolutions on the ball. In general, the spin bowler delivers the ball significantly slower than their fast bowling counterpart, relying on deviations during flight (drift and dip) and after bounce (side-spin) to influence the contest. Using a single measure of performance such as ball release (BR) velocity, as is common in fast bowling research, fails to take into account the many variables required for spin bowling success. These include placing revolutions on the ball, as well as appropriately directing the axis of rotation and orientating the seam of the ball. In order to optimise these variables, the spin bowler must deliver the ball with the appropriate revolutions and BR velocity created through a series of complex and rapid upper-body movements between back foot impact (BFI) and BR.

While some attempts have been made to measure initial ball flight kinematics in both FS and WS bowlers, to date no research has attempted to quantify ball seam location during flight. Research exploring the biomechanical aspects of spin bowling has also received limited attention, with only a single study attempting to explore the kinematics of FS bowlers and its relationship to ball velocity and revolutions. Therefore, the aim of this thesis was to advance our understanding of ball and upper-body kinematics for both FS and WS bowlers, and to extend this knowledge to include upper-body kinetics and underlying physical attributes (e.g., anthropometry and isokinetic strength) in bowlers with varying expertise. This was achieved through a series of four connected research studies (chapters four, five, six and seven). For each study, bowlers were stratified into pathway (FS n=24, WS n=12) or elite (FS n=12, WS n=8) groups reflective of their playing level with ball kinematics and upper-body mechanics calculated. For studies two and three, anthropometry and isokinetic strength data were collected and compared with performance measures identified in study one. Study four (chapter seven), included a cohort of 12 FS bowlers, who exhibited an illegal bowling action that precluded them from the initial three studies (pathway illegal).
Results from study one (chapter four) indicated that when comparing ball kinematics between FS and WS bowlers, FS bowlers delivered the ball with an increased axis of rotation elevation angle, while WS bowlers imparted greater revolutions on the ball. These differences reflect the bowling strategies adopted by each type of bowler, with FS bowlers relying on flight and drift compared with WS bowlers who appear to rely on increased side-spin rates. When comparing between skill levels within each bowling type, elite FS and WS bowlers recorded increased BR velocity, revolutions and velocity/revolution indices. Elite FS bowlers displayed an increased seam stability measure, while seam azimuth and spin axis elevation angles were greater in elite WS bowlers compared with pathway bowlers. These findings identify a number of ball kinematic measures that appear to be useful in distinguishing between skill level for both FS and WS bowlers. From an applied perspective, these differences identified between skill levels will likely influence the ball flight characteristics both in flight (drift and dip), as well as post bounce (angle of ball bounce and direction of side-spin).

Studies two (FS) and three (WS) (chapters five and six) adopted the velocity/revolution index, developed in study one as a discriminator of performance across bowler types. Results from study two, indicated that elite FS bowlers make better use of the degrees of freedom (DoF) within the kinetic chain by rotating their trunks (thorax and pelvis) and extending their elbow joint through the point of BR. When the data from both the elite and pathway cohorts were combined and a regression analysis performed, results revealed that isokinetic extension/adduction strength of the shoulder; peak metacarpophalangeal (MCP) flexion angle, ulna deviation angular velocity at BR and the linear velocity of the wrist joint centre were the best predictors of performance. These results highlighted the importance of the trunk early within the bowling phase and the subsequent movements at the distal arm (elbow, wrist and MCP joints) through the point of BR.

When comparing elite and pathway WS bowlers (study three), elite bowlers displayed lower levels of trunk rotation about the long axis (anti clockwise for a right hand bowler) between BFI-BR, delivered the ball in a more front-on position, but exhibited increased forward pelvis rotation angular velocity at BR. They also displayed an increased peak shoulder internal rotation moment, as
the shoulder moved from external rotation into internal rotation. This internal rotation movement was subsequently responsible for the kinetic and kinematic differences observed at the elbow (pronation) and wrist (ulna deviation and extension) through better utilisation of the DoF within the body’s kinetic chain. Elite bowlers also exhibited anthropometry variations at the wrist (active radial deviation and total range in the frontal plane); hand (length) and phalange (MCP 4 flexion and extension range of motion) that may be used to form the basis of talent identification (TID) protocols. When the data from both the elite and pathway cohorts were combined and a regression analysis performed, peak isokinetic radial deviation torque, peak shoulder internal rotation moment, the shoulder extension moment at BR and the peak elbow pronation moment were the best predictors of performance (velocity/revolution index). These results highlighted the importance of baseline upper arm strength and the long axis rotations of the bowling limb, particularly shoulder internal rotation, in what is considered the most technically demanding form of cricket bowling.

During data collection a cohort of FS bowlers (n=12) were identified with illegal bowling actions. In an attempt to understand if illegal actions influence performance as measured by ball revolutions and ball velocity (variables identified in study one), were again used to compare this pathway illegal group with the existing legal pathway and elite FS bowlers (no data were collected on illegal elite FS bowlers). Results indicated that the pathway illegal cohort performance variables reflected that of the more experienced elite legal group, providing evidence that a performance benefit of ball revolutions and velocity were apparent when elbow extension levels exceed regulation thresholds. To examine if differences, other than elbow extension were present, a range of additional upper-body kinematics were compared between the pathway illegal and elite legal bowlers. These results highlighted that pathway illegal bowlers displayed a more front-on delivery technique at BFI and BR, and relied on increased amounts of elbow flexion and supination in the lead up to BR. Subsequently, pathway illegal bowlers exhibited increased amounts of elbow extension and wrist flexion angular velocity to the detriment of ulna deviation angular velocity. Results suggest that coaching staff should encourage a more side-on technique at BFI and encourage bowlers to rotate their trunks through to the point of BR, when attempting to remediate illegal bowling actions.
In summary, these four studies have advanced the understanding of both FS and WS bowling across the development pathway and identified ball kinematic measures that can be used to discriminate between skill levels. Further, we have identified kinematic, kinetic and isokinetic strength measures that are critical in both FS and WS bowling and as such should form the basis for coaching and conditioning programs. Finally, this research is the first experimental study to report a performance benefit when FS bowlers deliver the ball with an illegal action. Recommendations have also been provided that may be used to assist bowlers in remediating an illegal bowling technique.
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Chapter 1: Introduction

1.1 Background

The game of cricket is played between two teams of 11 players over varying formats ranging from single innings 20 overs per side (T20), through to multiple innings spread over five days (Test match cricket). Essentially, the game is a contest between bat and ball and while the formats may vary, the outcome is always defined by the team who scores the most runs. Teams generally comprise of six specialist batsmen, a wicket keeper and four specialist bowlers, one of which is usually a spin bowler (Bradman, 1969; Tyson, 1994; Woolmer, Noakes, & Moffett, 2008). The spin bowler delivers the ball significantly slower than that of their fast bowling counterpart, relying on “drift” and “dip” through the air, a result of the Magnus effect and deviation from the pitch after bounce in order to deceive the batsmen (Beach, Ferdinands, & Sinclair, 2014; Robinson & Robinson, 2013; Woolmer et al., 2008). The drift, dip and deviation of the ball are all influenced by the revolutions and velocity imparted on the ball, as well as the direction of the axis of rotation and orientation of the seam (Chin, Elliott, Alderson, Lloyd, & Foster, 2009; Mehta, 2005; Robinson & Robinson, 2013; Sayers & Hill, 1999).

Spin bowlers are classified as either having a finger-spin (FS) or wrist-spin (WS) action. These categorisations loosely reflect the end point of the body’s kinetic chain responsible for placing revolutions on the ball. In FS bowling, the ball leaves from the radial side of the hand controlled by the first and second phalanges, while the wrist flexes and deviates to the ulna side as the elbow supinates and undergoes extension (Bradman, 1969; Chin et al., 2009; Spratford, Portus, Wixted, Leadbetter, & James, 2014; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). An example of the release position is seen in the time series images in Figure 1.1.
The WS bowler releases the ball out of the ulna/fifth phalange side of the hand, under the influence of the pronating elbow and a rapidly extending and radially deviating wrist (Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). An example of the release is shown in the time series images in Figure 1.2.

Given the influence of the finger and thumb in controlling ball release, FS bowling is seen as an easier craft to master, a view reinforced by the playing populations that generally comprises far fewer WS than FS bowlers (Wilkins, 1991; Woolmer et al., 2008). The trade-off between the two styles is that the wrist dominated action of WS bowling produces more revolutions on the ball when compared with the finger dominated action (Beach et al., 2014; Bradman, 1969; Justham, West, & Cork, 2008; Wilkins, 1991; Woolmer et al., 2008).

While each team may only have a single specialist spin bowler, they play an integral role within the game of cricket, both in taking wickets and/or restricting the flow of runs. In the longer form of the game, first class and Test cricket (played over four and five days respectively), the spin bowler is expected to be dominant during the third or fourth innings of the game, as the batting surface
(pitch) begins to deteriorate (break up) and become more conducive to ‘spin’ (James, Carre, & Haake, 2004, 2005). This ability for the spin bowler to become the ‘match winner’ late in the game has direct links to the performance of a team. This was highlighted by Shane Warne, statistically the game’s greatest WS bowler, who over a 15 year career took 708 Test wickets at an average of 25.41 (Cricinfo, 2015). Significantly, the Australian team was ranked the number one Test playing nation for 64% of this period (rankings retrospectively applied prior to 2003) (Cricinfo, 2015). While it is acknowledged that this team also contained other great players, since Warne’s retirement in 2007 Australia were not again ranked in the top position until May 2014. Since this time Australia has used 14 different spin bowlers (as of June 2015) (Cricinfo, 2015), highlighting the influence a World Class spin bowler can have on a side’s continued successful performance. This is further reinforced by the International Cricket Council’s (ICC) bowling statistics (wickets taken as of June 2015), which show that the top three bowlers in Test match cricket, the top bowler in one-day cricket and T20 cricket are all spin bowlers of some form (Cricinfo, 2015).

Indeed, Sri Lankan bowler Muttiah Muralitharan, a FS bowler who took 800 Test wickets at an average of 22.72 and has been rated the greatest ever Test match bowler by Wisden Cricketers Almanac (Wisden Cricketers’ Almanack, 2014), held the number one spot in the ICC player rankings for a Test match bowler for a period of almost five years (Cricinfo, 2015).

However, the success of spin bowlers within the game is not reflected in the scientific literature, with very few peer reviewed journal articles examining any aspect of spin bowling. This inequity may be fuelled by cricket allied staff focusing predominantly on the high levels of injuries suffered by fast bowlers and the small number of spin bowlers typically found within a team.

While there are many facets that contribute to a successful spin bowler, such as drift through the air or subtle changes in delivery speed, the limited coaching literature focusses on the need to impart high levels of revolutions on the ball during the delivery. Anecdotally this is seen to be of critical importance and the primary contributor to effective ball deviation following ball-pitch impact. The importance of imparting adequate spin is perhaps best summed up by Woolmer and colleagues (2008),
“Spin the ball, turn it, masses of it, this must be their aim above all. They must want to turn it square, make it kick to the leg or to the off side at 90°; they must dream of bowling bat smen around their legs or of getting the ball to skip into middle-stump from two feet outside off-stump, before he or she even begins to experiment with flight, drift and quicker flatter deliveries” (p.288)

In support of the anecdotal decrees surrounding the importance of ball revolutions from the wider cricket community, Chin et al. (2009), reported one of the first scientific investigations in the area, that higher level FS bowlers produced more ball revolutions, delivered the ball at a higher velocity and showed various biomechanical differences during the delivery action, when compared with lower level counterparts. Of these identified biomechanical differences was the finding that elite level bowlers deliver the ball with greater amounts of elbow extension between upper-arm horizontal (UAH) and ball release (BR), a movement that, when excessive, reflects an illegal bowling action. While there has been other limited spin bowling research (Beach et al., 2014; Chauhan & Gregory, 2003; Justham, Cork, & West, 2010; Justham et al., 2008), there exists significant gaps within the literature that warrant exploration. These include; expanding on the simplistic model of ball revolutions as a single measure of performance, understanding how upper-body mechanics, anthropometry and isokinetic strength of bowlers differs across skill level and how each influences performance. There is also a need to better explore the performance outcomes and mechanics of bowlers who bowl with an illegal action, an emotive yet increasingly prevalent finding in FS bowlers.

1.2 Statement of the problem

To date limited biomechanical research exists comparing elite level spin bowlers, both FS and WS (1st Class and above), to developing pathway bowlers within elite programs (national U18 and list A players). Little is known about orientation of the ball’s seam at release, its relationship with the axis of rotation after release, and the direction of the axis of rotation as well as ball revolutions
and velocities during flight. It is also unknown if upper-body biomechanical measures (kinematic and kinetic) and/or physical attributes such as bowling limb anthropometric and isokinetic strength differences exist between skill levels. A greater understanding of these variables will allow coaching staff to make informed decisions for interventions based around quantitative data to better facilitate progression through the development pathway. It is also hoped that a greater understanding of the anthropometry of elite level bowlers will allow for the development of talent identification programs targeting characteristics observed within successful bowlers.

No published research currently exists comparing the biomechanical characteristics of bowlers with legal and illegal bowling actions. It is also unknown if there are any performance benefits in delivering the ball with greater than a 15° range of elbow extension in the forward swing phase of the bowling action delineated by UAH and BR. A greater understanding of the biomechanical attributes observed within an illegal bowler cohort will facilitate targeted remediation processes and assist in preventing illegal actions developing in the first instance. Finally, an understanding of the influence of elbow extension on ball characteristics will facilitate informed and constructive debate around possible changes to the current illegal delivery law (ICC, 2005).

1.3 Definition of terms

Cricket has many terms specific to the game, the definitions of which, including those used in the following studies are:

**Finger-spin bowler (FS - see Figure 1.1):** A spin bowler who delivers the ball from the radial side of the hand, controlled by the first and second phalange, while the wrist flexes and deviates to the ulna side as the elbow supinates and extends.

**Wrist-spin bowler (WS - see Figure 1.2):** A spin bowler who delivers the ball out of the ulna or the fifth phalange side of the hand under the influence of the
internally rotating humerus, pronating elbow, extending and radially deviating wrist.

**Pathway bowler:** A bowler who has played up to and including list A level cricket.

**Elite bowler:** A bowler who has played at a minimum level of 1st Class cricket.

**Drift:** A spin bowling specific term that describes the lateral deviation of the ball during flight that is controlled by the Magnus effect.

**Dip:** A spin bowling specific term that describes the vertical deviation of the ball during flight that is controlled by the Magnus effect.

**Magnus effect:** The aerodynamic principle that applies lift and drag forces perpendicular and opposite to the linear velocity vector of a smooth spinning object.

**Side-spin:** The lateral deviation of the cricket ball post bounce.

**Revolutions:** A term that describes the amount of rotations the ball undergoes per second during ball flight.

**Leg-side:** The side that is to the left of the middle stump for a right handed batsman when they are in their normal stance.

**Off-side:** The side that is to the right hand of the middle stump for a right handed batsman when they are in their normal stance.

**Back foot impact (BFI):** Is the instance of the initial second last foot contact made by the bowler before they release the ball. For a right handed bowler this is the right foot (Figure 1.3).
Upper arm horizontal (UAH): When the upper arm segment, defined by the shoulder joint centre (SJC) to the elbow joint centre (EJC) is aligned with the absolute horizontal (parallel to the ground) (Figure 1.4).

Ball release (BR): When the ball breaks contact with the fingers (Figure 1.5).
Carry angle: Deviation of the forearm from the line of the upper arm when the elbow is in full extension, i.e. forearm abduction.

Illegal action: When the elbow extension range of the bowling arm exceeds 15° from the maximum flexed position after UAH through to BR (Figure 1.6).

Figure 1.6. Illegal action of a FS bowler. The measure of elbow extension starts from the maximum flexed position (B) after UAH (A) until BR (C). Note that the elbow is flexed in pictures A and B, but finally extended in panel C. When this elbow extension exceeds 15°, the delivery is considered illegal.
1.4 Aims and hypotheses

The aims of the series of studies in this thesis are:

Study 1: *The effect of performance level on initial ball flight kinematics in finger and wrist-spin cricket bowlers.*

**Aims**
- Compare ball kinematics of elite and pathway FS and WS bowlers at BR and during early ball flight.
- To determine if ball kinematics discriminate performance levels in FS and WS bowlers.

**Hypotheses**
- At BR, FS bowlers will display a significantly higher axis of rotation elevation angle and ball velocity compared with WS bowlers.
- During initial ball flight WS bowlers will exhibit a higher level of ball revolutions compared with FS bowlers.
- Compared with their pathway counterparts elite bowlers will display significantly higher:
  i. axis of rotation elevation angle,
  ii. seam azimuth angle rotated toward the intended direction of side-spin,
  iii. ball velocity,
  iv. ball revolutions,
  v. relative seam to axis of rotation angle closer to 90° (indicative of a stable seam during initial ball flight).

Study 2: *The influence of upper-body mechanics, anthropometry and isokinetic strength in finger-spin cricket bowling.*

**Aims**
- Compare upper-body mechanics, anthropometry and isokinetic strength between elite and pathway FS bowlers.
• Establish if a relationship exists between upper-body mechanics, anthropometry and isokinetic strength, to ball kinematics.

Hypotheses
• Compared with the pathway cohort, at BR elite bowlers will generate higher linear joint endpoint velocities of the bowling limb:
  i. shoulder,
  ii. elbow,
  iii. wrist,
  iv. second metacarpophalangeal joint (MCP).
• The pathway cohort will display increased peak MCP flexion and wrist ulna deviation between UAH-BR.
• Between BFI-BR and UAH-BR the pathway cohort will display higher peak angular velocities of the following:
  i. thorax rotation,
  ii. shoulder external rotation,
• Increased shoulder external rotation; elbow supination and wrist ulna deviation joint angular velocities at BR will be observed by elite bowlers
• Elite bowlers will demonstrate higher peak elbow supination and wrist ulna deviation moments in comparison to the pathway cohort.
• Greater wrist ulna deviation, and lower elbow extension, ranges of motion will be seen for elite bowlers.
• Compared with the pathway cohort, elite bowlers will exhibit greater peak isokinetic torque in the following movements:
  i. shoulder extension/adduction,
  ii. elbow joint supination,
  iii. wrist ulna deviation.
• The following variables will best explain ball kinematics (velocity/revolution index) when used as a dependant variable in a regression analysis:
  i. thorax rotation peak angular velocity between BFI-BR,
  ii. shoulder external rotation peak angular velocity between UAH-BR,
  iii. elbow supination angular velocity at BR,
  iv. MCP flexion at BR,
v. wrist ulna deviation at BR,
vi. peak wrist ulna deviation between UAH-BR,
vii. peak elbow supination between UAH-BR,
viii. peak isokinetic ulna deviation torque.

Study 3: The influence of performance on upper-body mechanics, anthropometry and isokinetic strength in wrist-spin cricket bowling.

Aims
• Compare upper-body mechanics, anthropometry and isokinetic strength during bowling between elite and pathway WS bowlers.
• Establish if a relationship exists between upper-body mechanics, anthropometry and isokinetic strength, to ball kinematics.

Hypotheses
• At BR elite bowlers will generate higher linear endpoint velocities of the bowling limb when compared to the pathway cohort:
  i. shoulder,
  ii. elbow,
  iii. wrist.
• Compared with the pathway cohort, elite bowlers will display an increased elbow pronation and wrist radial deviation between UAH-BR.
• Elite bowlers will display higher peak angular velocities for shoulder internal rotation and elbow supination between UAH-BR:
• At BR elite bowlers will display higher peak angular velocities of the following when compared to pathway bowlers:
  i. shoulder internal rotation,
  ii. elbow supination,
  iii. wrist radial deviation.
• Compared with the pathway cohort, elite bowlers will display higher peak shoulder internal rotation and wrist radial deviation moments.
• Greater active wrist radial deviation range of motion will be seen for elite bowlers.
• Elite bowlers will exhibit greater peak isokinetic torque in the following movements:
  i. shoulder internal rotation,
  ii. elbow joint pronation,
  iii. wrist radial deviation.
• The following variables will best explain ball kinematics (velocity/revolution index) when used as a dependant variable in a regression analysis:
  i. peak shoulder internal rotation angular velocity between UAH-BR,
  ii. peak elbow supination angular velocity between UAH-BR,
  iii. wrist radial deviation angular velocity at BR,
  iv. peak shoulder internal rotation moment between UAH-BR,
  v. peak wrist radial deviation moment between UAH-BR,
  vi. peak isokinetic shoulder internal rotation torque,
  vii. peak isokinetic elbow pronation torque.

Study 4: *The influence of elbow extension on bowling performance and upper-body mechanics in finger-spin bowling.*

**Aims**
• Establish if bowlers with an illegal action gain a performance benefit.
• Compare upper-body mechanics between groups of bowlers who deliver the ball with an illegal action to those who do not.

**Hypotheses**
• In comparison to their legal counterparts, illegal bowlers will deliver the ball with more revolutions and greater velocity.
• Compared with their legal counterparts, illegal bowlers will deliver the ball with a greater range of elbow extension between UAH-BR.
• Illegal bowlers will have decreased displacements of the following joints and segments at BR:
  i. wrist ulna deviation,
  ii. elbow extension,
  iii. thorax forward rotation,
iv. pelvis forward rotation.

- Between BFI-BR, illegal bowlers will have decreased peak thorax forward rotation and pelvis forward rotation between BFI-BR.
- Illegal bowlers will display significantly greater peak elbow extension angular velocity and wrist peak extension angular velocity between UAH-BR.
- Decreased peak elbow supination angular velocity and peak wrist ulna deviation angular velocity will be observed for illegal bowlers between UAH-BR.
- Compared with their legal counterparts, illegal bowlers will have increased elbow extension angular velocity and wrist extension angular velocity at BR.
- Illegal bowlers will observe decreased elbow pronation and wrist ulna deviation at BR.

1.5 Limitations

- The sample reflected the entire population of bowlers that would be considered elite and pathway within Australia. As such, the findings may not apply to bowlers at lower performance levels or bowlers from other countries. However, given Australian bowlers have experienced coaches and international competition experience, it is likely that bowlers from other countries can apply the findings and principles highlighted herein.
- Data collection occurred in a custom designed indoor cricket laboratory and as such lacked task representation. However, this environment allowed complex methods to be implemented and data collected that would not be possible in an in situ environment.
- All deliveries were bowled as if bowling to a right handed batsman.

1.6 Delimitations

- All participants, 48 FS and 20 WS bowlers were identified by national coaches as either elite or pathway and were injury free at the time of testing.
- All subjects bowled with a four piece 156 g turf cricket ball.
• All testing was carried out indoors and at the same venue allowing for conditions to be controlled between testing sessions.
• Only bowlers with a legal action (less than 15° range of elbow joint extension from UAH to BR) were considered for inclusion in studies 1-3.
Chapter 2: Literature Review

2.1 Overview

As its name suggests, a spin bowler’s main aim is to deceive the opposing batsmen through the lateral deviation (side-spin) that occurs after the ball hits the pitch. Evidence suggests that if a ball deviates from its intended direction when it is less than 200 ms from the batter, as is common in cricket, any change in direction of the ball will need to be predicted due to movement time constraints (Mann, Spratford, & Abernethy, 2013; McLeod & Jenkins, 1991; Renshaw & Fairweather, 2000). Deviation from the pitch however is only part of the spin bowler’s armoury, with both lateral (drift) and vertical (dip) deviation during flight and steepness in bounce, all playing critical roles in deceiving the batsmen.

Spin bowlers are broadly categorised as either finger-spin (FS), with the ball being delivered out of the front or radial side of the hand (Figure 1.1) or wrist-spin (WS), out of the back or ulna side of the hand (Figure 1.2) (Bradman, 1969; Philpott, 1995; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). While each type of delivery uses the wrist and the fingers, the delineation for the bowler naming convention stems from how the ball is delivered at the terminal end of the kinetic chain. The FS bowler ends the action with the first and second fingers applying a “turning action”; this is commonly called “screwing off the lid of a jar” or “turning a doorknob violently” in the coaching literature (Bradman, 1969; Woolmer et al., 2008). The WS bowler uses their wrist to flick the ball out of the back/side of the hand, as if they were opening a door anti-clockwise (for a right handed bowler). This action is considerably more difficult in comparison with the FS bowler, who has the index finger and thumb to help guide the ball during the release. It is this increased difficulty that results in the development of far fewer WS bowlers compared with the more common FS bowler (Philpott, 1995; Wilkins, 1991; Woolmer et al., 2008).

The limited research in the area of spin bowling biomechanics has primarily focused upon illegal actions, that is, exceeding the allowable 15° of elbow
extension range from upper arm horizontal (UAH) to ball release (BR) (Aginsky, Lategan, & Stretch, 2004; Ferdinands & Kersting, 2007; Lloyd, Alderson, & Elliott, 2000; Marshall & Ferdinands, 2003; Yeadon & King, 2015). A few studies have explored the kinematics of the ball during its initial flight (Beach et al., 2014; Chin et al., 2009; Cork, Justham, & West, 2012; Justham et al., 2010; Justham et al., 2008; Spratford & Davison, 2010) with only one biomechanical based study investigating the mechanics of the FS bowler (Chin et al., 2009). By comparison, the far more prolific fast bowling research has primarily explored the biomechanical link to BR speeds (Crewe, Campbell, Elliott, & Alderson, 2013b; Ferdinands, Marshall, & Kersting, 2010; Glazier, Paradis, & Cooper, 2000; Loram et al., 2005; Salter, Sinclair, & Portus, 2007; Wormgoor, Harden, & Mckinon, 2010; Worthington, King, & Ranson, 2013), and attempted to understand the causal link between fast bowling and lumbar injury development and risk (Bayne, Elliott, Campbell, & Alderson, 2015; Crewe, Campbell, Elliott, & Alderson, 2013a; Crewe et al., 2013b; Ferdinands, Kersting, & Marshall, 2009; Glazier, 2010; Glazier et al., 2000; Portus, Mason, Elliott, Pfitzner, & Done, 2004; Ranson, Burnett, King, Patels, & O’Sullivan, 2008).

The following is a review of literature that encompasses research relevant to spin bowling and includes:

- Biomechanics of spin bowling,
- Biomechanics of overhand throwing,
- Illegal actions,
- Aerodynamics of spinning balls,
- Isokinetic strength of the arm,
- Anthropometry and range of motion of the arm,
- Conclusion.

### 2.2 Biomechanics of spin bowling

There has been limited research focusing specifically on the biomechanics of spin bowling, with only a single research article investigating the biomechanical variables of spin bowlers (Chin et al., 2009) and marginally more work aimed at investigating the kinematics of initial ball flight (Beach et al., 2014; Cork et al., 2012; Justham et al., 2010; Justham et al., 2008; Spratford & Davison, 2010).
Chin et al. (2009) compared the bowling actions and kinematics of initial ball flight of 19 FS bowlers from two distinct groups; elite level (n=6) and high performance level (n=13), bowling “stock deliveries (standard off-spinning delivery)”, in addition to a difficult variation delivery known as a “doosra (delivery were revolutions imparted in the opposite direction to that of a stock delivery in an attempt to spin the ball in the opposite direction)”, albeit in a reduced cohort numbers (elite n=4 and high performance n=2). Results for the “stock delivery” showed large effect size (ES) differences between groups with elite bowlers displaying a significantly higher side-on alignment of the pelvis and thorax at back foot impact (BFI), and subsequently greater rotation for both segments between BFI and BR. Increased horizontal (forward) shoulder linear velocity, higher ranges of forearm rotation and greater elbow extension displacement were also observed in the elite cohort. Differences were also observed for ball kinematics, with the elite group producing more ball revolutions and delivering the ball with an increased BR velocity. It was hypothesised by the authors that a more side-on position at BFI assists the body to rotate through to BR, a traditional coaching point referred to in numerous coaching manuals (Bradman, 1969; Woolmer et al., 2008). It was also assumed, that this increased trunk range of motion was responsible for the higher horizontal linear velocity recorded at the shoulder, and also a primary contributor to increased ball velocities (Chin et al., 2009). Increases in elbow extension and supination displacement displayed by the elite bowlers was also linked to the higher ball velocities and revolutions, as a function of the increased rotation rates of the forearm segment close to BR.

Various researchers have quantified ball kinematics at the point of; BR, during initial flight, ball pitch impact (bounce), as well as the angle of side-spin after bounce for both FS and WS bowlers. Methodologies have ranged from three dimensional (3D) data collected within a match using a “Hawkeye” system (Justham et al., 2010), high-speed video analysis (Cork et al., 2012; Justham et al., 2008) as well laboratory based 3D modelling of the ball using a motion analysis system (Beach et al., 2014; Chin et al., 2009; Spratford & Davison, 2010). Samples have ranged from two to 20 participants with skill levels ranging from district level through to elite or national standard (Tables 2.1 and 2.2). To
date no research has attempted to model the seam of the cricket ball or explore its relationship with the ball's axis of rotation (stability).
Table 2.1. Summary of the mean and standard deviations of ball kinematic data for FS bowlers.

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>20 (5 elite &amp;15 development)</td>
<td>19 (6 elite &amp;13 high performance)</td>
<td>2</td>
<td>20</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Level</td>
<td>Elite &amp; development</td>
<td>Elite (E) and high performance (HP)</td>
<td>Development</td>
<td>Elite</td>
<td>National standard (NS) Elite (E)</td>
<td>District level</td>
</tr>
<tr>
<td>Ball velocity (m.s(^{-1}))</td>
<td>20.1 (2.3)</td>
<td>20.9 (E) - 18.6 (HP) (1.7)</td>
<td>19.1 (0.2)</td>
<td>20.1 (2.3)</td>
<td>18.7 (NS) - 18.8 (E) (2.1)</td>
<td>18.6 (1.1)</td>
</tr>
<tr>
<td>Revolutions (rev.s(^{-1}))</td>
<td>25.8 (4.9)</td>
<td>26.7 (E) - 22.2 (HP) (4.6)</td>
<td>28.4 (1.2)</td>
<td>25.8 (4.9)</td>
<td>23.4 (NS) - 27.7 (E) (5.6)</td>
<td>25.0 (4.2)</td>
</tr>
<tr>
<td>Release angle (°)</td>
<td>4.9 (2.0)</td>
<td>18.7 (E) - 14.2 (HP) (11.1)</td>
<td>18.5 (2.1)</td>
<td>4.9 (2.0)</td>
<td>4.0 (NS) - 4.2 (E) (3.6)</td>
<td>17.0 (7.9)</td>
</tr>
<tr>
<td>Release width (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.03 (NS) - 0.73 (E) (0.49)</td>
<td></td>
</tr>
<tr>
<td>Release height (m)</td>
<td></td>
<td>121 (E) -123 (HP) (1.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitching length (m)</td>
<td>1.8 - 5.9</td>
<td>1.8 - 5.9</td>
<td>3.8 (NS) - 4.4 (E) (0.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitching width (m)</td>
<td>-0.2 - 0.6</td>
<td>-0.2-0.6</td>
<td>-0.4 (0.9)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Spin axis azimuth (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30.4 (NS) - 44.9 (E) (13.3)</td>
<td>-67.6 (12.9)</td>
</tr>
</tbody>
</table>
Table 2.2. Summary of the mean and standard deviations of ball kinematic data for WS bowlers

<table>
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<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>Level</td>
<td>Development-elite</td>
<td>Elite</td>
<td>National standard</td>
<td>District level</td>
</tr>
<tr>
<td>Ball velocity (m.s(^{-1}))</td>
<td>17.6 (2.4)</td>
<td>21.6 (0.1)</td>
<td>19.1</td>
<td>18.8 (1.0)</td>
</tr>
<tr>
<td>Revolutions (rev/s)</td>
<td>26.6 (0.8)</td>
<td>25.9</td>
<td>29.3 (4.7)</td>
<td></td>
</tr>
<tr>
<td>Release angle (°)</td>
<td>4.6 (0.1)</td>
<td>-6.4 (0.1)</td>
<td>6.4</td>
<td>1.1 (9.2)</td>
</tr>
<tr>
<td>Release width (m)</td>
<td>0.7 (0.01)</td>
<td>-0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Release height (m)</td>
<td>2.0 (0.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitching length (m)</td>
<td>1.8 - 5.9</td>
<td>4.3 (0.1)</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Pitching width (m)</td>
<td>-0.5 - 0.8</td>
<td>0.5 (0.03)</td>
<td>-0.3</td>
<td></td>
</tr>
<tr>
<td>Deviation angle (°)</td>
<td>-7.6 (0.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spin axis azimuth (°)</td>
<td></td>
<td>-31.0</td>
<td>46.7 (11.7)</td>
<td></td>
</tr>
</tbody>
</table>
2.3 Biomechanics of overhand throwing

In over-hand throwing tasks that rely on producing the maximum possible speed at the distal segment, the body takes advantage of what is known as the kinetic link principle (Fleisig, Barrentine, Escamilla, & Andrews, 1996; Marshall & Elliott, 2000; Roach & Lieberman, 2014). This requires the initial movement to occur at the larger proximal segments before transferring and increasing to the smaller distal segments. The angular velocities of this coordinated proximal to distal sequencing of the body are controlled by torques applied to each segment (Atwater, 1979; Kreighbaum & Barthels, 1996). While this theory has not been explored in spin bowling, research exists examining this within fast bowling, as well as other overhand throwing activities and hitting activities (Elliott, Marshall, & Noffal, 1995; Ferdinands, 2011; Glazier, 2010; Glazier et al., 2000; Reid, Giblin, & Whiteside, 2015; Urbin, Fleisig, Abebe, & Andrews, 2012).

While there is a paucity of spin bowling research, other overhead throwing tasks, such as baseball pitching are far more extensive. While there is much to learn from this body research there are also fundamental differences between the two mechanical tasks. While both movements require correct execution of the kinetic chain principle to increase performance and reduce injury, clear differences in the manner and sequencing of joint rotations or degrees of freedom (DoF) are evident (Hirashima, Yamane, Nakamura, & Ohtsuki, 2008; Keeley, Wicke, Alford, & Oliver, 2010; Putnam, 1993). Both tasks rely on rotations of the trunk and long axis of the humerus (pitching and WS bowling internal rotation and FS external rotation), pitchers however, undergo large amounts of elbow extension to transfer energy passively to the distal segments of the pitching arm in the sagittal plane (Hirashima et al., 2008; Naito, Takagi, Norimasa, Hashimoto, & Maruyama, 2014). Conversely, spin bowlers rely on the long axis rotation of the forearm as well as multi direction movement at the wrist to transfer energy from proximal to distal segments, in a similar fashion to that reported in tennis and squash players (Marshall & Elliott, 2000; Martin, Kulpa, Delamarche, & Bideau, 2013; Reid et al., 2015; Woolmer et al., 2008).

The majority of baseball pitching research has focused on injury prevention or measuring stresses and mechanical loading at the shoulder and elbow (Anz et
al., 2010; Dun, Kingsley, Fleisig, Loftice, & Andrews, 2007; Fleisig, Andrews, Dilman, & Escamilla, 1995; Fleisig et al., 2006; Werner, Gill, Murray, Cook, & Hawkins, 2001). However, some research has explored the kinetic differences between age groups and playing levels (Aguinaldo, Buttermore, & Chambers, 2007; Fleisig, Barrentine, Escamilla, Zhenga, & Andrews, 1999). Aguinaldo et al. (2007) showed that although similar values were recorded for peak trunk rotation, professionals commenced trunk rotation at a later stage of the pitching cycle and hence, a significantly lower rotational torque was developed at the shoulder for the higher skilled players. Hirashima et al. (2008) also found that the angular velocities of the trunk and upper-arm produced a velocity-dependent torque for initial elbow extension acceleration that served to increase resultant elbow and forearm angular velocities. This highlights the importance of the trunk in overhand throwing. Research exploring differences between youth (10-15 years), high school (15-20 years), college (17-23 years) and professional (20-29 years) baseball pitchers found significant differences in many velocity and kinetic parameters, but only reported a single significant angular displacement difference in the 11 measured variables. They concluded that the risk of injury increases as joint torques increase due to the increased demands of playing at a higher level, and that kinetic differences were responsible for the subsequent angular velocity differences observed throughout the development pathway. Therefore it is important for pitchers to learn proper mechanics as early as possible, and build strength as the body matures (Fleisig et al., 1999).

2.4 Illegal actions

In 2000, the holder of the laws of cricket, the Marylebone Cricket Club (MCC) clarified the law involving elbow extension during the bowling action. They defined a legal delivery as one that does not see straightening, either partially or completely, at the elbow joint during the swing phase from upper arm horizontal (UAH) until the ball has left the hand (MCC, 2000). In 2002, the world’s governing body, the International Cricket Council (ICC) introduced a tiered system of thresholds for elbow straightening depending on bowler type with tolerances set at 5° for spin-bowlers, 7.5° for medium pace bowlers and 10° for fast bowlers. It is unclear how these thresholds were set as no reference is made to any scientific literature supporting these absolute values (ICC, 2005;
Portus, Rosemond, & Rath, 2006). In 2005 the ICC reviewed testing data from 21 international fast bowlers collected from the Australian Institute of Sport (AIS), University of Auckland (sample of fast and spin bowlers), University of Western Australia (UWA, sample of fast and spin bowlers), as well as an internal funded project (personal communication, June 2015). This review highlighted that elbow extension range of motion values ranged from 3° to 26° with a mean of 9°. Subsequently the ICC increased the allowable threshold to 15° of elbow extension for all bowlers rather than simply referring to it as elbow straightening. Bowlers were also required to have their actions independently assessed in a laboratory setting, using a motion analysis system and a consistent kinematic model (Portus et al., 2006). The current kinematic model adopts a Calibrated Anatomical Systems Technique (CAST), which attempts to minimise the presence of skin movement artefact through a cluster based approach (Capozzo, Catani, Della Croce, & Leardini, 1995).

While there has been significant research in the area of illegal actions in cricket, the focus in the main has been on quantifying or exploring better methods of measuring elbow kinematics, as opposed to understanding if performance benefits exist when the elbow extends by 15° or more. This current body of research has included measuring kinematics for bowlers with varying elbow anthropometry (Aginsky & Noakes, 2010; King & Yeadon, 2012), improving kinematic modelling techniques and exploring other potential variables as a measure for illegality (Chin, Lloyd, Alderson, Elliott, & Mills, 2010; Elliott, Alderson, & Denver, 2007; Ferdinands & Kersting, 2007; Wells, Donnelly, Dunne, Elliott, & Alderson, 2015; Yeadon & King, 2015), as well as exploring more task representative means of testing using inertial sensor based technology (Spratford et al., 2014; Wells, Cereatti, et al., 2015; Wixted, Portus, Spratford, & James, 2011). While these are all important issues, the underlying questions that have yet to be answered remain; does a bowler gain a performance benefit and what biomechanical variables other than elbow extension differ between bowlers who deliver the ball with an illegal, compared with a legal, action? The ability to answer these questions will either reinforce the current law or provide administrators with quantitative data to make a more informed decision around subsequent future changes. It will also provide
support staff with knowledge that will allow them to better remediate bowlers with illegal actions.

While attempts have been made to explore performance benefits, limitations remain. Researchers have attempted to model fixed flexion elbow angles and their relationship to wrist velocity, inferred as ball speed (Marshall & Ferdinands, 2003). Results indicated a positive relationship driven by the increased humeral rotation that occurs when the elbow is flexed. The limitation to this modelling approach is that fixed elbow flexion during delivery phase is rarely reflected in in-vivo bowling due to the centrifugal accelerations acting on the long axis of the forearm causing extension at the elbow joint (Wixted, James, & Portus, 2011). Those bowlers who have a naturally occurring fixed flexion, that is they are unable to fully extend their arm (at full extension the arm is still flexed), have the obvious capacity to report a flexion angle at BR. This naturally occurring deformity is clearly observed for prominent Sri Lankan off-spin bowler and world leading Test wicket taker Muttiah Muralitharan, allowing him to take advantage of increased humeral rotations via recruitment of musculature that contributes to humeral rotation when the elbow is in fixed flexion/abduction. Mr. Muralitharan’s fixed elbow flexion has been reported as 37°, with an elbow abduction angle (also referred to as “carry angle”) of 18°. In theory, for Muttiah Muralitharan to return an elbow extension range greater than 15°, he would have to exhibit an absolute peak magnitude of at least 52° of elbow flexion following the UAH event. This coupled with high levels of elbow abduction can make it extremely difficult for umpires to subjectively discern if the elbow extension range is greater than 15°, particularly given the likelihood of parallax error associated with non-standard upper limb alignments (Aginsky & Noakes, 2010).

Ferdinands and Kersting (2007) also explored the link between elbow extension angular velocities at the point of BR, and its influence on ball release speeds in both legal and illegal fast, medium, and spin bowling groups. The limitation to this study was the small illegal cohort, which consisted of six bowlers from the above three groups and only a single finger spin (FS) bowler, however they suggested that elbow angular velocity measures may be a valid measure of bowling illegality. Subsequently the authors recommended further research was warranted. Research by Middleton and colleagues (2015) explored the use of
an intuitive forward kinematic modelling process that utilised a substantial data set from a sample of fast bowlers, which permitted influences of both elbow flexion/extension and the abduction axis to be altered and the resultant influence on ball release speed estimated. This study's finding reported elbow extension and range of motion to be negatively related to wrist velocity and subsequent ball speeds, whereby the elbow extension nearing BR was associated with reduced ball velocity. This can be explained by the relatively planar (sagittal) alignment of the fast bowler’s upper limb near ball release (where elbow extension will cause the wrist joint centre to move in the opposite direction of the ball’s delivery). Although this is an interesting finding at odds with the current law, with respect to performance benefits, the relevance of the result to the more non-planar spin bowling motion is unknown.

While it is important to understand the implications that bowling with an illegal action has on performance for all types of bowlers, it is especially important for FS bowlers, as their basic biomechanical movement includes a natural tendency to extend the elbow through the point of ball release (BR) (Chin et al., 2009; Spratford et al., 2014). Researchers also need to move past a simplistic model of using BR speeds as the criterion measure of performance and include other variables such as the ability to place revolutions on the ball, which has been consistently shown in the literature as a distinguishing factor in spin bowling performance (Beach et al., 2014; Chin et al., 2009; Justham et al., 2008).

2.5 Aerodynamics of a cricket ball during spin bowling

The aerodynamics of a cricket ball is complex due to its construction and changing condition throughout a match. It is made from four separate pieces of leather, two per hemisphere, joined together at its equator by series of six seams each of between 80-90 stitches (Sayers & Hill, 1999) (Figure 2.1). Depending on the type of match, a ball can be used anywhere between 20 overs (T20) and 80 overs (Test match and 1st Class cricket) (Cricket Australia playing conditions). During play, it is common for the bowling team to shine one side of the ball and leave the other rough in order to maximize the swing produced by the unequal distribution of the air flow during flight aided by the
orientation of the seam tripping the lamina flow (Mehta, 1985, 2005; Mehta, Bentley, Proudlove, & Varty, 1983).

![Figure 2.1. The seam of the cricket ball is described by the stitching (six rows) depicted vertically and the join between the white and red panels. In international competitions, the ball is either all red or white.](image)

To date, a majority of the aerodynamic research has focused on the mechanisms that produce both conventional and reverse swing via wind tunnel modelling for fast bowling. Methods have included; rolling balls down a ramp (Mehta et al., 1983), balls mounted on a pendulum (Mehta et al., 1983), mounted stationary and mounted spinning balls (Sayers, 2001; Sayers & Hill, 1999), as well as various conceptual modelling methods (Baker, 2010; Pahinkar & Srinivasan, 2010; Robinson & Robinson, 2013). The basic mechanics of ball flight for a fast bowler, with the axis of rotation orthogonal to the direction of travel, make wind tunnel testing possible as the ball can be rotated without influencing airflow (Mehta, 2005). In general, the results of this research have indicated that the swing of the ball is influenced by the Reynolds number (Re), defined as $Re = \frac{Ud}{\nu}$ where $U$ = ball velocity, $d$ = diameter of the ball and $\nu$ = the air kinematic viscosity, BR velocity, angle and stability of the seam during flight (Mehta, 2005). At certain levels the seam trips one side of the balls laminar boundary layer into turbulent flow, while flow on the other side remains laminar (Mehta & Pallis, 2001).
Aerodynamic research dedicated to spin bowling is rare, due mainly to the complexities in facilitating ball revolutions at high frequencies, in a similar direction to that of the airflow (Robinson & Robinson, 2013). Sayers and Hill (1999) successfully did this for a top spinning delivery with a ball that had a ‘roughened’ side (they were limited to top spin due to the mechanism that held the ball) and reported that the circulation of air around the spinning ball, in conjunction with the free stream velocity, created what is known as a Magnus effect. This force acts in the opposite direction to the ball rotation. In applied terms, when a right-arm FS bowler delivers a ball to a right handed batsman, the natural drift will be towards the off-side or away from the batsmen and opposite for right-arm wrist-spin bowlers (their revolutions are in the opposite direction) (Robinson & Robinson, 2013; Woolmer et al., 2008). They also found that the force created was dependent on the free stream velocity (air moving around the boundary layer of the ball influenced by the roughened surface of the ball) and the speed of rotation. It must be noted that ball revolutions reached only 16 per second, which is much lower than both FS and WS bowlers.

Comparable research in tennis serving has found that a kick serve is influenced more by Magnus force than any other serve type. During the kick serve the axis of rotation is orthogonal to the direction of travel, undergoes topspin and trades-off high levels of ball revolutions for lower ball velocity (Sakurai, Reid, & Elliott, 2013). These biomechanical characteristics, while not identical (axis of rotation is not orthogonal to direction of travel) to spin bowling, share more in common (topspin imparted) when compared with fast bowling, where the ball undergoes backspin and doesn’t rely on the Magnus effect to produce movement through the air (Baker, 2010; Mehta, 2005; Mehta et al., 1983; Pahinkar & Srinivasan, 2010; Sayers, 2001; Sayers & Hill, 1999).

2.6 Isokinetic strength of the arm

To date there has been no research that has explored the isokinetic strength of the bowling limb for spin bowlers of any type. Research does exist for fast bowlers, with peak isokinetic shoulder extension torque being correlated with increased BR speeds (Wormgoor et al., 2010) whereas peak shoulder internal
rotation and external rotation torque were not related to BR speed (Loram et al., 2005; Wormgoor et al., 2010).

While there is limited research within cricket, a significant body exists for other sports that involve throwing, such as handball and baseball. Handball research has reported that peak isokinetic strength of the shoulder (internal rotation and external rotation) was not a good indicator of throwing velocity or accuracy, regardless of the type of throw or ability of the subject (Bayios, Anastasopoulou, Sioudris, & Boudolos, 2001; Zapartidis, Gouvali, Bayios, Boudolos, & 2007). Conversely, baseball pitching research suggests a correlation between peak torque production during shoulder adduction/extension and resultant throwing speed (Bartlett, Mitchell, Storey, & Simons, 1989; Pedegana, Elsner, Roberts, Lang, & Farewell, 1982). Pedegana et al. (1982) also reported a positive correlation between peak elbow and wrist extension torques and throwing velocity in professional baseball pitchers. Finally, authors also purport that increased upper extremity strength is extremely important in preventing injury and critical to injury rehabilitation (Noffal, 2003; Powers, 1998).

It is assumed that strength at the shoulder will play an important role in spin bowling, however, given the mechanics of the action, and that performance is not solely judged by throwing speed or velocity, muscular strength at the elbow and wrist may be of more importance. The results of this research will provide foundation knowledge about the isokinetic strength of spin-bowlers and its relationship to performance. It will also highlight any strength differences that might occur between skill levels, subsequently assisting both coaching and conditioning staff in implementing targeted strength programs to improve performance. Numerous examples within the literature exist of strength based interventions that have been shown to improve performance (Carter, Kaminski, Douex, Knight, & Richards, 2007; Raeder, Fernandez-Fernandez, & Ferrauti, 2015; Wooden et al., 1992).

2.7 Anthropometry and range of motion

To date, no anthropometric data exists for either FS or WS bowlers, and there is limited data regarding active range of motion at the shoulder, elbow, wrist or
phalangeal joints. Non-standard upper-limb anatomical characteristics of elbow fixed flexion and carry angle have been reported from the bowling arms of international and high performance FS bowlers, with a reported higher levels of fixed flexion ($19.9° \pm 9.4 - 13.2° \pm 5.4$) and “carry angle” ($21° \pm 4.7 - 18.3° \pm 8.8$) in elite bowlers when compared with high performance bowlers (Chin et al., 2009). In comparison several studies have examined anthropometry and range of motion in fast bowlers, with authors finding no correlation to BR velocity when assessing height and various mass measures (fat, bone, residual, muscle and percentage muscle), bone lengths (acromiale-radiale, radale-stylion, stylion-dactylion) and bone girths (trochanterion, biacromial, bi-iliocristal, chest depth) (Pyne, Duthie, Saunders, Petersen, & Portus, 2006; Wormgoor et al., 2010). However, one study reported a high correlation between increased BR velocity and shoulder to wrist length and total arm length (Glazier et al., 2000). Fast bowlers have also been reported to have several morphological differences compared with batsmen. These include, decreased shoulder internal rotation and increased external rotation range of motion about the glenohumeral joint (Giles & Musa, 2008; Stretch, 1991).

Significantly more literature exists exploring the anthropometry and range of motion for baseball pitchers with research showing significant differences in body morphology between playing levels (Carvajal et al., 2009; French, Spurgeon, & Nevett, 2007). Pitchers have also shown to have on average 9° greater magnitude in shoulder external rotation (arm abducted), 5° more forearm pronation, and 9° less shoulder extension in comparison with other playing positions (Brown, Niehues, Harrah, Yavorsky, & Hirshman, 1988). Within athlete asymmetries have also been reported with greater shoulder external rotation range of motion and lower internal rotation range of motion values of up to 15° found in pitching versus non-pitching arms (Bigliani et al., 1997; Brown et al., 1988; Crockett et al., 2002).

### 2.9 Conclusion

Spin bowling plays an important role within the game of cricket, with long axis rotations of the pelvis, thorax and elbow, as well as increased shoulder
horizontal linear velocity reported in FS bowlers who participate at higher levels. However, much about the FS and WS spin bowling actions are poorly understood and include questions surrounding:

- The influence of ball kinematics on performance in WS bowlers,
- Quantifying the location of the seam at BR and during initial flight, and investigating its links to performance,
- The influence of upper-body mechanics on performance in WS bowlers,
- The influence of bowling limb angular velocities and joint kinetics on performance in FS bowlers,
- The influence of upper-body anthropometry on performance in both FS and WS bowlers,
- The influence of upper-body isokinetic strength on performance in both FS and WS bowlers.
Chapter 3: General Methodology

3.1 Introduction

This chapter details the methods and procedures used in studies one through four (chapters four through seven of this thesis). Ethics approval was granted in accordance with the requirements of the Australian Institute of Sport and the University of Western Australia’s Human Research Ethics Committees (approval number 20091201, Appendices A and B). Both verbal and written project information were provided to each participant before informed consent was obtained and testing commenced (Appendices A, B, C D and E).

3.2 Participant information

Sixty-eight elite male spin bowlers, consisting of 48 finger-spin (FS) (36 right-arm and 12 left-arm bowlers) and 20 wrist-spin (WS) (20 right-arm) bowlers were invited to participate in these studies. Participants were assigned by the author to one of three groups for FS bowlers and two groups for WS bowlers, based on the level of cricket they had previously played (pathway or elite) and the legality of their bowling action when considering the current ICC law.

- **Pathway** FS and WS groups comprised of bowlers who were currently competing at a minimum level of state U19 representation and up to and including List A level cricket (open age state based 1-day level).
- **Elite** FS and WS groups comprised of bowlers who were currently playing at 1st class level or above (Test cricket).
- The **pathway FS illegal** group comprised of pathway level bowlers who presented with elbow extension values greater than 15° between upper arm horizontal (UAH) and ball release (BR) (ICC, 2005).

These cohorts represented the entire population within Australia for this level of bowler plus another 11 international participants, who were, at the time of testing, representing their country at the U19 Cricket World Cup. The cohort included nine bowlers, who had played Test cricket (74 games and 300 wickets) and five who had played International 1-day cricket (131 games and 129
Subsequent to this testing, three more players were selected to play Test cricket for Australia. The physical characteristics of the participants are outlined in Table 3.1

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway FS</td>
<td>24</td>
<td>19.4 ± 2.7</td>
<td>181.8 ± 6.9</td>
<td>74.0 ± 8.2</td>
</tr>
<tr>
<td>Elite FS</td>
<td>12</td>
<td>24.9 ± 6.5</td>
<td>179.6 ± 6.9</td>
<td>76.0 ± 12.2</td>
</tr>
<tr>
<td>Pathway WS</td>
<td>12</td>
<td>19.6 ± 3.6</td>
<td>179.6 ± 6.9</td>
<td>71.0 ± 8.0</td>
</tr>
<tr>
<td>Elite WS</td>
<td>8</td>
<td>29.6 ± 7.8</td>
<td>180.2 ± 4.2</td>
<td>71.8 ± 8.0</td>
</tr>
<tr>
<td>Pathway illegal</td>
<td>12</td>
<td>19.4 ± 2.7</td>
<td>173.3 ± 9.8</td>
<td>66.9 ± 12.8</td>
</tr>
</tbody>
</table>

**Laboratory equipment**

Bowling data collection took place in a purpose built indoor cricket laboratory at the Australian Institute of Sport. (Figure 3.1).

Marker trajectories were tracked using a 22 camera (MX 13 and 40) Vicon MX motion analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. The capture volume was approximately 10 m long, 5 m wide and 4 m high allowing for two full strides before the delivery stride and 3 m of ball flight post release to be collected.
**Laboratory calibration**

Prior to data collection, calibration of the cameras was undertaken following manufacturer recommendations by moving a calibration wand with five markers (Figure 3.2) of known locations throughout the capture volume, allowing for the calculation and orientation of all cameras relative to each other. The global coordinate system (CS) was then set by placing the calibration wand at the front crease with the \( x \)-axis pointing right, \( y \)-axis pointing towards the batsman and the cross product \( z \)-axis pointing upwards. A residual error of \( \leq 0.3 \) pixels per camera was considered acceptable during the dynamic calibration process.

![Five point calibration wand](image)

**Figure 3.2.** Five point calibration wand used for calibrating and orientating the motion analysis cameras.

### 3.3 Marker set

**Subject calibration**

An upper-body marker set was attached to the participant’s body with double sided non-allergenic toupee tape (Creative Hair Products, Melbourne, Australia). A combination of Fixomull stretch (BSN Medical, Hamburg, Germany) and 3.8 cm Leuko Sports Tape Premium Plus (Beiersdorf, North Ryde, Australia) were then placed over each marker for additional stabilisation (Figure 3.3).
Figure 3.3. Upper-body markers affixed to the skin using toupee tape and a combination of Fixomull and Leuko Sports Tape

Once markers were affixed to the participant a static calibration was performed in the anatomical position allowing for the location of joint centres (JC), joint axes of rotation, and for the associated segmental technical (TCS) and anatomical coordinate systems (ACS) to be defined. In accordance with the calibrated anatomical systems technique (CAST) (Capozzo et al., 1995) pointer trials were used to identify and store the location of the lateral and medial elbow epicondyles.

**Marker locations**
The 56 retro-reflective markers, consisting of 48 dynamic and eight static were consistent with the University of Western Australia’s (UWA) upper-body model (Campbell, Lloyd, Alderson, & Elliott, 2009; Chin et al., 2010; Lloyd et al., 2000) and was extended to include a metacarpophalangeal joint (MCP) for FS bowlers. Markers ranged from 9 mm (finger markers) to 12 mm (all others) in diameter and were either attached to bony landmarks, or comprised of three marker clusters located on semi-rigid plastic or lightweight aluminium bases (Figures 3.4, 3.5 and 3.6).
Figure 3.4. The UWA’s dynamic upper-body marker set

Figure 3.5. Static markers used to define the wrist joint centres.

Figure 3.6. Static and dynamic markers used to create the MCP joint are shown in figure A, with dynamic markers of the finger and static markers of the wrist shown in panel B.
A detailed description of all marker placements and naming conventions are presented in Tables 3.2 and 3.3.

Table 3.2. Upper-body marker placements and naming conventions

<table>
<thead>
<tr>
<th>Segment</th>
<th>Marker</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>RFHD</td>
<td>Right front head</td>
</tr>
<tr>
<td></td>
<td>RBHD</td>
<td>Right back head</td>
</tr>
<tr>
<td></td>
<td>LFHD</td>
<td>Left front head</td>
</tr>
<tr>
<td></td>
<td>LBHD</td>
<td>Left back head</td>
</tr>
<tr>
<td>Thorax</td>
<td>C7</td>
<td>Spinous process of 7th cervical vertebra</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>Spinous process of 10th thoracic vertebra</td>
</tr>
<tr>
<td></td>
<td>CLAV</td>
<td>Sternal notch</td>
</tr>
<tr>
<td></td>
<td>STRN</td>
<td>Xyphoid process of the sternum</td>
</tr>
<tr>
<td>Pelvis</td>
<td>RASI</td>
<td>Right anterior superior iliac spine</td>
</tr>
<tr>
<td></td>
<td>RPSI</td>
<td>Right posterior superior iliac spine</td>
</tr>
<tr>
<td></td>
<td>LASI</td>
<td>Left anterior superior iliac spine</td>
</tr>
<tr>
<td></td>
<td>LPSI</td>
<td>Left posterior superior iliac spine</td>
</tr>
<tr>
<td>Right Shoulder</td>
<td>RACR1</td>
<td>Right acromion cluster: posterior</td>
</tr>
<tr>
<td></td>
<td>RACR2</td>
<td>Right acromion cluster: superior</td>
</tr>
<tr>
<td></td>
<td>RACR3</td>
<td>Right acromion cluster: anterior</td>
</tr>
<tr>
<td>Left Shoulder</td>
<td>LACR1</td>
<td>Left acromion cluster: posterior</td>
</tr>
<tr>
<td></td>
<td>LACR2</td>
<td>Left acromion cluster: superior</td>
</tr>
<tr>
<td></td>
<td>LACR3</td>
<td>Left acromion cluster: anterior</td>
</tr>
<tr>
<td>Right Upper Arm</td>
<td>RUA1</td>
<td>Right upper arm cluster: superior</td>
</tr>
<tr>
<td></td>
<td>RUA2</td>
<td>Right upper arm cluster: intermediary</td>
</tr>
<tr>
<td></td>
<td>RUA3</td>
<td>Right upper arm cluster: inferior</td>
</tr>
<tr>
<td>Left Upper Arm</td>
<td>LUA1</td>
<td>Left upper arm cluster: superior</td>
</tr>
<tr>
<td></td>
<td>LUA2</td>
<td>Left upper arm cluster: intermediary</td>
</tr>
<tr>
<td></td>
<td>LUA3</td>
<td>Left upper arm cluster: inferior</td>
</tr>
<tr>
<td>Distal Right Upper Arm</td>
<td>dRUA1</td>
<td>Distal right upper arm cluster: superior</td>
</tr>
<tr>
<td></td>
<td>dRUA2</td>
<td>Distal right upper arm cluster: intermediary</td>
</tr>
<tr>
<td></td>
<td>dRUA3</td>
<td>Distal right upper arm cluster: inferior</td>
</tr>
<tr>
<td>Distal Left Upper Arm</td>
<td>dLRUA1</td>
<td>Distal left upper arm cluster: superior</td>
</tr>
<tr>
<td></td>
<td>dLUA2</td>
<td>Distal left upper arm cluster: intermediary</td>
</tr>
<tr>
<td></td>
<td>dLUA3</td>
<td>Distal left upper arm cluster: inferior</td>
</tr>
<tr>
<td>Right Forearm</td>
<td>RFA1</td>
<td>Right forearm cluster: medial</td>
</tr>
<tr>
<td></td>
<td>RFA2</td>
<td>Right forearm cluster: intermediary</td>
</tr>
<tr>
<td></td>
<td>RFA3</td>
<td>Right forearm cluster: lateral</td>
</tr>
<tr>
<td>Left Forearm</td>
<td>LFA1</td>
<td>Left forearm cluster: medial</td>
</tr>
<tr>
<td></td>
<td>LFA2</td>
<td>Left forearm cluster: intermediary</td>
</tr>
<tr>
<td></td>
<td>LFA3</td>
<td>Left forearm cluster: lateral</td>
</tr>
</tbody>
</table>
Table 3.3. Static calibration marker placements and naming conventions

<table>
<thead>
<tr>
<th>Marker</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wrist</strong></td>
<td></td>
</tr>
<tr>
<td>RWRU</td>
<td>Right wrist: ulna side</td>
</tr>
<tr>
<td>RWRR</td>
<td>Right wrist: radius side</td>
</tr>
<tr>
<td>LWRU</td>
<td>Left wrist: ulna side</td>
</tr>
<tr>
<td>LWRR</td>
<td>Left wrist: radius side</td>
</tr>
<tr>
<td><strong>Metacarpophalangeal</strong></td>
<td></td>
</tr>
<tr>
<td>RMCPJ</td>
<td>posterior of the right metacarpophalangeal joint</td>
</tr>
<tr>
<td>LMCPJ</td>
<td>posterior of the left metacarpophalangeal joint</td>
</tr>
<tr>
<td><strong>Proximal interphalangeal</strong></td>
<td></td>
</tr>
<tr>
<td>RPIPU</td>
<td>Right PIP ulna side</td>
</tr>
<tr>
<td>RPIPR</td>
<td>Right PIP radius side</td>
</tr>
<tr>
<td>LPIPU</td>
<td>Left PIP ulna side</td>
</tr>
<tr>
<td>LPIPR</td>
<td>Left PIP radius side</td>
</tr>
</tbody>
</table>

**Ball calibration**

In order to measure ball kinematics and to recreate the seam during bowling trials, at the commencement of each testing session all testing cricket balls were statically calibrated using a custom approach. Four markers were evenly distributed around the seam and three dynamic hemispherical markers, comprised of ultralight foam (<0.1g) were affixed in positions that did not impede each individual during bowling (Figure 3.7A and 3.7B). The positions of the four markers were recorded with reference to a technical coordinate system.
created using the three hemispherical markers. Seam markers were subsequently removed before dynamic bowling trials commenced, however their ball embedded location could be reconstructed during any dynamic bowling trial where the TCS could be reconstructed from the three hemispherical markers.

![A B](image)

Figure 3.7. The four static seam markers and one dynamic marker are shown in figure A (ball front) with the remaining two (of 3) dynamic markers in figure B (ball rear).

A detailed description of all ball marker placements and naming conventions are presented in Table 3.4.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Marker</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball (dynamic)</td>
<td>CBall1</td>
<td>Placed on the ball in positions that do not interfere with technique (bowler input required).</td>
</tr>
<tr>
<td></td>
<td>CBall2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CBall3</td>
<td></td>
</tr>
<tr>
<td>Seam (static)</td>
<td>Seam1</td>
<td>Centre of the seam: polar opposite to Seam3</td>
</tr>
<tr>
<td></td>
<td>Seam2</td>
<td>Centre of the seam: polar opposite to Seam4</td>
</tr>
<tr>
<td></td>
<td>Seam3</td>
<td>Centre of the seam: polar opposite to Seam1</td>
</tr>
<tr>
<td></td>
<td>Seam4</td>
<td>Centre of the seam: polar opposite to Seam2</td>
</tr>
</tbody>
</table>

3.4 Bowling trials

Set up
As the laboratory was a purpose built cricket facility a permanent artificial pitch existed (Figure 3.1). Crease markings at the bowling end were installed using Cloth Tape (3M, Australia) and stumps placed at both the bowling and facing
batsman’s end (20.12 m apart) (ICC, 2013). Two aluminium frames straddled the pitch, two metres behind the bowler’s stumps and six metres in front. Four Vicon cameras, two per frame, were mounted above the bowler to facilitate adequate reconstruction of the ball and phalange markers. The remaining 18 cameras were evenly distributed around the capture volume (Figure 3.8)

![Figure 3.8. An example of the capture volume and aluminium frames.](image)

Participants were asked to nominate where their standard FS or WS delivery would pass the batsman based on a clear target that consisted of a series of 20 cm x 20 cm grids positioned on the batting crease (Figure 3.9). This allowed for the identification of valid delivery as one that impacted the target on the nominated grid, the one directly above, underneath or immediately next to the nominated grid to the off-side (to the batsman’s right).
Bowling trials
Participants were instructed to warm up as per their normal pre game routine and bowl six overs as per a game situation to a right handed batsman, with a timed two minute break between each over to replicate match conditions. For task representation the six overs consisted of 20 stock off-spin (FS) or leg-spin (WS) deliveries and 16 self-nominated variation deliveries broken into two types to reflect those that they would normally bowl in a game. The deliveries were bowled in a randomised order.

3.5 Modelling

3.5.1 Joint centre definitions

During static subject calibration, the three dimensional (3D) locations of the static joint markers (Table 3.3) relative to the associated segment technical CS were calculated and stored. This enabled virtual markers and JCs to be created during dynamic bowling trials thus reducing the influence of skin artefact during dynamic motion (Fuller, Lui, Murphy, & Mann, 1997; Leardini, Chiari, Della Croce, & Cappozzo, 2005; Reinschmidt et al., 1997)
Shoulder

The glenohumeral joint is assumed to be the centre of the shoulder and was calculated using the regression equation of Campbell and colleagues (Campbell, Lloyd, et al., 2009). The equation incorporates the sternal notch (CLAV), 7th cervical vertebra (C7), the midpoint of the lateral ridge of the acromial plateau (AcrLR), the centre point CLAV and C7 (CP) and the subject’s height and mass and was expressed as the following:

Shoulder Joint Centre (SJC)

\[
\begin{align*}
    z &= 96.2 - 0.302 \times (\text{CLAV} - \text{C7mm}) - 0.364 \times \text{height(cm)} + 0.385 \times \text{mass(kg)} \\
    y &= -66.32 + 0.30 \times (\text{CLAV} - \text{C7mm}) - 0.432 \times \text{mass(kg)} \\
    x &= 66.48 - 0.531 \times (\text{AcrLR} - \text{C7mm}) + 0.571 \times \text{mass(kg)}
\end{align*}
\]

The position of the SJC was calculated during the static calibration procedure with the subject in the anatomical position. Its position is held relative to both the TCSs of the acromion and upper arm clusters. To reduce the error in the location of the SJC during overhead dynamic motion, its location is expressed as the mean of the two positions relative to the acromion and upper arm TCS.

Elbow

To better estimate the position of the elbow joint centre (EJC) the pointer method was adopted to identify the locations of the medial and lateral epicondyles of the humerus. The pointer contained five 16 mm retro-reflective markers and required data to be captured while the tip of the pointer was placed on the most lateral and medial aspects of the humeral epicondyles. The location of these critical landmarks were stored in the distal upper arm TCS (Figure 3.10).
Figure 3.10. Spherical 6-marker pointer that was used to define the medial and lateral humeral epicondyles

**Wrist**

The wrist joint centre (WJC) was defined as the midpoint between markers placed on the styloid processes of the radius and ulna during the static calibration process and held in the TCS of the forearm segment.

**Metacarpophalangeal (MCP)**

The metacarpophalangeal joint centre (MCPJC) of the second phalange was defined as the midpoint between the anterior and posterior side of the joint between the metacarpal and proximal phalanx. A marker was placed on the posterior side of the joint with the thickness of the joint distance manually measured. During the static calibration procedure, the hand was held horizontal to the ground and a vertical line projected down from the posterior marker half that of the measured distance and held in the TCS of the hand segment.

### 3.5.2 Defining anatomical coordinate systems (ACS)

ACS were constructed to represent the rigid segments in the human body; these are explained below, with examples shown in Figure 3.11.
Head
The head CS was created with the origin located at the midpoint of the RFHD and LBHD markers. The \( z \)-axis was defined as LFHD to RFHD. The cross product of the \( z \)-axis and the vector running from the midpoint of RBHD to LBHD to the origin defined the \( y \)-axis. The \( x \)-axis was the cross product of the \( y \) and \( z \)-axes.

Thorax
The thorax CS was created with the origin located at the midpoint of the CLAV and C7 markers. The \( y \)-axis was defined as the unit vector running from the midpoint of STRN and T10 markers to the origin. The cross product of the \( y \)-axis and the vector running from the STRN marker defined the \( x \)-axis and the cross product of the \( z \) and \( y \)-axes completed the CS.

Torso
The torso CS was created with the origin located at the midpoint of T10 and STRN markers, and the \( x \)-axis the unit vector running from T10 to STRN. The \( z \)-axis was the cross product of the \( x \)-axis and the unit vector running from C7 to T10, with the \( y \)-axis orthogonal to the \( x-z \) plane.

Pelvis
The pelvis CS was created with the origin located at the midpoint of the LASI and RASI markers. A virtual sacrum marker (SACR) was created in order to define the pelvis. The \( z \)-axis was defined as the unit vector running from the LASI and RASI markers. The cross product of the \( z \)-axis and the vector running from SACR to the pelvis origin defined the \( y \)-axis. The cross product of the \( z \) and \( y \) axes produced the \( x \)-axis of the pelvis coordinate system.

Upper arm
The upper arm CS was created with the origin located at the EJC. The unit vector directed proximally between the EJC and SJC defined the \( y \)-axis of each upper arm segment. The cross product of the \( y \)-axis and the vector running from the lateral to medial elbow markers produced the \( x \)-axes of the right upper arm CS. The \( y \)-axis was crossed with an inverted vector (medial to lateral) to
define the $x$-axes of the left upper arm coordinate system. Crossing the $x$ and $y$ axes produced the final defining axis ($z$).

**Forearm**
The forearm CS was created with the origin located at the WJC. The unit vector directed from WJC to the EJC defined the $y$-axis of the forearm CS. The $x$-axis of the right forearm was defined as the cross product of the $y$-axis and the vector running from the lateral to medial wrist markers. Conversely, the $y$-axis was crossed with the vector running from the medial to lateral wrist markers to produce the $x$-axis for the left forearm. The cross product of the $x$ and $y$ axes produced a unit vector that defined the $z$ axis of the coordinate system.

**Hand**
The hand segment CS was created with the origin located as the midpoint of the three hand markers. The $y$-axis was defined as the unit vector running from the hand origin to the WJC, the cross product of the $y$-axis and the vector running from RNHR to RNHU defined the $x$-axis for the right hand. For the left hand the cross product of the $y$-axis and the vector running from LHNU to LHNR defined the $x$-axis. The cross product of the $x$ and $y$-axes produced a unit vector that defined the $z$ axis of the coordinate system.

**Proximal phalange**
The proximal phalange segment CS was created with the origin located as the midpoint of the medial and lateral proximal phalange segment markers (RPP1 and RPP3). The $y$-axis was defined as the unit vector running from the proximal phalange origin to the MCPJC, the cross product of the $y$-axis and the vector running from RPP3 to RPP1 defined the $x$-axis for the right proximal phalange. For the left proximal phalange, the cross product of the $y$-axis and the vector running from LPP1 to LPP3 defined the $x$-axis. The cross product of the $x$ and $y$-axes produced a unit vector that defined the $z$ axis of the coordinate system.
Figure 3.11. Selected examples of the anatomical coordinate systems within the upper-body segments.

**Ball**

The ball’s CS was created with the origin located as the midpoint of the three ball markers (CBall1, CBall2 and CBall3). The $x$-axis of the ball was defined as the unit vector running from the balls origin to CBall3. The $y$-axis was defined as the cross product of the $x$-axis with the vector running from the ball origin to CBall2. The $z$-axis was the cross product of the $x$ and $y$-axes. The seam of the cricket ball was defined by a circular plane (Figure 3.12) joining the four seam markers and dividing the ball of known diameter (70 mm) into two even hemispheres, with the origin of the ball calculated as the centre of this plane. The origin of the ball was held within the balls TCS created from the hemisphere soft markers. Data were then modelled using the University of Western Australia’s (UWA) ball model based on previous validated work (Jinji & Sakurai, 2007; Sakurai et al., 2013; Whiteside, Chin, & Middleton, 2012) and extended to incorporate seam kinematics based on known mathematical methods. Ball revolutions and angles were expressed relative to the global coordinate system.
3.5.3 Creating anatomical CS during dynamic trials

After the static calibration trials were completed, static markers were removed in preparation for the dynamic or bowling trials. During the dynamic trials, static marker locations were recreated virtually to allow the recreation of the ACS.

3.5.4 Joint coordinate system (JCS) definitions

Once the various ACSs were created, JCSs were constructed to describe the functional movement at each joint. With the exception of the shoulder, all anatomical joints corresponded to the standard Euler angle decomposition convention (Grood & Suntay, 1983) as per International Society of Biomechanics standards (Wu et al., 2005). Functionally, this order corresponds to flexion-extension, adduction-abduction and internal-external rotation with the child segment CS relative to the parent segment CS. Movement at the shoulder joint was described as humeral relative to the thoracic motion (Wu et al., 2005) with the first y-axis of rotation being fixed to the thorax and corresponding with the y-axis of the thoracic CS with superior being positive. The positive x-axis was fixed to the humerus and corresponded with the positive x-axis of the upper arm CS. The second y-axis, defined from EJC to SJC, was that of the upper arm and represented rotation of the humerus. This allowed for joint rotations to be expressed using a Y-X-Y decomposition. Sequence and direction of rotations are described in Table 3.5.
Table 3.5. Sequence and direction of rotations within the joint coordinate system

<table>
<thead>
<tr>
<th>Joint</th>
<th>Z</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>+ Anterior tilt</td>
<td>Upward tilt left</td>
<td>Forward rotation</td>
</tr>
<tr>
<td></td>
<td>- Posterior tilt</td>
<td>Downward tilt left</td>
<td>Backward rotation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(anticlockwise)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(clockwise)</td>
</tr>
<tr>
<td>Elbow</td>
<td>+ Flexion</td>
<td>Adduction (varus)</td>
<td>Pronation</td>
</tr>
<tr>
<td></td>
<td>- Extension</td>
<td>Abduction (valgus)</td>
<td>Supination</td>
</tr>
<tr>
<td>Wrist</td>
<td>+ Flexion</td>
<td>Ulna deviation</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>- Extension</td>
<td>Radial deviation</td>
<td>N/A</td>
</tr>
<tr>
<td>MCP</td>
<td>+ Flexion</td>
<td>Adduction</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>- Extension</td>
<td>Abduction</td>
<td>N/A</td>
</tr>
</tbody>
</table>

3.5.5 Calculation of joint moments

The Vicon motion analysis system uses the custom software scripting package BodyBuilder (Oxford Metrics, Oxford, UK) to construct biomechanical models. It uses a “reaction” function to group together a force and a moment with the moment reference point, around which the force is deemed to act as a single unit, consistent with a conventional inverse dynamics approach. Calculations hard-coded into “reaction” function enabled the output of the three inverse dynamic components of application, force and moments. To be functionally and clinically relevant and to allow for the interpretation of joint moments with respect to joint kinematics, all joint moments were then reported in the JCS, except for those at the shoulder. For the shoulder, joint moments were described relative to the floating axis, rather than relative to the child and parent CSs. Therefore, the flexion-extension moments were output relative to the z-axis of the parent segment (thorax) the internal-external rotation moments relative to the y-axis of the child segment and the abduction-adduction moments relative to the floating axis.

3.6 Data processing

Vicon Nexus software (Oxford Metrics, Oxford, UK), was used to create 3D marker trajectories from two dimensional (2D) data collected from each of the
22 cameras. Broken trajectories of less than 10 frames were filled using a pattern copied from another marker on the same cluster. Data was filtered using a Woltring filter (quintic spline) at a mean square error (MSE) of 20 following a residual analysis and visual inspection of the data (Winter, 2005). Raw markers were then modelled (as outlined in section 3.3) using the custom UWA static and dynamic upper-body models.

Segment and joint motions were calculated and joint kinetics estimated using a standard inverse dynamics approach using inertial parameters from de Leva (1996). All cricket balls were assumed to weigh 156 g with force only being applied to the system when the ball’s origin was within the combined distance of the second phalange (measured prior) and the radius of the ball (35 mm) measured from the CAR marker (Spratford et al., 2014). A customised MATLAB (The Mathworks, Natrick, MA, USA) program was used to normalise time periods to 101 points using a cubic spline technique. To enable this, the following events were added to each trial before the data was exported.

- Back foot impact (BFI), as defined by the first instance the back foot contacts the ground during the delivery phase,
- Upper arm horizontal (UAH), as defined when the EJC and SJC were at their closest vertical position relative to the ground,
- Ball release (BR), as defined above when the ball breaks contact with the fingers.

### 3.7 Anthropometric profile data collection

The anthropometric profile consisted of mass, height (standing and sitting), four girths, three lengths and three breadths and one depth taken from participant’s bowling side of their body and trunk and adhering to International Society for the Advancement of Kinanthropometry (ISAK) procedures (Marfell-Jones, Olds, Stewart, & Lindsay Carter, 2007). All variables were measured in triplicate with the criterion being the median recorded value.
3.7.1 Height and mass

Digital standing scales were used to measure the body’s mass to the nearest 0.1 kg. Stretch height was measured during inspiration using a stadiometer (Holtain Ltd, Crymych, Dyfed, UK) (Figure 3.13).

Figure 3.13. An example of stretch height being measured

Sitting height
Sitting height was measured as the distance from the most superior point of the skull, in the midsagittal plane (vertex) to the base of the sitting surface with the subject sitting tall, with gentle traction applied to the head with the feet on the floor.

3.7.2 Girths

Four girths were measured using a flexible steel tape (Lufkin Executive, Thinline W 606 PM, Cooper Industries, Lexington, SC, USA), calibrated in cm with mm graduations.
Arm girth relaxed
The arm girth relaxed was the perimeter distance measured at the mid acromiale radiale, orthogonal to the long axis of the humerus with the arm hanging relaxed by the side of the participant.

Arm girth flexed
Arm girth flexed was the maximum circumference that can be achieved when the upper arm is raised horizontal to the ground while in the sagittal plane with the elbow supinated and flexed (Figure 3.14)

Figure 3.14. An example of the arm girth flexed being measured

Forearm girth
Forearm girth was the maximum girth of the forearm, measured no more than six cm from the radiale with the elbow in supination and held by the participant’s side.

Wrist girth
Wrist girth was the girth of the wrist distal to the styloid processes.

3.7.3 Lengths
The three lengths were measured using a large sliding calliper (British Indicators Ltd).
Arm length
Arm length was measured as the distance between the superior and external border of the acromion process (acromiale) and the upper and lateral border of the head of the radius (radiale) with the participant standing upright with hands by their sides.

Forearm length
The forearm length was measured as the distance from the radiale to the most distal point of the styloidus radius (stylion) parallel to the long axis of the radius (Figure 3.15).

Figure 3.15. An example of the forearm length being measured

Hand length
The hand length was measured as the distance from the mid-stylion to the distal point of the third phalange (dactylion), while the elbow was in a supinated position and fingers fully extended.
3.7.4 Breadths

The four breadths were measured using a large sliding calliper (British Indicators Ltd).

**Biacromial breadth**
The biacromial breadth was measured as the distance between the most lateral points on the acromion process.

**Transverse chest breadth**
The transverse chest breadth was measured as the distance between the lateral aspects of the thorax at the level of the most lateral aspect of the fourth rib.

**Humerus breadth**
The humerus breadth was measured as the distance between the medial and lateral epicondyles of the humerus when the upper arm is horizontally flexed and the elbow joint at 90° of flexion.

**Anterior and posterior chest depth**
Anterior and posterior chest depth was measured as the distance from mesosternale to the vertebrae at the mesosternale level.

3.8 Range of motion data collection

Active range of motion of the upper bowling limb was assessed using validated methods by experienced clinicians (Gerhardt, Cocchiarella, & Lea, 2002). All variables were measured in triplicate using a bi-level inclinometer (US Neurologicals, Poulsbo, Washington, United States) or goniometer (US Neurologicals, Poulsbo, Washington, United States), with the median value of these being the criterion.
3.8.1 Shoulder

The shoulder range of motion was measured in all three planes.

*Flexion and extension (sagittal plane)*

The participant was placed on a bench against the corner of a wall with one armed braced against the wall to prevent anterior or posterior trunk movement with the measured arm freely moveable (Figure 3.16). The neutral or zero position was set with the forearm in mid-position between pronation and supination directly by their side and orthogonal to the ground. The inclinometer was aligned with the long axis of the humerus in the vertical gravity position. When measuring extension the participant was asked to extend their arm back as far as possible while keeping their trunk straight before returning to the zero position. This process was repeated but in the opposite direction for shoulder flexion.

![Figure 3.16. An example of shoulder range of motion in the sagittal plane being measured](image)

*Abduction (frontal plane)*

The abduction measure was taken while the participant was in the same position as per the shoulder flexion and extension measure. The zero position was also set with the forearm in the pronation and supination mid-position with the inclinometer rotated 90° (to enable measurement in the correct plane) and aligned with the long axis of the humerus in the vertical position. The participant
was asked to abduct their arm as high as possible, while keeping their trunk straight and their forearm in the mid-position.

*Internal and external rotation (transverse plane)*

The internal and external rotation measure was taken while the participant was in the supine position with the shoulder joint in 90° of abduction and elbow joint flexed at 90° (Figure 3.17). The neutral or zero position was set with the forearm vertical and orthogonal to the horizontal and the inclinometer aligned along the long axis of the forearm in the vertical gravity position. When measuring external rotation, the participant was asked to externally rotate at the shoulder as far as they could before returning to the neutral position. This process was repeated but in the opposite direction for internal rotation with the scapula stabilised against the plinth (as seen in Figure 3.17).

![Figure 3.17. An example of shoulder range of motion in the transverse plane being measured](image)

### 3.8.2 Elbow

The elbow range of motion was measured in all three planes.

*Flexion and extension (sagittal plane)*

Flexion and hyper-extension measures were taken with the participant in the sitting position with the upper arm stabilised on the examination table. The
elbow was in the supinated position and beyond the margin of the table to allow free motion of the forearm segment. The zero or neutral position was aligned to the long axis of the forearm in horizontal gravity position, so the inclinometer read 0°. When measuring extension the participant was asked to extend as far as possible before returning to the 0° position. This process was repeated but in the opposite direction for movement into flexion.

**Abduction (carry angle) (frontal plane)**

The carry angle or abduction measure was taken in the sitting position with the elbow supinated and shoulder in flexion (Figure 3.18). The goniometer was extended and aligned along the long axis of the upper arm and forearm with 0° indicating a straight arm and a positive number indicating a carry angle was present.

![Figure 3.18. An example of elbow range of motion in the frontal plane being measured](image)

**Pronation and supination (transverse plane)**

Pronation and supination were measured with the participant sitting in a chair with the upper arm stabilised against the body and the forearm in the mid-position between pronation and supination. The inclinometer was set to the vertical gravity position with participant holding it in the palm of their hand; 0° represented the neutral position. Pronation was measured by asking the participant to pronate their forearm maximally before returning to the neutral position. This process was repeated but in the opposite direction for supination.
3.8.3 Wrist

The wrist range of motion was measured in the sagittal and frontal planes.

*Flexion and extension (sagittal plane)*

Flexion and extension was measured in the sitting position with the forearm pronated and stabilised on a table with the wrist extending past the table margin, allowing unimpeded movement at the wrist. The inclinometer was set in the horizontal gravity position and placed on the long axis of the third metacarpal bone on the dorsal side of the hand, with 0° representing the neutral position. Flexion was measured by asking the participant to flex maximally before returning to the neutral position. This process was repeated but in the opposite direction for extension.

*Radial and ulna deviation (frontal plane)*

Radial and ulna deviation was measured in the sitting position with the forearm in the mid-position between pronation and supination and stabilised on a table to allow movement at the wrist. The inclinometer was placed on the axis of the third metacarpal (palmar side), aligned with the long axis of the forearm and the third digit, and set to 0° to indicate the neutral or starting position. Radial deviation was measured by asking the participant to move into maximal radial deviation while stabilising the forearm with their other hand before returning to the neutral position. This process was repeated but in the opposite direction for ulna deviation.

3.8.4 Metacarpophalangeal

The metacarpophalangeal range of motion was measured in the sagittal plane.

Metacarpophalangeal flexion and extension was measured in the sitting position with the forearm and hand stabilised on a table to allow movement at the fingers. The inclinometer was placed on the proximal phalanx while the finger was supported by the table and set to 0° to indicate the neutral starting position. The participant then moved the forearm and hand forward until the joint was
beyond the stabilisation of the table. Flexion was then measured by asking the participant to move to maximum flexion while the free hand was holding down the tested hand. This process was repeated but in the opposite direction for extension.

3.9 Isokinetic data collection

Participants undertook five upper-limb isokinetic strength tests on the bowling side of their body using a HUMAC NORM dynamometer (CSMI2009, version 9.5.2), as per the manufactures instructions. Data were collected over five continuous cycles at angular velocities of $60^\circ \cdot s^{-1}$ and $180^\circ \cdot s^{-1}$ per movement (Saccol, Zanca, & Ejnisman, 2014; Zanca, Oliveira, Saccol, & Mattiello, 2011). To reduce the likelihood of fatigue one minute’s rest was given between each test. Prior to testing, participants warmed-up using a rowing ergometer for a period of five minutes.

3.9.1 Shoulder

Two strength measures were recorded at the shoulder; these consisted of flexion-abduction/extension-adduction and internal rotation and external rotation.

*Flexion-abduction/extension-adduction*

Flexion-abduction/extension-adduction was measured in the supine position (Figure 3.19) with the participant’s acromion aligned with the Dyna input arm, the elbow/shoulder adapter attached and the handgrip rotation set at H-ABD/H-ADD. The $0^\circ$ point and gravity were set in full extension with the hand resting on the leg. Data were collected through a $140^\circ$ range starting at $10^\circ$ and ending at $150^\circ$ with the first movement being flexion-abduction.
Internal rotation and external rotation

Prior to testing the footrest was installed on the chair, elbow stabiliser pad attached on the input arm and the wrist/shoulder adapter secured with the handgrip set at position 109. Internal rotation and external rotation were measured in the supine position with the shoulder joint in 90° of abduction, elbow joint flexed at 90° (Figure 3.20), axis of rotation (forearm longitudinal line and shoulder) aligned with the Dyna input arm. The 0° point was set with the forearm orthogonal to the body with the measurement range moving from 70° internal rotation through to 70° external rotation for 140° range of motion. Gravity was corrected in internal rotation with the first movement being external rotation from the internal rotation position.
3.9.2 Elbow

Pronation and supination strength was the only measurement recorded at the elbow.

Pronation and supination
Prior to testing the counterbalance weight was attached on the wrist/shoulder adapter, forearm stabiliser pad attached, wrist/shoulder adapter secured at the PRO/SUP line and the handle set at the 112 position. Pronation and supination was measured in the sitting position with the elbow in 90° of flexion (Figure 3.21) with the axis of rotation being the centre of the forearm at the fourth phalange. The 0° position was located in the mid-pronation and supination position with the range of motion moving from 70° pronation to 70° supination (140° total range of motion). No gravity correction was required.

Figure 3.21. An example of pronation and supination at the elbow (Humac Norm, Testing and Rehabilitation System, 2010).

3.9.3 Wrist

Two strength measures were recorded at the wrist and consisted of flexion and extension, and radial and ulna deviation.

Flexion and extension
Prior to testing the thigh/forearm stabiliser tube was attached to the chair, the forearm stabiliser pad installed on the thigh/forearm stabiliser tube, wrist/shoulder adapter secured and the handgrip set to the 113 position. Flexion
and extension were measured in the sitting position with the elbow in 90° of flexion with the axis of rotation being the wrist joint. The 0° position was located in the supinated position with the range of motion moving from 80° flexion to 70° extension (150° total range of motion) (Figure 3.22). No gravity correction was required.

Figure 3.22. An example of flexion and extension at the wrist (Humac Norm, Testing and Rehabilitation System, 2010).

Radial and ulna deviation
Prior to testing the thigh/forearm stabiliser tube was attached to the chair, the forearm stabiliser pad installed on the thigh/forearm stabiliser tube, wrist/shoulder adapter secured and the handgrip set to the 114 position. Radial and ulna deviation was measured in the sitting position with the elbow in 90° of flexion with the axis of rotation being the wrist joint. The 0° position was located in the mid-supinated and pronated position with the range of motion moving from 20° of radial deviation to 30° of ulna deviation (50° total range of motion) (Figure 3.23). No gravity correction was required.
Figure 3.23. An example of radial and ulna deviation at the wrist (Humac Norm, Testing and Rehabilitation System, 2010).
Chapter 4: The effect of performance level on initial ball flight kinematics in finger and wrist-spin cricket bowlers

4.1 Abstract

Spin bowling plays a fundamental role within the game of cricket yet little is known about the initial ball kinematics in elite and pathway spin bowlers and their relationship to performance. Therefore, the purpose of this study was to record three-dimensional ball kinematics in both elite and pathway finger-spin (FS) and wrist-spin (WS) bowlers, identifying potential performance measures that can be subsequently used in future research. A 22-camera Vicon motion analysis system captured markers placed on the seam (static) and ball (dynamic) to quantify ball kinematics in 36 FS and 20 WS bowlers. Results indicated that FS bowlers delivered the ball with an increased axis of rotation elevation, while wrist-spin bowlers placed greater amounts of revolutions on the ball. It also highlighted that ball release (BR) velocity, revolutions and velocity/revolution index scores for both groups and seam stability for FS bowlers, and seam azimuth angle and spin axis elevation angle for WS bowlers, were discriminators of playing level. As such these variables could be used as indicators of performance (i.e. performance measures) in future research.
4.2 Introduction

Bowling is a fundamental aspect of cricket with techniques broadly categorised as either being that of a spin or fast bowler. Spin bowlers can be further classified as finger-spin (FS) or wrist-spin (WS), named loosely to reflect the end point of the body’s kinetic chain responsible for placing revolutions on the ball, causing fundamental differences in ball kinematics (Beach et al., 2014; Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). A right-handed FS bowler places clockwise revolutions on the ball around the horizontal axis with the seam rotated and directed laterally to the leg-side or the direction of the intended side-spin (to the left of a right-handed batsman). Whereas a right-handed WS bowler places anticlockwise revolutions with the seam rotated and directed laterally to the off-side (to the right of a right-handed batsman), in effect creating a mirror image of each other. Figure 1 shows this ball in hand orientation differences between FS (A) and WS (B) at ball release (BR).

Figure 4.1. Posterior view of the ball in hand orientations at BR for FS (A) and WS (B), highlighting the “mirror image” that occurs for the two techniques. Note that the black arrow signifies the direction of rotation for each spin type.

A spin bowler delivers the ball considerably slower than that of their fast bowling counterpart, aiming to land (pitch) the ball between 2 and 3 m in front of the batting crease (Bradman, 1969; Justham et al., 2010; Woolmer et al., 2008). In order to influence the contest, a spin bowler needs to rely on an array of skills to deceive the batsman. Specifically these skills include the ability to control the deflection of ball flight both laterally (drift) and vertically (dip), deviation from the
pitch after bounce (side-spin) and the steepness (reflection) of the ball after bounce (Bradman, 1969; Justham et al., 2010; Justham et al., 2008; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008).

Although fast bowling has been a focal point for cricket research, spin bowling has been afforded comparatively less attention. The few existing studies include descriptive injury surveillance (Corrigan, 1984; Finch, Elliott, & McGrath, 1999; Leary & White, 2000; Orchard, James, Alcott, Carter, & Farhart, 2002; Orchard, James, & Portus, 2006; Stretch, 2003), a comparison of fast bowling injuries with spin bowling injuries (Gregory, Batt, & Angus Wallace, 2002) and a single biomechanical-based FS study (Chin et al., 2009). Ball kinematics in spin bowlers have been studied, with existing research reporting a combination of ball revolutions, ball speed and spin axis angles (vertical and horizontal planes) (Beach et al., 2014; Chin et al., 2009; Cork et al., 2012; Justham et al., 2010; Justham et al., 2008). However no single study reporting these variables has attempted to describe ball seam kinematics, or contained large enough sample sizes to make comparison between skill levels possible. Fundamental research examining rotating spherical objects also provides insight to modelling and ball flight equations specific to spin bowling (Robinson & Robinson, 2013).

Performance based research in fast bowling has used BR speed or velocity as the criterion performance measure and attempted to link this to various kinematic correlates (Glazier et al., 2000; Loram et al., 2005; Wormgoor et al., 2010). This approach is generally justified on the premise that higher release speed reduces the time available for a batsman to make decisions and execute their shot (Abernethy, 1981; Bartlett, Muller, Lindinger, Brunner, & Morriss, 1996; Sarpeshkar & Mann, 2011). It has also been shown to be a discriminator of performance, although significant differences generally occur between elite and youth cohorts (Phillips, Portus, Davids, & Renshaw, 2012; Pyne et al., 2006) and may simply be an artefact of maturation. While it is easy to argue that a single performance measure is a flawed approach, it is a time efficient, reasonably inexpensive, non-invasive variable to collect and is a primary focus of coaching staff at all levels (Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). However, using a single measure of performance such as BR speed for spin bowlers, fails to take into account the many variables that
are needed for a spin bowler to be successful. To enable performance measures to be identified, it is necessary to explore the initial ball kinematics that have been shown to influence ball movement through the air (drift and dip) and after bounce (side-spin and bounce characteristics), allowing a multifactorial approach for performance to be considered.

Drift and dip during ball flight are controlled by the aerodynamic principle known as the Magnus effect, which applies lift and drag forces perpendicular and opposite to the linear velocity vector of a smooth spinning object (Robinson & Robinson, 2013). The magnitude of this force is proportional to the projectile velocity, rate of revolutions and the angle between the ball’s projectile velocity vector and spin axis (Mehta, 1985; Robinson & Robinson, 2013; Watts & Ferrer, 1987). Adding complexity to our understanding of its influence on spin bowling is that traditional theorems are generally based on the assumption that the spin axis is perpendicular to the velocity vector, indicating top-spin is present (Mehta, 1985; Robinson & Robinson, 2013). Whereas, in spin bowling, the spin axis is directed in a similar direction to that of ball travel (Beach et al., 2014; Robinson & Robinson, 2013; Wilkins, 1991).

Modelling specifically focused on ball flight in spin bowlers suggests that during the ball’s ascent to its zenith location (high point of the ball’s trajectory), initial horizontal drift occurs in the same direction the ball is rotating, as a result of the Magnus force arising from the vertical and horizontal components of the velocity vector. During descent, the vertical component of the velocity vector reverses in direction, causing the Magnus force to reverse and the ball to drift laterally at a greater rate, and in the direction opposite to the ball rotation. This change causes the ball to dip vertically towards the ground (Robinson & Robinson, 2013; Wilkins, 1991; Woolmer et al., 2008). It could therefore be assumed, the greater the zenith location, the greater the drift observed during its descent. The amount of dip that occurs during the latter stages of flight increases as the ball’s projectile velocity vector becomes closer to perpendicular to the spin axis (Robinson & Robinson, 2013; Sakurai et al., 2013). In practical terms, a right-handed FS bowler, places clockwise revolutions on the ball indicating that the initial drift during the ball’s ascent will be to the left (leg-side) of a right-handed batsman, and during the descent it will drift away (off-side) from the batsman.
and dip toward the ground. The opposite will occur for a WS bowler, initially to the batsman’s right (off-side) and then to their left (leg-side) during the descent and again dipping toward the ground.

A cricket pitch comprises of closely mown grass on a compacted layer of soil (James et al., 2004, 2005). The characteristics of which, can be influenced by the climatic conditions, geography, differing methods adopted by the ground staff and the deterioration of the surface throughout play (Carre, Baker, Newell, & Haake, 1999; James et al., 2004, 2005; Wilkins, 1991). These inconsistencies make it effectively impossible for science to provide uniform guidelines on bounce characteristics (James et al., 2005). If we assume a cricket pitch is generally flat, the reflection angle of the ball will be governed by the oblique angle of incidence (law of reflection), as well as by the direction and magnitude of the ball’s rotation and velocity (Carre et al., 1999; Carre & Haake, 2000; Cross, 2005; James et al., 2005). Whereas the incidence angle for a fast bowler is primarily a product of release height as the ball is directed down (Bradman, 1969; Cork et al., 2012; Justham et al., 2008). In contrast, the reduced ball speed and inclined projection angle (Beach et al., 2014; Chin et al., 2009; Cork et al., 2012; Justham et al., 2008) in a spin bowling delivery means that the incidence angle is more contingent on the orientation of the ball’s spin axis at release. A ball delivered with back-spin will skid along the surface losing reflection angle and speed as seen in fast bowling, whereas a ball delivered with a degree of top-spin will roll off the surface projecting forward, while maintaining a greater percentage of its incidence angle and speed post bounce, as observed in spin bowling (Cross, 2005; James et al., 2005).

In this case, a spin bowler will deliver the ball with an elevated spin axis (horizontal plane) at BR, with increases producing a higher zenith location in the ball’s trajectory and, subsequently, a steeper descent (and thus incidence angle). Equally, if the spin axis is directed closer to perpendicular to the ball’s projectile velocity vector (horizontal plane), the ball will possess greater top-spin causing the ball to ‘dip’ into the ground, again increasing the incidence angle.

Another confounder is that a cricket ball is not completely smooth, it is made of four pieces of leather, two per hemisphere joined together at its equator by a
series of six raised seams, each between 80-90 stitches (Figure 2.1) (Sayers & Hill, 1999). As these seams are known to influence the aerodynamics of a cricket ball (Baker, 2010; Mehta, 2005; Mehta et al., 1983; Robinson & Robinson, 2013; Sayers, 2001; Sayers & Hill, 1999), it is critical to consider this factor in spin bowling. To date, no in-vivo research has investigated how the orientation of the seam, relative to the spin axis, influences the ball’s trajectory and its influence on performance is therefore unclear.

It is a common claim in the coaching literature as well as being mentioned in some scientific literature, that the amount of “side-spin” experienced by a ball after bounce is directly influenced by the amount of revolutions at BR and the orientation of the seam at bounce (Beach et al., 2014; Bradman, 1969; Wilkins, 1991). Although it must be noted, that this relationship has yet to be empirically substantiated. Research has however shown that ball revolutions and BR velocities act as performance level discriminators between elite and high performance FS bowlers (Chin et al., 2009).

Therefore, the purpose of this study was to provide foundation knowledge of the three dimensional (3D) ball kinematics, including BR velocity, revolutions, and orientations of the spin axis and seam in elite (currently competing at a minimum of 1st Class up to and including Test level) and pathway (currently competing at a minimum level of state U19, up to and including List A level (open age national 1-day level)) FS and WS bowlers. This will allow differences to be identified that can be used to distinguish between skill levels and subsequently used as performance measures in future research. It is hypothesised that elite bowlers will deliver the ball with significantly more velocity, revolutions and with a more stable seam during ball flight.

**4.3 Methods**

Sixty-eight elite male spin bowlers (48 FS and 20 WS) were invited by the national spin bowling coach to participate in this study, with 12 pathway FS subsequently excluded due to an illegal action. Participants were assigned to
one of four groups; Pathway FS, Elite FS, Pathway WS and Elite WS based on the level of cricket they were playing.

This cohort represented the entire population of bowlers at these levels within Australia plus another 11 international participants, who were at the time representing their country at the U19 Cricket World Cup. Within the elite cohort, six FS bowlers had played Test cricket (28 games and 89 wickets) and four who had played International 1-day cricket (128 games and 123 wickets) at the time of testing. The WS cohort had three players who had played Test cricket (46 games and 211 wickets) and one who had played International 1-day cricket (3 games and 6 wickets). Subsequent to this testing, three more players went onto play international Test cricket. Only bowlers who were deemed to have a legal bowling action, less than 15\(^\circ\) of extension, as measured by the ICC protocol (ICC, 2005) were included in this study. The physical characteristics of the participants are outlined in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway FS</td>
<td>24</td>
<td>19.4 ± 2.7</td>
<td>181.8 ± 6.9</td>
<td>74.0 ± 8.2</td>
</tr>
<tr>
<td>Elite FS</td>
<td>12</td>
<td>24.9 ± 6.5</td>
<td>179.6 ± 6.9</td>
<td>76.0 ± 12.2</td>
</tr>
<tr>
<td>Pathway WS</td>
<td>12</td>
<td>19.6 ± 3.6</td>
<td>179.6 ± 6.9</td>
<td>71.0 ± 8.0</td>
</tr>
<tr>
<td>Elite WS</td>
<td>8</td>
<td>29.6 ± 7.8</td>
<td>180.2 ± 4.2</td>
<td>71.8 ± 8.0</td>
</tr>
</tbody>
</table>

Ethics approval was granted and written informed consent was obtained for each participant before the commencement of the study (Appendices A-E).

**Experimental Design**

Participants warmed up as per their normal pre game routine and then bowled six overs with a timed two minute break between each to replicate match conditions. The six overs consisted of 20 stock deliveries (their preferred FS or WS delivery) and 16 self-nominated variation deliveries. Participants were asked to nominate where their usual deliveries would pass a right-handed
batsman based on a clear target that consisted of a series of 20 cm x 20 cm grids (Figure 4.2). Aside from those that struck the target directly, deliveries that impacted a grid directly above, underneath, or horizontally adjacent to the nominated grid on the off-side (to the batsman’s right) were considered successful deliveries. The deliveries were bowled in a randomised order.

![Figure 4.2. Accuracy target used to determine successful deliveries.](image)

**Camera and laboratory set-up**

Bowling data collection took place in an indoor motion capture laboratory that was purpose built for cricket analysis and contained a permanent artificial pitch. Trajectories created from reflective markers adhered to the ball were tracked using a 22-camera (MX 13 and 40) Vicon MX motion analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. The capture volume was 10 m long and 5 m wide allowing for two full strides before the delivery stride and 3 m of ball flight post-BR to be collected. The global reference frame originated at the bowling crease with the $y$-axis pointing down the pitch, the $z$-axis upward and the $x$-axis the right-handed cross product of the previous vectors.

**Data collection and procedures**

In order to recreate the seam during bowling trials, each cricket ball was subject to a static calibration with four retro-reflective markers evenly distributed around the seam and three dynamic hemispherical markers comprised of ultralight
foam (<0.1g) affixed in locations that did not impede the bowler’s preferred grip on the ball (Figure 4.3).

![Figure 4.3. Static ball markers attached evenly around the plane of the seam.](image)

The x-axis of the ball was defined perpendicular to the seam plane, while the y- and z-axes were orthogonal and coincident with the plane of the seam. The static markers were removed prior to the bowling trials. For the purpose of determining BR, a marker was placed on the third metacarpophalangeal joint (CAR) of the bowling hand.

Two dimensional (2D) data from each of the 22-cameras were reconstructed into 3D marker trajectories and labelled using Vicon Nexus software (Oxford Metrics, Oxford, UK). Data were then modelled using the University of Western Australia’s (UWA) ball model based on previous validated work (Jinji & Sakurai, 2007; Sakurai et al., 2013; Whiteside et al., 2012), and extended to incorporate seam kinematics. BR was determined for each individual based on the movement of the origin of the ball in reference to the CAR marker exceeding the distance of the second phalangeal (measured prior) plus the radius of the ball (35mm).
The ball velocity, revolutions and spin axis' orientation in each delivery were computed using the data collected from 30 frames post release. Given the potential variability of the movement of the seam post release, seam angles (azimuth and elevation) were treated as discrete variables from the mean of three frames post-BR and these data were not filtered (Linthorne & Patel, 2011). Representative mean data were then calculated from the best six valid FS trials based on where the ball hit the accuracy target as explained above. To allow comparisons between right and left-handed bowlers, data was matched to reflect that off a right-handed bowler (note, there were no left arm WS bowlers). The kinematic movement patterns (i.e. bowling technique) associated with each delivery are not included in this chapter, but are analysed in subsequent chapters.

**Variables of interest**

Ball velocity was measured as the magnitude of the ball's (centre of the ball) resultant velocity vector. The magnitude of the ball's angular velocity vector denoted revolutions, while its orientation was measured relative to the fixed global coordinate system (CS). The relationship ($x$) between ball velocity ($V$) and revolutions ($\omega$) was calculated using the following equation to produce a velocity/revolution index score:

$$x = (V + \omega) + \frac{V^2}{\omega}$$

(1)
This allowed for increases in BR velocity, relative to revolutions and velocity to be considered and expressed based on evidence that increases in ball revolutions come at a detriment to ball speed (Sakurai et al., 2013).

The spin axis’ azimuth angle ($\theta_{\omega}$) was defined as the excursion of the angular velocity vector from the $x$-axis of the global CS, in the horizontal plane ($0^\circ = \text{coincident with global } x\text{-axis} \rightarrow \text{pointing to on-side}; 90^\circ = \text{coincident with global } y\text{-axis} \rightarrow \text{pointing down the pitch at the batter’s end stumps}; 180^\circ = \text{pointing to off-side}; 270^\circ = \text{pointing back at bowler’s end stumps}$) (Figure 4.5)

![Direction of travel](image)

Figure 4.5. A superior view of the spin axis azimuth angle, whereby ($\theta_{\omega}$) is the angle measured between the angular velocity vector (dotted line) and the $x$-axis of the global CS.

The spin axis’ elevation angle $\phi_{\omega}$ was the angular excursion of the ball’s angular velocity vector from the horizontal ($x$-$y$) plane ($90^\circ = \text{pointing up}; 0^\circ = \text{coincident with horizontal}; -90^\circ = \text{pointing down}$) (Figure 4.6).
Figure 4.6. A sagittal plane view of the spin axis elevation angle, whereby $\varphi_{\omega}$ is the angle measured between the angular velocity vector (dotted line) and the horizontal plane of the global CS.

Novel to this study were the calculations of the seam relative to the global coordinate system and the spin axis. The seam elevation angle $\varphi_{\text{ Seam}}$ was measured as the angle between the plane of the seam and the horizontal (x-y) plane ($0^\circ =$ seam plane “flat” and coincident with horizontal; $90^\circ =$ seam plane “upright” and perpendicular to horizontal) (Figure 4.7).

Figure 4.7. A sagittal plane view of the seam elevation angle, whereby $\varphi_{\text{ Seam}}$ is the angle measured between the plane of the seam and the horizontal plane of the global CS.

After defining a vector originating at the centre of the ball and directed toward the most superior aspect of the seam, the seam azimuth angle ($\theta_{\text{ Seam}}$) was
calculated as the excursion of this vector from the $x$-axis of the global CS, in the horizontal plane (Figure 4.8).

![Figure 4.8. A superior plane view of the seam axis azimuth angle, whereby ($\theta_{\text{Seam}}$) is the angle measured between the plane of the seam and the $x$-axis of the global CS](image)

The acute angle between the ball’s angular velocity vector and the plane of the seam was used to define seam stability ($\omega_{\text{Seam}}$) (Figure 4.9) and expressed as a percentage value according to:

$$\omega_{\text{Seam}} = \frac{\arccos\left(\frac{\text{Ball}_x/\omega}{90}\right)}{100} \times 100$$  \hspace{1cm} (2)

A value of 100 denoted the theoretical condition of perfect stability, whereby the ball’s $x$-axis and angular velocity vector were coincident. On the contrary, a value of 0 denoted perfect instability of the seam (more commonly termed a “scrambled seam”).
Figure 4.9. A sagittal plane view of the seam elevation angle, whereby $\omega_{\text{Seam}}$ is the angle measured between the plane of the seam and the angular velocity vector (dotted line).

**Statistical analysis**

A one-way analysis of variance with a Bonferroni post-hoc was conducted for each dependent variable to identify differences between pathway and elite FS and WS bowlers, as well as between FS and WS groups as a whole. Statistical significance was accepted at the level of $\alpha < 0.05$ with both the assumption of independence and normality being met. Effect sizes were calculated to functionally differentiate between groups, with levels of 0.2, 0.5 and 0.8 representing small, moderate and large effect sizes (Cohen, 1992).

### 4.4 Results

Compared with FS bowlers, WS bowlers generated significantly less ball velocity ($p = 0.050$), greater angular velocity (revolutions) ($p = <0.001$), greater velocity/revolution index ($p = 0.002$), less spin axis elevation angle ($p = <0.001$) and greater seam azimuth angle (once normalised) ($p = <0.001$) (Table 4.2). For the purpose of comparing spin axis and seam azimuth angles between FS and WS bowlers, the WS data were inverted to account for the mirror like differences that occur between delivery types.
Table 4.2. Mean (± standard deviations) ball kinematics for WS and FS bowlers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>FS</th>
<th>WS</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball velocity (m.s(^{-1}))</td>
<td>19.6 (1.2)</td>
<td>19.0 (0.8)</td>
<td>0.050*</td>
<td>0.59</td>
</tr>
<tr>
<td>Revolutions (rev.s(^{-1}))</td>
<td>27.5 (3.2)</td>
<td>36.2 (4.4)</td>
<td>&lt;0.001*</td>
<td>2.26*</td>
</tr>
<tr>
<td>Velocity/revolution index</td>
<td>61.2 (3.9)</td>
<td>65.1 (4.3)</td>
<td>0.002*</td>
<td>0.95*</td>
</tr>
<tr>
<td>Spin axis azimuth (°)</td>
<td>325.3 (11.5)</td>
<td>319.6 (12.0)</td>
<td>0.103</td>
<td>0.48</td>
</tr>
<tr>
<td>Spin axis elevation (°)</td>
<td>14.5 (8.1)</td>
<td>4.9 (6.2)</td>
<td>&lt;0.001*</td>
<td>1.33*</td>
</tr>
<tr>
<td>Seam azimuth (°)</td>
<td>35.4 (9.2)</td>
<td>52.4 (14.9)</td>
<td>&lt;0.001*</td>
<td>1.37*</td>
</tr>
<tr>
<td>Seam elevation (°)</td>
<td>72.9 (11.9)</td>
<td>74.9 (5.7)</td>
<td>0.518</td>
<td>0.21</td>
</tr>
<tr>
<td>Seam stability (%)</td>
<td>81 (11)</td>
<td>75 (13)</td>
<td>0.091</td>
<td>0.49</td>
</tr>
</tbody>
</table>

*Significant p ≤0.05 and *Large ES <0.80

Compared with developing FS bowlers, elite FS bowlers generated significantly greater ball velocity (p = 0.004), ball angular velocity (revolutions) (p = <0.001) and velocity/revolution index (p = <0.001). Seam stability, while not significantly different (p = 0.065) displayed a large effect size (ES = 0.81) (Table 4.3).

Table 4.3. Mean (± standard deviations) ball kinematics for FS bowlers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball velocity (m.s(^{-1}))</td>
<td>19.2 (0.9)</td>
<td>20.4 (1.4)</td>
<td>0.004*</td>
<td>1.02*</td>
</tr>
<tr>
<td>Revolutions (rev.s(^{-1}))</td>
<td>26.4 (2.7)</td>
<td>30.0 (2.8)</td>
<td>0.001*</td>
<td>1.29*</td>
</tr>
<tr>
<td>Velocity/revolution index</td>
<td>59.7 (3.0)</td>
<td>64.5 (3.7)</td>
<td>&lt;0.001*</td>
<td>1.24*</td>
</tr>
<tr>
<td>Spin axis azimuth (°)</td>
<td>324.7 (9.2)</td>
<td>325.5 (12.6)</td>
<td>0.858</td>
<td>0.07</td>
</tr>
<tr>
<td>Spin axis elevation (°)</td>
<td>13.6 (7.3)</td>
<td>16.5 (9.7)</td>
<td>0.313</td>
<td>0.34</td>
</tr>
<tr>
<td>Seam azimuth (°)</td>
<td>34.9 (9.9)</td>
<td>36.6 (8.4)</td>
<td>0.632</td>
<td>0.21</td>
</tr>
<tr>
<td>Seam elevation (°)</td>
<td>73.3 (12.4)</td>
<td>71.9 (11.3)</td>
<td>0.788</td>
<td>0.12</td>
</tr>
<tr>
<td>Seam stability (%)</td>
<td>78 (11)</td>
<td>86 (10)</td>
<td>0.065</td>
<td>0.81*</td>
</tr>
</tbody>
</table>

*Significant p≤0.05 and *Large ES <0.80

Compared with developing WS bowlers, elite WS bowlers generated significantly greater ball velocity (p = 0.015), velocity/revolution index (p = 0.001), spin axis azimuth (p = 0.021) and seam azimuth (p = 0.017). Spin axis
elevation angle, while not significantly different \((p = 0.107)\) did return a large effect size \((ES = 0.83)\) (Table 4.4).

**Table 4.4.** Mean \((\pm\) standard deviations) ball kinematics for WS bowlers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball velocity ((m.s^{-1}))</td>
<td>18.6 (0.7)</td>
<td>19.5 (0.7)</td>
<td><strong>0.015</strong></td>
<td>1.28*</td>
</tr>
<tr>
<td>Revolutions ((rev.s^{-1}))</td>
<td>34.3 (4.0)</td>
<td>38.7 (4.9)</td>
<td>0.184</td>
<td>0.98#</td>
</tr>
<tr>
<td>Velocity/revolution index</td>
<td>62.9 (2.7)</td>
<td>68.3 (3.5)</td>
<td><strong>&lt;0.001</strong></td>
<td>1.24#</td>
</tr>
<tr>
<td>Spin axis azimuth (°)</td>
<td>41.2 (14.5)</td>
<td>39.0 (7.1)</td>
<td><strong>0.021</strong></td>
<td>0.30</td>
</tr>
<tr>
<td>Spin axis elevation (°)</td>
<td>3.0 (4.9)</td>
<td>7.9 (4.8)</td>
<td>0.107</td>
<td>0.83#</td>
</tr>
<tr>
<td>Seam azimuth (°)</td>
<td>314.0 (15.3)</td>
<td>297.7 (2.7)</td>
<td><strong>0.017</strong></td>
<td>1.39#</td>
</tr>
<tr>
<td>Seam elevation (°)</td>
<td>76.0 (5.6)</td>
<td>73.1 (5.7)</td>
<td>0.313</td>
<td>0.51</td>
</tr>
<tr>
<td>Seam stability (%)</td>
<td>74 (15)</td>
<td>75 (10)</td>
<td>0.933</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Significant \(p \leq 0.05\) and ¦Large ES <0.80

### 4.5 Discussion

It has long been accepted within the coaching and scientific literature that WS bowlers deliver the ball with greater revolutions, a view supported by the results of this study (Beach et al., 2014; Justham et al., 2008; Wilkins, 1991; Woolmer et al., 2008). Recent research has also shown that WS bowlers utilise a lower spin axis elevation angle compared with FS bowlers (Beach et al., 2014), a finding also reflected in the current investigation. However, the current study is the first to report that WS bowlers' orient the seam (seam azimuth angle) further from the midline of the pitch (Figure 4.10).
Figure 4.10. An example of the seam azimuth being rotated further from the midline of the pitch for a WS bowler (A) in comparison with a FS bowler (B) (techniques are a mirror image of each other).

It is possible that these differences can be explained by the differing strategies each adopt to execute their skill (Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). In contrast to a FS bowler, WS bowlers rely on creating side-spin, supported by the increased revolutions and a seam that is rotated (seam azimuth angle) more to the off-side (batsman’s right), or the direction of the intended side-spin. Comparatively, FS bowlers rely more on “flight and drift” through the air as well as increased levels of reflection or bounce angle to deceive batsman and take wickets. This is supported by a higher spin axis elevation angle, which subsequently flows onto increases in the zenith delivery height, greater Magnus force and drift, greater angle of incidence and subsequent reflection angle.

Both ball velocity and spin axis elevation angles were similar to previously collected FS data, ball revolutions were considerably higher within the current study with the exception of Justham et al.’s (2008) elite group, which also consisted of national representatives. The current pathway group had revolutions equal to or greater than those previously reported (23.4-27.7 rev.s\(^{-1}\) compared with 26.4 rev.s\(^{-1}\)) (Beach et al., 2014; Chin et al., 2009; Cork et al., 2012; Justham et al., 2008) but considerably less than those seen within the current elite group (30.0 rev.s\(^{-1}\)). A similar trend was observed for ball velocity, with WS bowlers previous reported values (15.9 – 19.3 m.s\(^{-1}\)) similar to that of
the current study (19 m.s\(^{-1}\)) (Beach et al., 2014; Chin et al., 2009; Cork et al., 2012; Justham et al., 2010; Justham et al., 2008). Again, reported ball revolution values were considerably lower in previous work (25.9 – 29.3 rev.s\(^{-1}\)) (Beach et al., 2014; Cork et al., 2012; Justham et al., 2008) compared with these data (pathway 34.3 and elite 38.7). It is assumed that the differences in revolution rates in the current study can be attributed to the participant cohort playing at considerably higher levels, perhaps illustrating their superior expertise or skill.

In order to distinguish between skill levels using ball kinematics, variables were compared between elite and pathway groups for their respective disciplines. Within the FS cohort significant differences were observed between ball velocity and revolutions. These findings support the work of both Chin et al. (2009) and Justham et al. (2008), and strengthen the theory that increased revolutions lead to increased side-spin, based on the assumption that elite level players do indeed achieve higher levels of ‘side-spin’. A significant difference was also observed for the velocity/revolution index, which highlighted that increasing revolutions observed in the elite group did not come at the detriment of ball velocity, as has been reported in other projectile sports (Sakurai et al., 2013). As the amount of Magnus force applied to the ball has been shown to be proportional to velocity and revolutions, the results indicate that elite bowlers will bowl with more drift and at a higher velocity (Mehta, 1985; Robinson & Robinson, 2013; Watts & Ferrer, 1987). Increases in drift and bounce characteristics have both been shown to be key elements in the FS bowler’s attempt to deceive the batsman (Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008).

A large ES was seen in the seam stability measure between elite and pathway bowlers. A perfectly stable seam is characterised by the spin axis being orthogonal to the plane of the seam. There is a paucity of wind tunnel research specifically focusing on spin bowling, due mainly to the complexities of enabling a ball to rotate at high frequencies with a spin axis directed in a similar direction as the direction of ball travel. Sayers and Hill (1999) reported, for a top-spinning delivery (spin axis perpendicular to the projectile velocity vector), the force created was dependent on the free stream velocity moving around the boundary
layer of the ball, as well as the speed of rotation. If the Magnus effect is adversely influenced when the free stream velocity is disrupted, the ability to deliver the ball with a stable seam may reduce this disruption. This theory is supported by wind tunnel research in fast bowlers that has shown a stable seam produces the necessary asymmetric orientation and asymmetry boundary layer separation to produce ball swing (Mehta, 2005). From an applied perspective, it is common for coaches to encourage bowlers to deliver the ball with a stable seam based on the assumption that this is effectively a measure of the bowler’s ability to “control” the ball while generating velocity and imparting revolutions, as well as increasing the chances of the seam making contact with the ground and increasing subsequent side-spin. Although no evidence for this exists, it would seemingly explain why the elite cohort ball returned higher seam stability values.

Within the WS cohort significant differences were found between BR velocity and velocity/revolution index, with large effect sizes observed for revolutions and spin axis elevation angle. Increases in BR velocity and revolutions would indicate that elite bowlers deliver the ball with more drift and at a higher velocity due to the subsequent increase in the Magnus force applied to the ball (Mehta, 1985; Robinson & Robinson, 2013; Watts & Ferrer, 1987). Elite bowlers also had a significantly lower seam azimuth angle at release, indicating that the seam was rotated further to the intended direction of side-spin post bounce and directing the ball away from the right handed batsman. Figure 4.11 depicts two balls with differing seam azimuth angles, the steeper seam angle (A) would reflect a ball with a larger azimuth angle as seen in the pathway cohort and the other a smaller angle (B) as observed in the elite group.
Figure 4.11. Examples of seam azimuth angles at BR for a right handed WS bowler, the first figure (A) would reflect a steeper angle than the second figure (B). The black arrow shows direction of travel.

Increases in the axis of elevation angle for elite WS bowlers would see increases in the post bounce characteristics, with increases in the reflection observed due the incidence angle being steeper caused by higher zenith location during flight. As seen with FS bowlers, these elements are all important in the attempt for a WS bowler to deceive the batsman.

4.6 Conclusion

The purpose of this study was to describe the 3D ball kinematics for both FS and WS bowlers from elite and pathway cohorts. The results showed that both types of bowlers employ different strategies when executing their respective deliveries. FS bowlers deliver the ball with an increased axis of rotation elevation, while wrist-spin bowlers place greater amounts of revolutions on the ball. It also highlighted that BR velocity; revolutions, velocity/revolution index for both groups and seam stability for FS bowlers and seam azimuth angle and spin axis elevation angle for WS bowlers were discriminators of playing level.

In an applied sense, the results from this research allow coaches to understand and make links between the biomechanical aspects of ball flight and supply feedback to bowlers with greater context based on a greater understanding of seam position and ball dynamics. From a research perspective, this study provides a number of ball kinematic measures such as ball velocities, revolutions, velocity/revolution index, spin axis azimuth and elevation angles as
well seam azimuth and stability that appear to be useful distinguishers between skill level for both FS and WS bowlers, and which can be used in future research as performance indicators.

4.7 Limitations

The data from this study were collected within a laboratory environment, allowing for sophisticated methodologies to be implemented. This however, came at the detriment to task representation due to the absence of a batsman and the clinical environment. It is also acknowledged that it is unknown how the presence of three small markers on the ball influences its aerodynamic characteristics.
Chapter 5: The influence of upper-body mechanics, anthropometry and isokinetic strength on performance in finger-spin cricket bowling

5.1 Abstract

As with all forms of cricket bowling, the aim of a spin bowler is to build pressure, restrict scoring and ultimately dismiss the opposing batsman. This is often achieved through a combination of subtle changes in delivery speed, ball flight, steepness of bounce, and lateral deviation of the ball post-bounce. To date very little biomechanical, isokinetic or anthropometric information exists comparing skill levels or linking the above ball movements to performance. Therefore, the purpose of this study was to compare biomechanical, isokinetic strength and anthropometric measures for elite and pathway finger-spin (FS) bowlers with performance measures identified in chapter four of this thesis. Data were collected using a 22-camera Vicon motion analysis system, a HUMAC NORM dynamometer and by a level two anthropometrist accredited with International Society for the Advancement of Kinanthropometry (ISAK). Results indicated that elite bowlers rotated their trunks faster and extended about the elbow through the point of ball release (BR) when comparing bowling techniques with pathway peers. A regression analysis highlighted the movements of the elbow, wrist and second phalange and the isokinetic strength of the shoulder as being the primary variables predicting performance. The increased rotation of the trunk and elbow extension (within legal limits of 15°) suggests a better utilisation of the degrees of freedom (DoF) within the kinetic chain by elite bowlers. The strengthening of the musculature responsible for shoulder extension and adduction such as the pectoralis major, triceps, teres major, teres minor and latissimus dorsi should be considered in the physical preparation of FS bowlers.
5.2 Introduction

While a cricket team may only have a single specialist finger spin (FS) bowler, they are integral to the offensive aspect of the game. As with all forms of cricket bowling, the aim of a spin bowler is to build pressure, restrict scoring and ultimately dismiss the opposing batsman (Bradman, 1969; Tyson, 1994; Woolmer et al., 2008). To do this, spin bowlers rely on a combination of subtle changes in delivery speed, deflection of ball flight both laterally (drift) and vertically (dip), steepness of bounce and most importantly, the lateral deviation the ball undergoes post bounce (side-spin) (Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). While the amount of side-spin a bowler can create has never been empirically linked to the quantity of ball revolutions around the horizontal axis, such an assumption is common in both the coaching and scientific literature (Beach et al., 2014; Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). These assumptions however, are reinforced by research linking increased ball revolution rates to those bowlers playing at higher levels (Chin et al., 2009; Justham et al., 2008), as also reported in chapter four of this thesis.

Playing statistics highlight the importance of FS bowlers in all forms of the game (Cricinfo, 2015). However, it is the longer form of the game, first class and Test cricket (played over four and five days respectively) where they are expected to be dominant during the third or fourth innings, when the batting surface (pitch) begins to deteriorate, ‘break up’, and become more conducive to side-spin (James et al., 2004, 2005). An example of this dominance is Sri Lankan FS bowler Muttiah Muralitharan who took 800 Test wickets at an average of 22.72, and has been rated the greatest ever Test match bowler by Wisden Cricketers Almanac (Wisden Cricketers’ Almanack, 2014). Muralitharan held the number one spot in the International Cricket Council (ICC) player rankings for a Test match bowler for a period of almost five years (Cricinfo, 2015).

While fast bowlers are generally categorised by the speed of their delivery, spin bowlers fall into two main categories that loosely reflect the end point of the body responsible for placing revolutions on the ball. A FS bowler releases the ball from the radial side of the hand, controlled by the first and second
phalange, while the wrist extends and deviates to the ulna side as the elbow supinates and extends (Chin et al., 2009; Spratford et al., 2014; Woolmer et al., 2008). An example of the release is depicted in Figure 5.1.

![Time series images prior to release for a FS bowler, note the position of the wrist.](image)

Figure 5.1. Time series images prior to release for a FS bowler, note the position of the wrist.

Currently there is a paucity of performance based biomechanical research investigating FS bowlers. Chin and colleagues (2009) reported that elite FS bowlers, in comparison with a high-performance cohort, displayed a more side-on pelvis and thorax alignment at back foot impact (BFI) and subsequently more trunk rotation to ball release (BR). Greater shoulder linear velocity, higher ranges of elbow pronation and elbow extension from upper arm horizontal (UAH) to BR were also shown to differentiate groups. However the authors suggested further research needed to be conducted on the role of the upper-limb angular velocities and their contribution to performance.

The contribution of elbow extension angular velocity has previously been investigated in FS bowlers, but constrained only in its relationship with illegal bowling actions (Ferdinands & Kersting, 2007). It was found that some bowlers could achieve a throw-like action due to increased elbow extension through the point of BR, a movement pattern that has been linked to increased ball speed (Marshall & Ferdinands, 2005). Research examining other throwing and hitting type activities such as baseball and tennis, has also linked increases in upper-body angular velocities to increased ball speed (Elliott et al., 1995; Fleisig, Nicholls, Elliott, & Escamilla, 2003; Stodden, Fleisig, McLean, & Andrews, 2005; Stodden, Fleisig, McLean, Lyman, & Andrews, 2001; Urbin et al., 2012). Given the rapid kinematic movements of the bowling limb in FS bowling (Chin et al., 2009; Spratford et al., 2014), it is plausible that upper-body angular velocity
contributions may have a greater influence on generating ball revolutions when compared with linear joint velocities reported in other throwing for distance sports or speed activities (Glazier et al., 2000; Morriss & Bartlett, 1996).

While empirical literature is scarce, opinion pieces and anecdotal commentary such as those commonly seen in coaching literature, consistently emphasise key upper-body movements associated with correct technique and performance. The role of the “index” or second phalange and the movement of the wrist joint in the frontal plane (ulna deviation) is a constant reference point for FS bowlers (Bradman, 1969; Tyson, 1976, 1994; Wilkins, 1991; Woolmer et al., 2008). Yet, there is limited evidence as to what role, if any, these biomechanical movements play in the performance of FS bowlers when considering ball revolutions or achieved side-spin.

The recognition of the importance of joint kinetics has been fundamental in understanding the causes of human motion, with numerous examples existing across a variety of sports (Elliott, Fleisig, Nicholls, & Escamilla, 2003; Fleisig et al., 2006; Inno & Kojima, 2011). However, cricket research investigating joint kinetics is scarce, with shoulder distraction forces in female fast bowlers shown to peak early and not considered to be any higher than studies conducted into similar sports such as baseball or softball pitching (Stuelcken, Ferdinands, Ginn, & Sinclair, 2010). Although the movement patterns observed in baseball pitching are fundamentally different to cricket bowling due to the large amounts of elbow extension observed in pitching, research has explored the kinetic differences between age groups, playing levels and the velocity dependent torques of the pitching limb (Aguinaldo et al., 2007; Fleisig et al., 1999; Hirashima et al., 2008). Aguinaldo and colleagues (2007) showed that although similar values were recorded for peak trunk rotation, professional’s baseball pitchers commenced trunk rotation at a later stage of the pitching cycle and hence a significantly lower rotational torque at the shoulder was observed for the higher skilled players. Hirashima et al. (2008) also concluded that angular velocities of the trunk and upper arm produced a velocity dependent torque for initial elbow extension acceleration.
There is also a paucity of FS bowling literature examining the role of common screening techniques such as anthropometric profiling, joint range of motion and isokinetic strength testing in discriminating performance levels. Clarity surrounding the contribution of which may help relevant support staff, implement more effective talent identification programs. Greater insight may also facilitate the design of better targeted strength and conditioning programs as evidenced in other sports (Bayios et al., 2001; Donti, Tsolakis, & Bogdanis, 2014; French et al., 2007; Hoare, 2000; Mohamed et al., 2009; Waldron, Worsfold, Twist, & Lamb, 2014). To date, cricket specific examples have been limited to fast bowlers, with authors linking increased ball speeds to shoulder-wrist and total arm length (Glazier et al., 2000; Pyne et al., 2006), chest girth, body composition, body mass and muscle mass (Portus, Sinclair, Burke, Moore, & Farhart, 2000). Skill level differences have also been reported for isokinetic strength at the shoulder for fast bowlers (Wormgoor et al., 2010).

Therefore the aims of this study were to examine the differences in upper-body bowling mechanics, anthropometry and isokinetic strength across skill level in FS bowlers. To also assess how these measures influence performance, as measured by a velocity/revolution index, a combination of variables that have been consistently shown as a valid measures of skill level in cricket research (Chin et al., 2009; Justham et al., 2008), chapter four of this thesis and anecdotally in coaching literature (Bradman, 1969; Tyson, 1976, 1994; Wilkins, 1991; Woolmer et al., 2008). It is hypothesised that elite bowlers will display greater bowling limb angular velocities and that movements at the elbow, wrist and metacarpophalangeal (MCP) joints will be linked to performance, as defined by a velocity/revolution index.

5.3 Methods

Thirty-six male spin bowlers were invited by the national spin bowling coach to participate in this study. Participants were assigned to one of two groups based on the level of cricket previously played, 1) pathway (up to 1st Class) or 2) elite (1st class and above).
This cohort represented the entire population within Australia for this level of FS bowler and included six bowlers who had played Test cricket (28 games and 89 wickets), and four who had played International 1-day cricket (128 games and 123 wickets) at the time of testing. Subsequent to this testing, three more players from the tested cohort were selected to play Test cricket for Australia, taking in excess of 150 Test wickets. Another eleven participants from seven different countries, who were national representatives at the U19 level, were also included. Only bowlers who were deemed to have a legal bowling action with less than 15° of elbow extension, as measured by the existing ICC protocol were included in the study. The physical characteristics of the participants are outlined in Table 5.1

Table 5.1. Mean (± standard deviations) age and physical characteristics of participants

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway FS</td>
<td>24</td>
<td>19.4 ± 2.7</td>
<td>181.8 ± 6.9</td>
<td>74.0 ± 8.2</td>
</tr>
<tr>
<td>Elite FS</td>
<td>12</td>
<td>24.9 ± 6.5</td>
<td>179.6 ± 6.9</td>
<td>76.0 ± 12.2</td>
</tr>
</tbody>
</table>

Ethics approval was granted and written informed consent was obtained for each participant before the commencement of the study, in accordance with the requirements of the Human Research Ethics Committees of the Australian Institute of Sport (AIS) and The University of Western Australia (Appendices A-E)

Camera and laboratory set-up
Bowling data collection took place in an indoor motion capture laboratory that was purpose built for cricket analysis and contained a permanent artificial pitch. Marker trajectories were tracked using a 22 camera (MX 13 and 40) Vicon MX motion analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. The capture volume was approximately 10 m long and 5 m wide allowing for two full strides before the delivery phase and 3 m of ball flight post-release to be collected. The global reference frame originated at the bowling crease with the x-axis pointing right, y-axis pointing towards the batsman and the cross product z-axis pointing upwards.
Data collection and procedures

Retro-reflective markers were affixed to each participant’s head, torso, upper-limbs and the ball according to a customised marker set and model (Campbell, Alderson, Lloyd, & Elliott, 2009; Chin et al., 2010; Lloyd et al., 2000). The set consisted of numerous single and three marker clusters attached to either semi-rigid plastic or lightweight aluminium bases. Participant specific static trials were collected to define joint centres. The shoulder joint centre was calculated using a regression equation based on anatomical landmarks, as well as height and mass (Campbell, Lloyd, et al., 2009). The elbow joint centre was estimated using a pointer method based on the location of the lateral and medial aspects of the humeral epicondyles (Chin et al., 2010) and the wrist joint centre as the midpoint of markers placed on the styloid processes of the radius and ulna (Lloyd et al., 2000). The second MCP joint centre was defined as the midpoint between the anterior and posterior side of the joint between the metacarpal and proximal phalanx (Figure 5.2). Three dynamic hemispherical markers comprised of ultralight foam (<0.1g) affixed in locations that did not impede the bowler’s preferred grip on the ball were used to calculate ball velocities and revolutions (Whiteside et al., 2012). For more in depth descriptions please see chapter three (p. 37)

Participants warmed up as per their normal pre game routine and then bowled six overs with a timed two minute break between each to replicate match conditions. The six overs consisted of 20 FS and 16 self-nominated variation deliveries. Participants were asked to nominate where their usual deliveries
would pass a right-handed batsman based on a clear target placed where the batsman would normally stand, that consisted of a series of 20 cm x 20 cm grids (accuracy target as seen in Figure 4.2). A valid delivery was one that struck the target on the nominated grid, the one directly above, underneath or immediately next to the nominated grid to the off-side (to the batsman’s right). The deliveries were bowled in a randomised order.

Two dimensional (2D) data from each of the 22 cameras were captured for each marker and reconstructed into three dimensional (3D) marker trajectories and labelled using Vicon Nexus software (Oxford Metrics, Oxford, UK). Trajectories were filtered using a quintic spline Woltring filter at a mean square error (MSE) of 20 after a residual analysis and visual inspection of the data (Winter, 2005). Data were then modelled using the University of Western Australia’s (UWA) upper-body and ball model extended to incorporate the MCP (Campbell, Lloyd, et al., 2009; Chin et al., 2009; Chin et al., 2010; Whiteside et al., 2012). Movement at the shoulder joint was described as humeral relative to the thoracic motion using a Y-X-Y decomposition (Wu et al., 2005). Joint moments were determined using standard inverse dynamic analysis starting from the hand and flowing to the shoulder of the bowling arm with all segment inertial characteristics taken from de Leva (1996). Moments were expressed in a non-orthogonal joint coordinate system to allow functional meaning and reduce potential cross talk introduced from kinematic measures (Middleton, 2011; Schache & Baker, 2007). The ball was assumed to have minimal inertia but with a point mass, and force applied by a simple \( F = ma \) calculation. The ball created a reaction if its origin was less than a distance calculated between it and a marker placed on the distal intermediate carpal as calculated by the length the fourth phalangeal and radius of the ball, indicating the ball had no influence on the inverse dynamic calculation once released.

Selected biomechanical data for the pelvis, thorax, shoulder, elbow, wrist and 2\textsuperscript{nd} MCP joint considered critical to bowling performance were included. Joint angles were determined relative to their adjoining segments, with 0° indicating alignment between segment coordinate systems. Segment angles (pelvis and thorax) were measured relative to the global coordinate system with 0° indicating a pelvis or thorax orthogonal with its defining vector. Therefore, a
rotation angle of 90° indicated a bowler would be front-on or orthogonal with the pitch. Data were reported at BR and the peak values returned in the phases delineated by the discrete events of BFI and BR for the pelvis and thorax, and UAH and BR for the bowling limb. All variables were normalised to 101 points using a cubic spline in a custom MATLAB program (Mathworks Inc; Natick, MA), with representative mean data being calculated from the first six valid trials where the ball made contact with the accuracy target.

**Anthropometry**

Selected anthropometric lengths, breadths, girths and sitting height were recorded from the bowling limb by an accredited Level 2 ISAK anthropometrist (Marfell-Jones et al., 2007). All variables were measured in triplicate with the criterion being the median. A combination of equipment was used that included a large sliding calliper (British Indicators Ltd), vernier callipers (Holtain, Cresswell, Dyfed, UK) and a flexible steel tape (Lufkin Executive, Thinline W 606 PM, Cooper Industries, Lexington, SC, USA). Lengths consisted of acromiale-radiale (arm), radiale–stylion (forearm) and midstylion–dactylion (hand). Breadths consisted of the biacromial, humerus, transverse chest, and anterior posterior chest depth. Girths consisted of upper arm, forearm and wrist. An assessment of the test-retest reliability was established with mean technical error measurement (TEM) being 1.4%.

Active range of motion of the bowling limb was assessed by the same experienced clinicians using a bi-level inclinometer and goniometer (US Neurologicals, Poulsbo, Washington, United States) using previously validated methods (Gerhardt et al., 2002). Measures consisted of; flexion, extension, abduction, internal and external rotation of the shoulder (with shoulder at 90° of abduction and elbow flexed at 90°), extension and ‘carry angle’ of the elbow. As well as flexion, extension, radial and ulna deviation of the wrist and flexion and extension of the metacarpophalangeal joint (MCP2). All variables were measured in triplicate with the mean value used as the criterion. An assessment of the test-retest reliability assessment was established with a mean TEM being 1.0%. A more in-depth explanation of methods can be found in chapter three (p.48).
Isokinetic

Bowlers undertook five isokinetic strength tests on their bowling arm using a HUMAC NORM (CSMI2009, version 9.5.2) dynamometer at angular velocities of 60°.s⁻¹ and 180°.s⁻¹ to reflect both slow and dynamic isokinetic strength (Frontera, Meredith, O'Reilly, Knuttgen, & Evans, 1985). To reduce the likelihood of fatigue, one minutes rest was provided between each test. Prior to testing, participants warmed-up using a rowing ergometer for a period of 5 minutes at sub maximal intensity (Claiborne, Armstrong, Gandhi, & Pincivero, 2006) and were allowed to perform self-selected stretches if desired. Measures of the shoulder consisted of; flexion/abduction-extension/adduction in the prone position, internal and external rotation in the prone position with the shoulder at 90° of abduction and elbow flexed at 90° and normal ised to gravity. At the elbow, pronation and supination and at the wrist, flexion, extension, radial and ulna deviation were taken in the sitting position and not corrected for gravity. All measures were normalised to body weight. A more in-depth explanation of the isokinetic measures can be found in chapter three (p.57).

Performance measure

The relationship \( x \) between ball velocity \( V \) and ball revolutions around the horizontal axis of the global coordinate system \( \omega \) was calculated using the following equation to produce a velocity/revolution index score and used as a performance measure. This allowed for increases in BR velocity, relative to revolutions and velocity to be considered and expressed based on evidence that increases in ball revolutions will come at a detriment to ball speed (Sakurai et al., 2013)

\[
x = (V + \omega) + \frac{V^2}{\omega}
\]  \hspace{1cm} (3)

Statistical analysis

Independent group t-tests were performed to establish differences between elite and pathway bowlers. A partial Bonferroni correction was adopted due to the multiple comparisons being made with an amended alpha level set at \( \alpha \leq 0.01 \). Effect sizes (ES) were calculated to functionally differentiate between groups,
with levels of, 0.2, 0.5 and 0.8 representing small, moderate and large effect sizes respectively (Cohen, 1992). A multiple stepwise regression analysis was then performed, collapsed across elite and pathway groups using variables that were shown to be significant ($p < 0.01$) and or had large effect sizes (ES ≥0.8) using the velocity/revolution index identified as the dependant variable. This enabled the measure or combination of measures that best predicted performance to be identified.

5.4 Results

*Angular displacements*

The majority of joint angular displacements between elite and pathway bowlers were invariant with variance only occurring at the MCP joint. Elite bowlers recorded significantly greater amounts of flexion at BR ($p = 0.006$), peak flexion ($p = 0.005$), peak adduction ($p = 0.006$) and MCP adduction at BR (ES = 1.08) (Table 5.2).

*Angular velocities*

Differences were observed at the pelvis, thorax, shoulder, elbow, wrist and MCP joint, with elite bowlers exhibiting higher levels of angular velocities compared with pathway bowlers. At the level of the trunk, significant differences were observed for pelvic forward rotation at BR ($p = 0.009$), thorax forward rotation at BR ($p = 0.010$) and peak thorax forward rotation ($p = 0.006$). At the shoulder and elbow joints significant differences were found in peak shoulder extension ($p = 0.006$), elbow extension at BR ($p = 0.010$) (pathway bowlers were flexing at BR), peak elbow extension ($p = 0.010$) and elbow supination at BR ($p = 0.001$). At the wrist joint a significant difference was observed in ulna deviation at BR ($p = 0.009$), with peak ulna deviation returning a large ES (ES = 0.80). At the MCP joint significant differences were displayed for flexion at BR ($p = 0.006$), abduction at BR ($p = 0.006$) and peak adduction ($p = 0.010$) with a large ES observed for peak flexion (ES = 1.56) (Table 5.3).
Linear velocities

Large ES were observed for linear velocities at the wrist joint with the elite bowlers exhibiting a higher velocity at BR (ES = 0.83) and peak velocity between UAH and BR (ES = 0.83) (Table 5.4).
Table 5.2. Mean (± standard deviations) and comparisons for angular displacement parameters for elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (°)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis forward rotation (BR)</td>
<td>94.0 (19.7)</td>
<td>87.2 (11.7)</td>
<td>0.203</td>
<td>0.42</td>
</tr>
<tr>
<td>Pelvis forward rotation peak (BFI-BR)</td>
<td>171.5 (13.1)</td>
<td>171.9 (10.0)</td>
<td>0.901</td>
<td>0.03</td>
</tr>
<tr>
<td>Thorax forward rotation (BR)</td>
<td>91.1 (15.3)</td>
<td>89.8 (8.2)</td>
<td>0.738</td>
<td>0.11</td>
</tr>
<tr>
<td>Thorax forward rotation peak (BFI-BR)</td>
<td>-75.3 (11.3)</td>
<td>176.2 (8.1)</td>
<td>0.786</td>
<td>0.09</td>
</tr>
<tr>
<td>Thorax lateral flexion (BR)</td>
<td>23.1 (8.7)</td>
<td>19.0 (8.8)</td>
<td>0.200</td>
<td>0.47</td>
</tr>
<tr>
<td>Thorax lateral flexion peak (BFI-BR)</td>
<td>23.1 (8.9)</td>
<td>19.0 (8.8)</td>
<td>0.224</td>
<td>0.46</td>
</tr>
<tr>
<td>Shoulder extension (BR)</td>
<td>14.9 (12.1)</td>
<td>11.7 (11.1)</td>
<td>0.437</td>
<td>0.28</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>14.9 (12.1)</td>
<td>11.7 (11.1)</td>
<td>0.437</td>
<td>0.28</td>
</tr>
<tr>
<td>Shoulder abduction (BR)</td>
<td>114.9 (7.4)</td>
<td>115.4 (8.6)</td>
<td>0.841</td>
<td>0.06</td>
</tr>
<tr>
<td>Shoulder external rotation (BR)</td>
<td>-38.4 (37.7)</td>
<td>-60.1 (42.5)</td>
<td>0.128</td>
<td>0.54</td>
</tr>
<tr>
<td>Shoulder external rotation peak (UAH-BR)</td>
<td>-64.1 (66.1)</td>
<td>-80.2 (25.5)</td>
<td>0.389</td>
<td>0.32</td>
</tr>
<tr>
<td>Elbow flexion (UAH)</td>
<td>20.8 (11.2)</td>
<td>24.0 (8.2)</td>
<td>0.209</td>
<td>0.51</td>
</tr>
<tr>
<td>Elbow flexion (BR)</td>
<td>23.6 (6.8)</td>
<td>24.0 (7.0)</td>
<td>0.344</td>
<td>0.29</td>
</tr>
<tr>
<td>Elbow extension range (UAH-BR)</td>
<td>1.5 (6.1)</td>
<td>5.5 (3.5)</td>
<td>0.207</td>
<td>0.45</td>
</tr>
<tr>
<td>Elbow supination (BR)</td>
<td>-82.9 (40.3)</td>
<td>-89.3 (21.7)</td>
<td>0.602</td>
<td>0.17</td>
</tr>
<tr>
<td>Elbow supination peak (UAH-BR)</td>
<td>-111.8 (64.5)</td>
<td>-106.8 (33.5)</td>
<td>0.767</td>
<td>0.10</td>
</tr>
<tr>
<td>Ulna deviation (BR)</td>
<td>22.1 (6.7)</td>
<td>20.7 (3.4)</td>
<td>0.512</td>
<td>0.26</td>
</tr>
<tr>
<td>Ulna deviation peak (UAH-BR)</td>
<td>25.3 (6.0)</td>
<td>24.2 (4.8)</td>
<td>0.618</td>
<td>0.20</td>
</tr>
<tr>
<td>MCP flexion (BR)</td>
<td>61.8 (14.7)</td>
<td>84.9 (14.6)</td>
<td>0.006*</td>
<td>1.58#</td>
</tr>
<tr>
<td>MCP flexion peak (UAH-BR)</td>
<td>63.0 (15.8)</td>
<td>89.6 (16.5)</td>
<td>0.005*</td>
<td>1.65#</td>
</tr>
<tr>
<td>MCP abduction/adduction (BR)</td>
<td>4.3 (5.8)</td>
<td>-1.9 (5.7)</td>
<td>0.046</td>
<td>1.08#</td>
</tr>
<tr>
<td>MCP abduction peak (UAH-BR)</td>
<td>12.3 (3.6)</td>
<td>18.9 (4.3)</td>
<td>0.006*</td>
<td>1.66#</td>
</tr>
</tbody>
</table>

*Significant p ≤0.010 and #Large ES ≥0.80
Table 5.3. Mean (± standard deviations) and comparison for angular velocity parameters between elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (°.s⁻¹)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis forward rotation (BR)</td>
<td>121.4 (47.4)</td>
<td>174.6 (51.2)</td>
<td>0.009*</td>
<td>1.08*</td>
</tr>
<tr>
<td>Pelvis forward rotation peak (BFI -BR)</td>
<td>367.2 (157.6)</td>
<td>416.1 (154.9)</td>
<td>0.384</td>
<td>0.31</td>
</tr>
<tr>
<td>Thorax forward rotation (BR)</td>
<td>128.6 (58.5)</td>
<td>186.8 (63.4)</td>
<td>0.010*</td>
<td>0.94*</td>
</tr>
<tr>
<td>Thorax forward rotation peak (BFI -BR)</td>
<td>436.7 (72.0)</td>
<td>511.4 (70.6)</td>
<td>0.006*</td>
<td>1.04*</td>
</tr>
<tr>
<td>Thorax lateral flexion (BR)</td>
<td>275.7 (69.2)</td>
<td>310.6 (88.2)</td>
<td>0.245</td>
<td>0.44</td>
</tr>
<tr>
<td>Thorax lateral flexion peak (BFI -BR)</td>
<td>580.2 (101.5)</td>
<td>603.0 (97.7)</td>
<td>0.520</td>
<td>0.23</td>
</tr>
<tr>
<td>Shoulder extension (BR)</td>
<td>-469.2 (216.8)</td>
<td>-434.0 (308.6)</td>
<td>0.722</td>
<td>0.13</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>-674.8 (154.7)</td>
<td>-842.6 (167.6)</td>
<td>0.006*</td>
<td>1.04*</td>
</tr>
<tr>
<td>Shoulder external rotation (BR)</td>
<td>-1404.8 (522.2)</td>
<td>-1360.8 (625.0)</td>
<td>0.825</td>
<td>0.08</td>
</tr>
<tr>
<td>Shoulder external rotation peak (UAH-BR)</td>
<td>-1552.0 (460.2)</td>
<td>-1465.8 (620.9)</td>
<td>0.641</td>
<td>0.56</td>
</tr>
<tr>
<td>Elbow flexion (+)/extension (-) (BR)</td>
<td>30.1 (213.1)</td>
<td>-115.6 (99.5)</td>
<td>0.010*</td>
<td>0.88*</td>
</tr>
<tr>
<td>Elbow extension peak (UAH-BR)</td>
<td>-176.7 (163.7)</td>
<td>-388.7 (184.6)</td>
<td>0.010*</td>
<td>1.22*</td>
</tr>
<tr>
<td>Elbow supination (BR)</td>
<td>-78.10 (409.9)</td>
<td>398.7 (259.4)</td>
<td>&lt;0.001*</td>
<td>1.39*</td>
</tr>
<tr>
<td>Elbow supination peak (UAH-BR)</td>
<td>515.3 (364.9)</td>
<td>553.5 (286.7)</td>
<td>0.757</td>
<td>0.11</td>
</tr>
<tr>
<td>Wrist flexion (BR)</td>
<td>499.4 (187.0)</td>
<td>480.7 (232.3)</td>
<td>0.801</td>
<td>0.09</td>
</tr>
<tr>
<td>Wrist flexion peak (UAH-BR)</td>
<td>646.4 (154.3)</td>
<td>642.6 (303.4)</td>
<td>0.960</td>
<td>0.02</td>
</tr>
<tr>
<td>Ulna deviation (BR)</td>
<td>-147.2 (130.8)</td>
<td>-250.0 (82.3)</td>
<td>0.009*</td>
<td>0.94*</td>
</tr>
<tr>
<td>Ulna deviation peak (UAH-BR)</td>
<td>-187.7 (135.0)</td>
<td>-289.2 (118.0)</td>
<td>0.041</td>
<td>0.80*</td>
</tr>
<tr>
<td>MCP flexion (BR)</td>
<td>1086.1 (400.4)</td>
<td>1574.9 (235.2)</td>
<td>0.006*</td>
<td>1.49*</td>
</tr>
<tr>
<td>MCP flexion peak (UAH-BR)</td>
<td>1254.1 (398.5)</td>
<td>1632.3 (232.6)</td>
<td>0.024</td>
<td>1.56*</td>
</tr>
<tr>
<td>MCP abduction (BR)</td>
<td>-635.6 (130.8)</td>
<td>-811.3 (98.2)</td>
<td>0.006*</td>
<td>1.52*</td>
</tr>
<tr>
<td>MCP abduction peak (UAH-BR)</td>
<td>-851.7 (261.2)</td>
<td>-1154.8 (231.5)</td>
<td>0.010*</td>
<td>1.23*</td>
</tr>
</tbody>
</table>

*Significant p ≤0.010 and "Large ES ≥0.80"
Table 5.4. Group mean (± standard deviations) and comparison for selected linear velocity parameters for elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (m.s$^{-1}$)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder joint centre (BR)</td>
<td>2.7 (0.5)</td>
<td>2.7 (0.7)</td>
<td>0.993</td>
<td>0.00</td>
</tr>
<tr>
<td>Shoulder joint centre peak (UAH-BR)</td>
<td>4.6 (0.6)</td>
<td>4.6 (0.5)</td>
<td>0.946</td>
<td>0.00</td>
</tr>
<tr>
<td>Elbow joint centre (BR)</td>
<td>8.0 (0.8)</td>
<td>8.6 (1.1)</td>
<td>0.104</td>
<td>0.62</td>
</tr>
<tr>
<td>Elbow joint centre peak (UAH-BR)</td>
<td>9.9 (0.7)</td>
<td>10.4 (1.1)</td>
<td>0.189</td>
<td>0.54</td>
</tr>
<tr>
<td>Wrist joint centre (BR)</td>
<td>14.3 (0.8)</td>
<td>15.1 (1.1)</td>
<td>0.049</td>
<td>0.83$^*$</td>
</tr>
<tr>
<td>Wrist joint centre peak (UAH-BR)</td>
<td>14.9 (0.8)</td>
<td>15.7 (1.1)</td>
<td>0.077</td>
<td>0.83$^*$</td>
</tr>
<tr>
<td>MCP joint centre (BR)</td>
<td>18.7 (1.1)</td>
<td>18.8 (1.7)</td>
<td>0.677</td>
<td>0.07</td>
</tr>
<tr>
<td>MCP joint centre peak (UAH-BR)</td>
<td>19.0 (1.0)</td>
<td>18.8 (1.7)</td>
<td>0.824</td>
<td>0.14</td>
</tr>
</tbody>
</table>

$^*$Significant p ≤0.010 and $^*$Large ES ≥0.80
Joint kinetics

Elite bowlers had a significantly greater shoulder abduction moment at BR ($p = 0.010$) and peak elbow supination moment ($p = 0.005$). At the wrist joint, elite bowlers displayed higher extension ($p = 0.004$) and ulna deviation ($p = 0.006$) moments at BR and a higher overall peak extension moment ($p = 0.004$). While not statistically significant, large ESs were recorded for peak shoulder abduction moments (ES = 0.81) and elbow supination moments at BR (ES = 0.81) when compared with pathway bowlers (Table 5.5).

Anthropometry

Pathway bowlers recorded a significantly larger humerus breadth in comparison to elite bowlers ($p = 0.010$) (Table 5.6), while elite bowlers displayed greater elbow extension full range of motion compared with pathway bowlers ($p = 0.007$) (Table 5.7).

Isokinetic

Elite bowlers reported large ES differences for peak isokinetic torques for shoulder extension/adduction at both the $60^\circ.s^{-1}$ (ES = 0.80) and $180^\circ.s^{-1}$ (ES = 1.00) conditions in comparison with pathway bowlers (Table 5.8).
Table 5.5. Group mean (± standard deviations) and comparisons for selected joint moments for elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (Nm)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder extension (BR)</td>
<td>-46.4 (30.3)</td>
<td>-53.5 (24.5)</td>
<td>0.466</td>
<td>0.26</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>-72.2 (32.2)</td>
<td>-83.6 (38.3)</td>
<td>0.387</td>
<td>0.32</td>
</tr>
<tr>
<td>Shoulder abduction (BR)</td>
<td>34.1 (19.9)</td>
<td>58.0 (25.7)</td>
<td>0.010*</td>
<td>1.04*</td>
</tr>
<tr>
<td>Shoulder abduction peak (UAH-BR)</td>
<td>69.1 (21.9)</td>
<td>89.5 (28.0)</td>
<td>0.041</td>
<td>0.81*</td>
</tr>
<tr>
<td>Shoulder external rotation (BR)</td>
<td>-7.9 (10.8)</td>
<td>-11.5 (7.6)</td>
<td>0.259</td>
<td>0.39</td>
</tr>
<tr>
<td>Shoulder external rotation peak (UAH-BR)</td>
<td>-20.8 (14.4)</td>
<td>-26.6 (18.6)</td>
<td>0.362</td>
<td>0.35</td>
</tr>
<tr>
<td>Elbow flexion (+)/extension (-) (BR)</td>
<td>6.7 (8.9)</td>
<td>-0.6 (5.6)</td>
<td>0.009*</td>
<td>0.98*</td>
</tr>
<tr>
<td>Elbow extension peak (UAH-BR)</td>
<td>-28.7 (21.2)</td>
<td>-48.0 (20.5)</td>
<td>0.019</td>
<td>0.93*</td>
</tr>
<tr>
<td>Elbow supination (BR)</td>
<td>-1.4 (2.2)</td>
<td>-3.0 (1.7)</td>
<td>0.058</td>
<td>0.81*</td>
</tr>
<tr>
<td>Elbow supination peak (UAH-BR)</td>
<td>-22.0 (16.5)</td>
<td>-43.7 (19.0)</td>
<td>0.005*</td>
<td>1.22*</td>
</tr>
<tr>
<td>Wrist extension (BR)</td>
<td>-1.4 (4.3)</td>
<td>-4.5 (1.7)</td>
<td>0.004*</td>
<td>0.95*</td>
</tr>
<tr>
<td>Wrist extension peak (UAH-BR)</td>
<td>-58.4 (31.0)</td>
<td>-94.9 (33.4)</td>
<td>0.004*</td>
<td>1.13*</td>
</tr>
<tr>
<td>Ulna deviation (BR)</td>
<td>1.8 (4.2)</td>
<td>-1.1 (1.8)</td>
<td>0.006*</td>
<td>0.90*</td>
</tr>
<tr>
<td>Ulna deviation peak (UAH-BR)</td>
<td>-34.3 (21.9)</td>
<td>-46.1 (19.7)</td>
<td>0.117</td>
<td>0.56</td>
</tr>
</tbody>
</table>

*Significant $p \leq 0.010$ and #Large ES $ \geq 0.80$
Table 5.6. Group mean (± standard deviations) and comparison for selected anthropometry for elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (cm)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acromiale-radiale length (arm)</td>
<td>34.7 (2.1)</td>
<td>34.2 (1.7)</td>
<td>0.531</td>
<td>0.26</td>
</tr>
<tr>
<td>Radiale–stylion length (forearm)</td>
<td>26.3 (1.2)</td>
<td>25.5 (1.7)</td>
<td>0.181</td>
<td>0.54</td>
</tr>
<tr>
<td>Midstylion–dactyliion length (hand)</td>
<td>20.0 (0.8)</td>
<td>19.9 (1.0)</td>
<td>0.783</td>
<td>0.11</td>
</tr>
<tr>
<td>Arm relaxed girth</td>
<td>29.2 (2.0)</td>
<td>31.1 (3.2)</td>
<td>0.107</td>
<td>0.71</td>
</tr>
<tr>
<td>Arm tensed girth</td>
<td>31.6 (2.0)</td>
<td>33.1 (2.8)</td>
<td>0.143</td>
<td>0.62</td>
</tr>
<tr>
<td>Forearm girth</td>
<td>26.9 (1.3)</td>
<td>27.6 (1.8)</td>
<td>0.282</td>
<td>0.45</td>
</tr>
<tr>
<td>Wrist girth</td>
<td>16.8 (0.6)</td>
<td>16.3 (0.9)</td>
<td>0.170</td>
<td>0.65</td>
</tr>
<tr>
<td>Humerus breadth</td>
<td>7.2 (0.3)</td>
<td>6.9 (0.3)</td>
<td>0.010*</td>
<td>1.00*</td>
</tr>
<tr>
<td>Biacromial breadth</td>
<td>42.2 (2.3)</td>
<td>42.7 (3.0)</td>
<td>0.649</td>
<td>0.19</td>
</tr>
<tr>
<td>Transverse chest breadth</td>
<td>30.2 (1.9)</td>
<td>30.9 (2.5)</td>
<td>0.442</td>
<td>0.32</td>
</tr>
<tr>
<td>Anterior posterior chest depth</td>
<td>19.3 (1.8)</td>
<td>19.7 (1.8)</td>
<td>0.574</td>
<td>0.22</td>
</tr>
<tr>
<td>Sitting height</td>
<td>95.0 (3.2)</td>
<td>92.9 (4.8)</td>
<td>0.209</td>
<td>0.51</td>
</tr>
</tbody>
</table>

*Significant p ≤0.010 and #Large ES ≥0.80
Table 5.7. Group mean (± standard deviations) and comparisons of joint ranges of motion for elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder flexion maximum</td>
<td>172.3 (16.9)</td>
<td>171.0 (13.6)</td>
<td>0.804</td>
<td>0.08</td>
</tr>
<tr>
<td>Shoulder extension maximum</td>
<td>44.3 (12.3)</td>
<td>51.2 (13.6)</td>
<td>0.171</td>
<td>0.53</td>
</tr>
<tr>
<td>Shoulder flexion/extension range</td>
<td>216.6 (24.3)</td>
<td>222.2 (20.1)</td>
<td>0.492</td>
<td>0.25</td>
</tr>
<tr>
<td>Shoulder internal rotation maximum</td>
<td>55.4 (19.1)</td>
<td>53.5 (13.6)</td>
<td>0.742</td>
<td>0.11</td>
</tr>
<tr>
<td>Shoulder external rotation maximum</td>
<td>188.3 (17.2)</td>
<td>183.1 (16.5)</td>
<td>0.406</td>
<td>0.31</td>
</tr>
<tr>
<td>Shoulder internal/external range</td>
<td>243.8 (22.7)</td>
<td>236.6 (25.4)</td>
<td>0.440</td>
<td>0.30</td>
</tr>
<tr>
<td>Shoulder abduction maximum</td>
<td>182.6 (18.8)</td>
<td>171.7 (28.8)</td>
<td>0.434</td>
<td>0.45</td>
</tr>
<tr>
<td>Elbow extension maximum</td>
<td>6.0 (4.2)</td>
<td>2.8 (2.1)</td>
<td>0.007*</td>
<td>0.96*</td>
</tr>
<tr>
<td>Elbow abduction (carry angle, extended)</td>
<td>11.6 (4.9)</td>
<td>11.0 (3.5)</td>
<td>0.657</td>
<td>0.14</td>
</tr>
<tr>
<td>Wrist flexion maximum</td>
<td>79.9 (7.8)</td>
<td>81.4 (12.9)</td>
<td>0.733</td>
<td>0.14</td>
</tr>
<tr>
<td>Wrist extension maximum</td>
<td>66.6 (14.3)</td>
<td>62.8 (11.4)</td>
<td>0.415</td>
<td>0.29</td>
</tr>
<tr>
<td>Wrist flexion/extension range</td>
<td>146.5 (18.8)</td>
<td>144.2 (16.7)</td>
<td>0.720</td>
<td>0.13</td>
</tr>
<tr>
<td>Radial deviation maximum</td>
<td>31.0 (9.3)</td>
<td>28.3 (16.0)</td>
<td>0.622</td>
<td>0.21</td>
</tr>
<tr>
<td>Ulna deviation maximum</td>
<td>43.4 (9.0)</td>
<td>42.0 (11.9)</td>
<td>0.753</td>
<td>0.13</td>
</tr>
<tr>
<td>Ulna/radial deviation range</td>
<td>74.3 (9.8)</td>
<td>70.4 (12.7)</td>
<td>0.380</td>
<td>0.36</td>
</tr>
<tr>
<td>MCP flexion maximum</td>
<td>98.2 (17.9)</td>
<td>94.6 (11.9)</td>
<td>0.493</td>
<td>0.24</td>
</tr>
<tr>
<td>MCP extension maximum</td>
<td>20.2 (8.2)</td>
<td>15.2 (12.3)</td>
<td>0.234</td>
<td>0.48</td>
</tr>
<tr>
<td>MCP flexion/extension range</td>
<td>118.5 (20.9)</td>
<td>109.8 (20.7)</td>
<td>0.270</td>
<td>0.42</td>
</tr>
</tbody>
</table>

*Significant p ≤0.010 and #Large ES ≥0.80
Table 5.8. Group mean (± standard deviations) and comparison for selected peak isokinetic parameters for elite and pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (Nm/kg)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60°.s'</td>
<td>180°.s'</td>
<td>60°.s''</td>
<td>180°.s''</td>
</tr>
<tr>
<td>Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex/abduction peak</td>
<td>0.84 (0.20)</td>
<td>0.62 (0.25)</td>
<td>0.82 (0.08)</td>
<td>0.66 (0.20)</td>
</tr>
<tr>
<td>Ext/adduction peak</td>
<td>1.18 (0.18)</td>
<td>0.89 (0.21)</td>
<td>1.32 (0.17)</td>
<td>1.09 (0.19)</td>
</tr>
<tr>
<td>Internal rotation peak</td>
<td>0.39 (0.07)</td>
<td>0.33 (0.08)</td>
<td>0.38 (0.08)</td>
<td>0.34 (0.08)</td>
</tr>
<tr>
<td>External rotation peak</td>
<td>0.46 (0.13)</td>
<td>0.37 (0.10)</td>
<td>0.45 (0.13)</td>
<td>0.37 (0.09)</td>
</tr>
<tr>
<td>Elbow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supination peak</td>
<td>0.12 (0.03)</td>
<td>0.10 (0.03)</td>
<td>0.10 (0.02)</td>
<td>0.10 (0.01)</td>
</tr>
<tr>
<td>Pronation peak</td>
<td>0.13 (0.05)</td>
<td>0.11 (0.03)</td>
<td>0.13 (0.03)</td>
<td>0.12 (0.03)</td>
</tr>
<tr>
<td>Wrist</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion peak</td>
<td>0.16 (0.09)</td>
<td>0.14 (0.06)</td>
<td>0.14 (0.06)</td>
<td>0.12 (0.05)</td>
</tr>
<tr>
<td>Extension peak</td>
<td>0.11 (0.04)</td>
<td>0.09 (0.03)</td>
<td>0.10 (0.04)</td>
<td>0.09 (0.04)</td>
</tr>
<tr>
<td>Radial deviation peak</td>
<td>0.17 (0.05)</td>
<td>0.14 (0.04)</td>
<td>0.17 (0.06)</td>
<td>0.14 (0.06)</td>
</tr>
<tr>
<td>Ulna deviation peak</td>
<td>0.17 (0.04)</td>
<td>0.14 (0.05)</td>
<td>0.18 (0.06)</td>
<td>0.15 (0.07)</td>
</tr>
</tbody>
</table>

*Significant p ≤0.010 and *Large ES ≥0.80
Regression analysis

The stepwise multiple regression analysis in which the velocity/revolution index (61.3 ± 3.9) was the dependant variable, revealed that the peak MCP joint flexion angle, ulna deviation angular velocity at BR, linear velocity of the wrist joint centre at BR and peak shoulder extension/adduction isokinetic torque were the best predictors of performance, explaining 64% of the variance ($r = 0.80$; $r^2 = 0.64$; $f = 18.90$, $p = <0.001$).

5.5 Discussion

The purpose of this study was to examine the differences in upper-body bowling mechanics, anthropometry and isokinetic strength across FS bowling skill levels and to assess the influence these variables have on bowling performance, as measured by a velocity/revolution index.

Biomechanical differences between elite and pathway bowlers

In order for the FS bowler to deliver the ball with the desired amount of revolutions and velocity, the upper-body undergoes a series of complex and rapid movements in multiple planes between BFI and BR. At BR the pelvis and thorax segments are rotating forward (about the long axis) and the shoulder is externally rotating and extending, the elbow extending and supinating, the wrist flexing and moving into ulna deviation, while the MCP joint is flexing and abducting. At this point the results reveal that several kinematic and kinetic variances were observed between elite and pathway bowlers based primarily around angular velocities and joint moments.

Traditional coaching literature has recommended a side-on position for the trunk (pelvis and thorax) at BFI as it assists in rotating the body through to the desired BR position (Woolmer et al., 2008). Forward rotational trunk displacements from this study reflected those reported by Chin et al. (2009) and were similar between elite and pathway bowling cohorts. However, elite bowlers had significantly higher angular velocity measures for the pelvis and thorax at BR as well as peak thorax angular velocity (occurring prior to BR). These results in part are reflective of previous baseball research showing that professional players moved their trunk later in comparison to lesser skilled players, which in
turn conserved the momentum generated by the trunk and unloads the shoulder joint (Aguinaldo et al., 2007). This unloading however, was not reflected in FS bowling, with results being similar between groups except for elite bowlers having increased shoulder adduction moment at BR and peak levels of shoulder extension angular velocity.

When differences at the elbow were assessed elite and pathway bowlers adopt different biomechanical strategies. At the point of BR, elite bowlers were extending and supinating, underpinned by an extension moment, while their pathway peers were flexing and pronating with a corresponding flexion moment. This ability to extend through release takes advantage of the velocity contributing mechanisms that are observed in a typical throwing technique (Ferdinands & Kersting, 2007). It is thought that these differences may be linked to the differences observed at the trunk and shoulder, as evidence suggests that the velocity dependant joint torques at these sites early in the baseball pitch have the ability to accelerate the distal elbow and wrist joints, similar to what was observed in the elite group of the current study (Hirashima et al., 2008).

This differing biomechanical strategy enables the bowling arm of the elite player to act in a similar manner to that of a whip. The upper arm acts as the handle and the forearm, hand and proximal phalange as the whip as they sequentially accelerate and decelerate, allowing each segment to take advantage of the multiple DoF of the upper limb, as joints either extend, deviate, flex or abduct through to BR in a typical kinetic link fashion (Kreighbaum & Barthels, 1996). This may explain the subsequent angular velocity and kinetic differences observed at the wrist (ulna deviation and wrist extension) and phalange joints (flexion and abduction), as well as the linear velocity increases at the wrist joint (Kreighbaum & Barthels, 1996). Anecdotally, it has generally been advocated that increases in elbow extension angular velocity permit FS bowlers to place greater revolutions on the ball. This is evidenced by numerous coaches providing “throw-like” deliveries during “net sessions” to batsman in an attempt to produce side-spin. This research is the first to quantify that such a relationship does exist. Secondly, the differences observed in elbow joint supination reflect those observed in tennis and squash rather than in throwing and baseball pitching, which rely on the traditional kinetic chain focusing on
flexion-extension actions of the elbow and wrist joints (Marshall & Elliott, 2000; Martin et al., 2013). Again it must be noted that all bowlers in this study were assessed to have legal bowling actions or less than 15° of elbow extension between UAH–BR (6.6° ± 5.5°).

**Anthropometry and isokinetic differences between elite and pathway bowlers**

All anthropometry measures recorded in this study were invariant except for elite bowlers exhibiting a greater range of elbow extension and significantly lower humerus breadth. The elbow extension measure was in contrast to the findings of Chin et al (2009), who reported elite FS bowlers to have a greater fixed flexion (less end range) than their high performance peers. It has been reported that a fixed flexion will shorten the arc of the bowling arm during the delivery phase, increasing upper arm rotational velocity and subsequently end point linear velocity resulting in increased BR velocity (Marshall & Ferdinands, 2003). However, it may also limit the naturally occurring centrifugal forces that occur, limiting elbow extension displacement and subsequent elbow extension angular velocities at the point of and through BR, as was seen with the elite cohort.

It is not obvious what the cause for the difference in humerus breadth is, as it may well have been expected that elite bowlers through maturation and development as well as bone remodelling adaptations would have a greater muscle and bone mass and subsequently a greater breadth (Bogenschutz, Smith, & Warden, 2011; Kontulainen, Sievanen, Kannus, Pasanen, & Vuori, 2003). The lack of variance highlights the limitations in using these types of measures as the basis for any type of talent identification screening.

Increased peak isokinetic torque at the shoulder for extension/adduction at 60°.s⁻¹ and 180°.s⁻¹ for the elite cohort is consistent with previous research for fast bowlers linking increases in shoulder extension values to increased BR speeds (Wormgoor et al., 2010). It may also contribute to increased shoulder extension angular velocity and shoulder abduction moment at BR that was observed for elite level bowlers. This highlights the potential benefits that may be gained in achieving optimal strength of the musculature responsible for shoulder extension and adduction.
Regression analysis

Understanding the differences between elite and pathway bowlers may assist coaching and support staff in their efforts to progress bowlers through the development pathway. Results from the regression analysis collapsed across both groups indicated that performance is best explained by maximum MCP joint flexion angle, ulna deviation angular velocity at BR, linear velocity of the wrist joint centre at BR and peak shoulder extension/adduction isokinetic torque. This finding reinforces the coaching literature that uniformly espouses the importance of ulna deviation or what is commonly termed “opening the door”, “screwing off the top of a jar” or “winding up a clock” at BR (coefficient = 0.358) and that the current naming convention for FS bowlers is relevant, as movement at the MCP joint is critical (coefficient = 0.406) (Bradman, 1969; Tyson, 1994; Woolmer et al., 2008).

5.6 Conclusion

The results of this study indicate that elite bowlers rotate their trunks faster, and have the ability to extend the elbow through the point of BR, making better use of the DoF within the proximal to distal linkage system throughout the upper-body. The regression analysis further reinforces the importance of the distal bowling limb as well as the isokinetic strength of the shoulder when explaining performance. In an applied sense, it appears that performance gains can be made through both technique and strength interventions that focus on rotating the trunk and extending the elbow through the point of BR. Additionally, strengthening the musculature responsible for shoulder extension and adduction, such as the pectoralis major, triceps, teres major, teres minor and latissimus dorsi is also warranted. It would also appear that using anthropometric measures as a basis for talent identification programs has limited value.
5.7 Limitations

The data from this study were collected within a laboratory environment, allowing for sophisticated methodologies to be implemented. This however, came at the detriment to task representation due to the absence of a batsman and the clinical environment. It also only examined stock FS deliveries from each bowler.
Chapter 6: The influence of upper-body mechanics, anthropometry and isokinetic strength on performance in wrist-spin cricket bowling

6.1 Abstract

Delivering a cricket ball with a wrist-spin (WS) bowling technique has long been considered one of the game’s most difficult skills. If mastered, it allows the bowler to impart greater revolutions on the ball compared with their finger-spin (FS) counterparts, and for the right handed bowler to deviate the ball to the off-side and away from the right handed batsman after ball bounce. To date almost no biomechanical information exists for WS bowlers across any skill level. Therefore, the purpose of this study was to compare biomechanical, isokinetic strength and anthropometric measures between elite and pathway WS bowlers using performance measure descriptors identified as key factors in WS bowling in chapter four of this thesis. Data were collected using a 22-camera Vicon motion analysis system, a HUMAC NORM dynamometer and by a level two anthropometrist accredited with international society for the advancement of kinanthropometry (ISAK). The results of this study suggested that elite WS bowlers rotated their trunks less and experienced less trunk deceleration between BFI-BR than pathway level performers, resulting in a more front-on position and increased pelvis rotation angular velocity at BR. Elite bowlers also displayed an increased maximum shoulder internal rotation moment as the upper arm moved from external rotation into internal rotation. This movement was a major contributor in the subsequent differences observed in the distal segments of the bowling limb. Anthropometric differences were also observed for radial deviation maximum and total frontal plane range of motion at the wrist joint as well as maximum flexion/extension and range of the fourth phalange and as such may be used to form the basis for talent identification programs. A regression analysis identified that performance was best explained by; peak isokinetic radial deviation torque, peak shoulder internal rotation moment, shoulder extension moment at BR and peak pronation moment. These results highlight the importance of long axis rotations of the bowling limb and the musculature responsible for producing these movements.
6.2 Introduction

Delivering a cricket ball with a wrist-spin (WS) bowling technique has long been considered one of the most difficult arts to master in the game of cricket (Bradman, 1969; Philpott, 1995; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). A bowler must release the ball out of the ulna or the fifth phalangeal side of the hand under the influence of the internally rotating humerus, pronating elbow, and extending and radially deviating wrist (Philpott, 1995; Spratford et al., 2014; Woolmer et al., 2008) without the control of the second phalangeal that is seen in their finger-spin (FS) colleagues. An example of the release profile is shown in Figure 6.1.

![Figure 6.1: A series of images prior to release for a WS bowler, note the position of the wrist.](image)

This type of technique enables the bowler to deliver the ball with considerably more revolutions in comparison with the more common FS bowler (Beach et al., 2014; Bradman, 1969; Philpott, 1995; Wilkins, 1991; Woolmer et al., 2008). Greater revolutions also allows the bowler to take advantage of the increase in the Magnus force applied to the ball and the subsequent increases in lateral and vertical deviation during flight (Robinson & Robinson, 2013), and the potential increase of lateral deviation (side-spin) after the ball bounces (Beach et al., 2014; Woolmer et al., 2008). The anti-clockwise horizontal axis revolutions placed on the ball by the right handed WS bowler causes the ball to “drift into” the right handed batsman after reaching its zenith height (Justham et al., 2010; Robinson & Robinson, 2013) and deviate away to the off-side of the batsman, in the direction of the revolutions after bounce (Beach et al., 2014; Bradman, 1969; Philpott, 1995; Wilkins, 1991; Woolmer et al., 2008). Anecdotally, a ball deviating, or in this case “spinning”, away from a batsman has always been considered a more difficult task for a batsman to intercept and
to then control their shot; however, no specific research exists to support these claims. Research does show that when the bearing angle (direction of motion relative to the current course of the ball) of a ball is directed away from a performer, as occurs after a WS delivery bounces, performers tend to misperceive its future arrival location (Diaz, Cooper, Rothkopf, & Hayhoe, 2013; Welchman, Tuck, & Harris, 2004). For these reasons, coaching based literature has stated that if a bowler can master this technique and bowl with control, they have long been considered a match winner (Woolmer et al., 2008). This is best evidenced by the career of Shane Warne, statistically the game’s greatest ever WS bowler. During a 15 year career, Warne took 708 Test wickets at an average of 25.41 with the Australian Test team being ranked the number one Test playing nation for 64% of this period (Cricinfo, 2015).

To date, techniques associated with WS bowlers are subjectively based, with guidelines limited to what is found within the coaching literature. This has focussed on the need for the body (trunk) to be rotating forward at ball release (BR) and for the “wrist to be turned on release”, which in essence is a combination of elbow pronation, radial deviation and wrist extension (Bradman, 1969; Philpott, 1995; Tyson, 1976, 1994; Wilkins, 1991; Woolmer et al., 2008). This late movement at the wrist also forms the basis for the bowling action’s naming convention; however there is limited evidence as to what role, if any, these biomechanical movements play in bowling performance. Without this foundation knowledge, it is difficult to quantify the basic technique of a WS bowler or attempt to understand the differences that may occur between bowlers as they progress through the development pathway. It is also difficult to make comparisons with other overhead throwing activities given the specific nature of a WS bowler’s technique. However, as with FS bowlers, it is assumed that rotations of the long axis of the bowling limb will be important within the kinetic chain, similar to that observed in racquet based sports such as tennis and squash (Marshall & Elliott, 2000; Martin et al., 2013; Reid et al., 2015).

It is also not understood if upper-limb isokinetic strength or anthropometry differences exist between bowlers of different skill levels or if these factors are linked to performance. In both FS and fast bowling, the bowler takes advantage of the elbow extension that naturally occurs late within the kinetic chain.
(Marshall & Elliott, 2000; Marshall & Ferdinands, 2003; Wixted, Portus, et al., 2011). However, given that a WS bowler is internally rotating at the shoulder and pronating at the elbow through BR, the passive extension of the forearm relative to the upper-arm does not occur and as such may require more strength to deliver the ball, although no evidence of this exists. Quantifying the role of these variables will facilitate a better understanding of the technique and functional muscle strength differences between skill levels, as well as identifying anthropometric variables that may be used in talent identification programs.

Therefore the aims of this study were to examine the differences in upper-body bowling mechanics, anthropometry and isokinetic strength across skill levels in WS bowlers. How these variables influence performance, as measured by a velocity/revolution index, a combination of variables shown in chapter four to differentiate skill level. It is hypothesised that elite bowlers will display higher joint moments, segment angular velocities and greater isokinetic strength of the bowling limb, and that the mechanics of the distal arm will be predictors of bowling performance.

6.3 Methods

Twenty male WS bowlers were invited by the national spin bowling coach to participate in this study. Participants were assigned to one of two groups based on the level of cricket previously played, 1) pathway (up to 1st Class) or 2) elite (1st class and above). This cohort represented the entire population within Australia for this level of spin bowler and included three players who had played Test cricket (46 games and 211 wickets) and one that had played International 1-day cricket (3 games and 6 wickets). The physical characteristics of the participants are outlined in Table 6.1.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway WS</td>
<td>12</td>
<td>19.6 ± 3.6</td>
<td>179.6 ± 6.9</td>
<td>71.0 ± 8.0</td>
</tr>
<tr>
<td>Elite WS</td>
<td>8</td>
<td>29.6 ± 7.8</td>
<td>180.2 ± 4.2</td>
<td>71.8 ± 8.0</td>
</tr>
</tbody>
</table>
Ethics approval was granted and written informed consent was obtained for each participant before the commencement of the study, in accordance with the requirements of the Human Research Ethics Committees of the Australian Institute of Sport (AIS) and The University of Western Australia (Appendices A-E).

Camera and laboratory set-up
Bowling data collection took place in an indoor motion capture laboratory that was purpose built for cricket analysis and contained a permanent artificial pitch. Marker trajectories were tracked using a 22 camera (MX 13 and 40) Vicon MX motion analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. The capture volume was approximately 10 m long and 5 m wide allowing for two full strides before the delivery phase and 3 m of ball flight post-release to be collected. The global reference frame originated at the bowling crease with the $x$-axis pointing right, $y$-axis pointing towards the batsman and the cross product $z$-axis pointing upwards.

Data collection and procedures (bowling)
Retro-reflective markers were affixed to each participants head, torso, upper-limbs and ball according to a customised marker set and model. The set consisted of numerous single and three marker clusters attached to either semi-rigid plastic or lightweight aluminium bases. Participant specific static trials were collected to define joint centres. The shoulder joint centre was calculated using a regression equation based on anatomical landmarks as well as height and mass (Campbell, Lloyd, et al., 2009). The elbow joint centre was estimated using a pointer method based on the location of the lateral and medial aspects of the humeral epicondyles (Chin et al., 2010) and the wrist joint centre as the midpoint of markers placed on the styloid processes of the radius and ulna (Lloyd et al., 2000). Three dynamic hemispherical markers comprised of ultralight foam (<0.1g) affixed in locations that did not impede the bowler’s preferred grip on the ball were used to calculate ball velocities and revolutions (Whiteside et al., 2012). For more in depth descriptions please refer to chapter three.
Participants warmed up as per their normal pre game routine and then bowled six overs with a timed two minute break between each to replicate match conditions. The six overs consisted of 20 WS and 16 self-nominated variation deliveries. Participants were asked to nominate where their usual deliveries would pass a right-handed batsman based on a clear target placed where the batsman would normally stand that consisted of a series of 20 cm x 20 cm grids (accuracy target as seen in Figure 4.2). A valid delivery was one that struck the target on the nominated grid, the one directly above, underneath or immediately next to the nominated grid to the off-side (to the batsman’s right). The deliveries were bowled in a randomised order.

Two dimensional (2D) data from each of the 22 cameras were captured for each marker and reconstructed into three dimensional (3D) marker trajectories and labelled using Vicon Nexus software (Oxford Metrics, Oxford, UK). Trajectories were filtered using a quintic spline Woltring filter at a mean square error (MSE) of 20 after a residual analysis and visual inspection of the data (Winter, 2005). Data were then modelled using the University of Western Australia’s (UWA) upper-body and ball model (Campbell, Lloyd, et al., 2009; Chin et al., 2009; Chin et al., 2010; Whiteside et al., 2012). Joint moments were determined using standard inverse dynamic analysis starting from the hand and flowing to the shoulder of the bowling arm with all segment inertial characteristics taken from de Leva (1996). Moments were expressed in a non-orthogonal joint coordinate system to allow functional meaning and reduce potential cross talk introduced from kinematic measures (Middleton, 2011; Schache & Baker, 2007). The ball was assumed to have minimal inertia but with a point mass, and force applied by a simple $F = ma$ calculation. The ball created a reaction if its origin was less than a distance calculated between it and a marker placed on the distal intermediate carpal as calculated by the length the fourth phalangeal and radius of the ball, indicating the ball had no influence on the inverse dynamic calculation once released.

Selected biomechanical data for the pelvis, thorax, shoulder, elbow and wrist considered critical to bowling performance were included. Joint angles were determined relative to their adjoining segments, with 0° indicating alignment between segment coordinate systems. Segment angles (pelvis and thorax)
were measured relative to the global coordinate system with 0° indicating a pelvis or thorax orthogonal with its defining vector. Therefore, a rotation angle of 90° indicated the bowler was standing front-on or orthogonal with the pitch. Data were reported at BR and the peaks between BFI-BR for the pelvis and thorax and UAH-BR for the bowling limb. All variables were normalised to 101 points using a cubic spline approach in a custom MATLAB program (Mathworks Inc; Natick, MA) with representative mean data being calculated from the first six valid WS trials based on where the ball made contact with the accuracy target.

**Anthropometry**

Selected anthropometric lengths, breadths, girths and sitting height were taken from the bowling limb by an accredited ISAK Level 2 anthropometrist (Marfell-Jones et al., 2007). All variables were measured in triplicate with the criterion being the median. A combination of equipment was used that included a large sliding calliper (British Indicators Ltd), vernier callipers (Holtain, Cresswell, Dyfed, UK) and a flexible steel tape (Lufkin Executive, Thinline W 606 PM, Cooper Industries, Lexington, SC, USA). Lengths consisted of acromiale-radiale (arm), radiale–stylion (forearm) and midstylion–dactylion (hand). Breadths consisted of the biacromial, humerus, transverse chest, and anterior posterior chest depth. Girths consisted of upper arm, forearm and wrist. An assessment of the test-retest reliability was established with a mean technical error of measurement (TEM) being 1.4%.

Active range of motion of the bowling limb was assessed by the same experienced clinicians using a bi-level inclinometer and goniometer (US Neurologicals, Poulsbo, Washington, United States) using previously validated methods (Gerhardt et al., 2002). Measures consisted of; flexion, extension, abduction, internal and external rotation of the shoulder with shoulder at 90° of abduction and elbow flexed at 90°, extension and ‘carry angle’ of the elbow, flexion, extension, radial and ulna deviation of the wrist and flexion and extension of the metacarpophalangeal joint (MCP4). All variables were measured in triplicate with the mean value used as the criterion. An assessment of the test-retest reliability was established with a mean TEM being 1.0%. A
more in-depth explanation of methods can be found in chapter three of this thesis.

**Isokinetic**

Bowlers undertook five isokinetic strength tests on their bowling arm using a HUMAC NORM (CSMI2009, version 9.5.2) dynamometer at angular velocities of 60°.s⁻¹ and 180°.s⁻¹. To reduce the likelihood of fatigue one minutes rest was provided between each test. Prior to testing, participants warmed-up using a rowing ergometer for a period of 5 minutes at sub maximal intensity (Claiborne et al., 2006) and were allowed to perform personally selected stretches if desired. Measures of the shoulder consisted of; flexion/abduction-extension/adduction in the prone position, internal and external rotation in the prone position with the shoulder at 90° of abduction and elbow flexed at 90° and normalised to gravity. At the elbow, pronation and supination and at the wrist, flexion, extension, radial and ulna deviation were taken in the sitting position and not corrected for gravity. All measures were normalised to body weight. A more in-depth explanation of the isokinetic measures can be found in chapter three of this thesis.

**Performance measure**

The relationship \( x \) between ball velocity \( V \) and revolutions around the horizontal axis of the global coordinate system \( \omega \) was calculated using the following equation to produce a velocity/revolution index score and used as a performance measure. This allowed for increases in BR velocity, relative to revolutions and velocity, to be considered and expressed based on evidence that increases in ball revolutions will come at a detriment to ball speed (Sakurai et al., 2013)

\[
x = (V + \omega) + \frac{v^2}{\omega}
\]  

(4)

**Statistical analysis**

Independent group t-tests were performed to establish differences between elite and pathway bowlers for measured variables. A partial Bonferroni correction was adopted due to the multiple comparisons being made with an amended
alpha level set at $\alpha \leq 0.01$. Effect sizes (ES) were calculated to functionally differentiate between groups, with levels of, 0.2, 0.5 and 0.8 representing small, moderate and large effect sizes respectively (Cohen, 1992). A multiple stepwise regression analysis was then performed, collapsed across elite and pathway groups using variables that were shown to be significant ($p < 0.01$) and or had large effect sizes (ES $\geq 0.8$) using the velocity/revolution index identified as the dependant variable. This enabled the measure or combination of measures that best predicted performance to be identified.

6.4 Results

Angular displacements
Significant biomechanical differences were observed at the pelvis, thorax, elbow and wrist joints between elite and pathway WS bowlers. Elite bowlers displayed lower peak pelvic forward rotation ($p = 0.007$) and while not significantly different, pelvic forward rotation at BR displayed a large effect size (ES = 1.22) with elite bowlers again exhibiting lower levels (more front-on pelvis) at BR. Thorax forward rotation followed a similar trend with elite bowlers having a lower peak thorax forward rotation ($p = 0.001$) indicating a more front-on position. Elite bowlers showed significantly greater amounts of elbow pronation at BR ($p = <0.001$), peak elbow pronation ($p = 0.003$) and while not statistically significant, a greater level of peak radial deviation as evidenced by a large ES (ES = 0.80). Wrist extension values at BR were significantly higher for elite bowlers ($p = 0.009$) and a large ES was recorded when comparing between group peak wrist extension values (ES = 1.29) (Table 6.2).

Angular velocities
Elite bowlers displayed increased levels of elbow pronation angular velocity at BR ($p = 0.007$), peak elbow pronation angular velocity ($p = 0.004$), radial deviation angular velocity at BR, peak radial deviation angular velocity ($p = 0.010$ and $p = 0.010$), wrist extension angular velocity at BR ($p = 0.004$) and peak wrist extension angular velocity ($p = 0.005$). At BR large ESs were also observed with elite bowlers displaying increased pelvic forward rotation (ES = 1.27) and increased shoulder internal rotation (ES = 1.78) (Table 6.3).
Linear velocities

No differences were observed between elite and pathway bowlers for any of the investigated linear velocity variables.
Table 6.2. Mean (± standard deviations) for selected angular displacement parameters for elite and pathway WS bowlers.

<table>
<thead>
<tr>
<th>Variable (°)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis forward rotation (BR)</td>
<td>114.2 (6.1)</td>
<td>105.9 (7.4)</td>
<td>0.042</td>
<td>1.22*</td>
</tr>
<tr>
<td>Pelvis forward rotation peak (UAH-BR)</td>
<td>176.5 (8.3)</td>
<td>157.6 (11.4)</td>
<td>0.007*</td>
<td>1.90*</td>
</tr>
<tr>
<td>Thorax forward rotation (BR)</td>
<td>102.4 (10.9)</td>
<td>105.4 (8.7)</td>
<td>0.567</td>
<td>0.25</td>
</tr>
<tr>
<td>Thorax forward rotation peak (UAH-BR)</td>
<td>170.0 (9.4)</td>
<td>157.6 (8.7)</td>
<td>0.001*</td>
<td>1.37*</td>
</tr>
<tr>
<td>Thorax lateral rotation (BR)</td>
<td>34.3 (5.7)</td>
<td>30.4 (4.1)</td>
<td>0.156</td>
<td>0.79</td>
</tr>
<tr>
<td>Thorax lateral rotation peak (UAH-BR)</td>
<td>34.4 (5.1)</td>
<td>30.6 (6.5)</td>
<td>0.189</td>
<td>0.65</td>
</tr>
<tr>
<td>Shoulder extension (BR)</td>
<td>7.6 (10.4)</td>
<td>8.7 (7.0)</td>
<td>0.823</td>
<td>0.12</td>
</tr>
<tr>
<td>Shoulder extension (UAH-BR)</td>
<td>8.3 (9.8)</td>
<td>8.7 (7.0)</td>
<td>0.921</td>
<td>0.05</td>
</tr>
<tr>
<td>Shoulder abduction (BR)</td>
<td>117.7 (11.8)</td>
<td>114.3 (11.3)</td>
<td>0.560</td>
<td>0.29</td>
</tr>
<tr>
<td>Shoulder internal rotation (BR)</td>
<td>27.4 (25.2)</td>
<td>28.8 (9.2)</td>
<td>0.899</td>
<td>0.07</td>
</tr>
<tr>
<td>Shoulder external rotation peak (UAH-BR)</td>
<td>41.6 (23.4)</td>
<td>44.7 (8.9)</td>
<td>0.764</td>
<td>0.17</td>
</tr>
<tr>
<td>Elbow flexion (BR)</td>
<td>27.2 (9.4)</td>
<td>28.8 (14.4)</td>
<td>0.766</td>
<td>0.13</td>
</tr>
<tr>
<td>Elbow pronation (BR)</td>
<td>62.1 (18.0)</td>
<td>89.2 (9.9)</td>
<td>&lt;0.001*</td>
<td>1.87*</td>
</tr>
<tr>
<td>Elbow pronation peak (UAH-BR)</td>
<td>67.7 (28.4)</td>
<td>101.3 (14.9)</td>
<td>0.003*</td>
<td>1.48*</td>
</tr>
<tr>
<td>Radial deviation (BR)</td>
<td>4.9 (6.1)</td>
<td>6.2 (9.0)</td>
<td>0.698</td>
<td>0.17</td>
</tr>
<tr>
<td>Radial deviation peak (UAH-BR)</td>
<td>20.6 (9.9)</td>
<td>28.5 (9.8)</td>
<td>0.123</td>
<td>0.80*</td>
</tr>
<tr>
<td>Wrist extension (BR)</td>
<td>-22.5 (15.2)</td>
<td>-37.9 (7.8)</td>
<td>0.009*</td>
<td>1.27*</td>
</tr>
<tr>
<td>Wrist extension peak (UAH-BR)</td>
<td>-29.7 (6.3)</td>
<td>-37.9 (6.4)</td>
<td>0.026</td>
<td>1.29*</td>
</tr>
</tbody>
</table>

*Significant ≤0.010 and Large ES ≥0.80
Table 6.3. Group mean (± standard deviations) for selected angular velocity parameters for elite and pathway WS bowlers.

<table>
<thead>
<tr>
<th>Variable (°·s⁻¹)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis forward rotation (BR)</td>
<td>111.5 (33.0)</td>
<td>162.7 (28.9)</td>
<td>0.026</td>
<td>1.27*</td>
</tr>
<tr>
<td>Pelvis forward rotation peak (UAH-BR)</td>
<td>541.8 (108.8)</td>
<td>486.8 (117.2)</td>
<td>0.366</td>
<td>0.49</td>
</tr>
<tr>
<td>Thorax forward rotation (BR)</td>
<td>244.1 (108.7)</td>
<td>233.2 (85.4)</td>
<td>0.832</td>
<td>0.11</td>
</tr>
<tr>
<td>Thorax forward rotation peak (UAH-BR)</td>
<td>466.1 (104.5)</td>
<td>398.5 (95.1)</td>
<td>0.178</td>
<td>0.67</td>
</tr>
<tr>
<td>Thorax lateral rotation (BR)</td>
<td>220.8 (64.4)</td>
<td>233.7 (85.2)</td>
<td>0.716</td>
<td>0.17</td>
</tr>
<tr>
<td>Thorax lateral rotation peak (UAH-BR)</td>
<td>491.7 (86.6)</td>
<td>474.7 (74.8)</td>
<td>0.684</td>
<td>0.21</td>
</tr>
<tr>
<td>Shoulder extension (BR)</td>
<td>-205.6 (92.3)</td>
<td>-244.5 (83.2)</td>
<td>0.392</td>
<td>0.45</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>-800.0 (188.7)</td>
<td>-794.9 (242.7)</td>
<td>0.960</td>
<td>0.02</td>
</tr>
<tr>
<td>Shoulder internal rotation (BR)</td>
<td>499.1 (147.7)</td>
<td>655.8 (116.5)</td>
<td>0.041</td>
<td>1.78*</td>
</tr>
<tr>
<td>Shoulder internal rotation peak (UAH-BR)</td>
<td>663.7 (156.2)</td>
<td>689.1 (125.1)</td>
<td>0.891</td>
<td>0.18</td>
</tr>
<tr>
<td>Elbow flexion (BR)</td>
<td>447.9 (166.7)</td>
<td>386.6 (191.0)</td>
<td>0.486</td>
<td>0.34</td>
</tr>
<tr>
<td>Elbow pronation (BR)</td>
<td>-368.9 (126.5)</td>
<td>-490.4 (35.7)</td>
<td>0.007*</td>
<td>1.31*</td>
</tr>
<tr>
<td>Elbow pronation peak (UAH-BR)</td>
<td>-509.6 (112.3)</td>
<td>-645.3 (63.9)</td>
<td>0.004*</td>
<td>1.49*</td>
</tr>
<tr>
<td>Radial deviation (BR)</td>
<td>-415.7 (142.9)</td>
<td>-608.4 (119.5)</td>
<td>0.010*</td>
<td>1.46*</td>
</tr>
<tr>
<td>Radial deviation peak (UAH-BR)</td>
<td>-549.4 (198.8)</td>
<td>-746.3 (132.0)</td>
<td>0.010*</td>
<td>1.46*</td>
</tr>
<tr>
<td>Wrist extension (BR)</td>
<td>-201.0 (131.2)</td>
<td>-396.1 (85.5)</td>
<td>0.004*</td>
<td>1.76*</td>
</tr>
<tr>
<td>Wrist extension peak (UAH-BR)</td>
<td>-819.2 (150.2)</td>
<td>-1056.7 (146.0)</td>
<td>0.005*</td>
<td>1.60*</td>
</tr>
</tbody>
</table>

*Significant ≤0.010 and “Large ES” ≥0.80
Table 6.4. Group mean (± standard deviations) for selected linear velocity parameters for elite and pathway WS bowlers.

<table>
<thead>
<tr>
<th>Variable (m.s(^{-1}))</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder joint centre (BR)</td>
<td>3.0 (0.4)</td>
<td>3.2 (0.5)</td>
<td>0.383</td>
<td>0.44</td>
</tr>
<tr>
<td>Shoulder joint centre peak (UAH-BR)</td>
<td>5.1 (0.3)</td>
<td>5.2 (0.8)</td>
<td>0.811</td>
<td>0.24</td>
</tr>
<tr>
<td>Elbow joint centre (BR)</td>
<td>8.7 (0.9)</td>
<td>8.5 (1.0)</td>
<td>0.546</td>
<td>0.21</td>
</tr>
<tr>
<td>Elbow joint centre peak (UAH-BR)</td>
<td>9.9 (0.6)</td>
<td>9.6 (1.0)</td>
<td>0.561</td>
<td>0.36</td>
</tr>
<tr>
<td>Wrist joint centre (BR)</td>
<td>14.7 (1.2)</td>
<td>14.1 (1.2)</td>
<td>0.320</td>
<td>0.50</td>
</tr>
<tr>
<td>Wrist joint centre peak (UAH-BR)</td>
<td>15.5 (0.7)</td>
<td>15.0 (1.4)</td>
<td>0.305</td>
<td>0.45</td>
</tr>
</tbody>
</table>
**Joint kinetics**

Elite bowlers displayed increased shoulder extension ($p = 0.007$) and internal rotation moments at BR ($p = 0.010$), with a large ES returned for peak shoulder internal rotation (ES = 0.81) when compared with pathway bowlers. At the elbow joint large ESs were reported with elite bowlers experiencing increased flexion moment (ES = 1.50) and pronation moment at BR ($p = 0.82$), as well as peak pronation moment ($p = 1.05$). Large ESs were also observed at the wrist joint with elite bowlers also displaying increased peak wrist extension (ES = 0.88) and peak wrist radial deviation (ES = 1.15) moments (Table 6.5).

**Anthropometry**

A large ES was observed for midstylion-dactylyion (hand) length (ES = 1.00) with elite bowlers recording a greater length. Range of motion differences were observed at the wrist and finger joints with elite bowlers having larger range of motion for absolute radial deviation (ES = 1.19), radial deviation full range (ES = 1.02), as well MCP4 absolute flexion (ES = 1.18), MCP4 absolute extension (ES = 1.48) and MCP4 total range of motion (ES = 1.46) (Tables 6.5 and 6.6).

**Isokinetic**

Elite bowlers reported increased amounts of isokinetic torque at the shoulder, elbow and wrist joints in comparison with pathway bowlers. Significant differences were seen for peak wrist extension torque at 60°.s$^{-1}$ ($p = 0.001$) and peak wrist ulna deviation torque at 60°.s$^{-1}$ ($p = 0.001$), while large ESs were returned for peak shoulder extension/adduction torque at 60°.s$^{-1}$ (ES = 1.13), peak wrist radial deviation torque at 60°.s$^{-1}$ (ES = 1.33) and 180°.s$^{-1}$ (ES = 1.32) and peak wrist ulna deviation torque at 180°.s$^{-1}$ (ES = 1.26) (Table 6.7).

**Regression analysis**

The stepwise multiple regression analysis in which the velocity/revolution index (65.1 ± 4.3) was the criterion variable revealed that peak isokinetic radial deviation torque (coefficient = 0.713), peak shoulder internal rotation moment (coefficient = 0.500), shoulder extension moment at BR (coefficient = -0.332) and peak pronation moment (coefficient = -0.288) were the best predictors of WS performance, explaining 82% of variance ($r = 0.90; r^2 = 0.82; f = 15.63, p < 0.001$).
Table 6.5. Group mean (± standard deviations) and comparison for selected joint moments for elite and pathway WS bowlers.

<table>
<thead>
<tr>
<th>Variable (Nm)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder extension (BR)</td>
<td>-23.7 (9.9)</td>
<td>-38.1 (8.6)</td>
<td>0.007*</td>
<td>1.55*</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>-47.8 (23.5)</td>
<td>-62.0 (32.1)</td>
<td>0.291</td>
<td>0.50</td>
</tr>
<tr>
<td>Shoulder abduction (BR)</td>
<td>53.8 (27.3)</td>
<td>48.4 (20.1)</td>
<td>0.635</td>
<td>0.23</td>
</tr>
<tr>
<td>Shoulder abduction peak (UAH-BR)</td>
<td>97.0 (32.8)</td>
<td>91.0 (24.9)</td>
<td>0.695</td>
<td>0.21</td>
</tr>
<tr>
<td>Shoulder internal rotation (BR)</td>
<td>1.3 (5.4)</td>
<td>7.8 (3.4)</td>
<td>0.010*</td>
<td>1.44*</td>
</tr>
<tr>
<td>Shoulder internal rotation peak (UAH-BR)</td>
<td>39.4 (13.1)</td>
<td>49.8 (12.6)</td>
<td>0.129</td>
<td>0.81*</td>
</tr>
<tr>
<td>Elbow flexion (BR)</td>
<td>2.0 (4.5)</td>
<td>9.6 (5.6)</td>
<td>0.020</td>
<td>1.50*</td>
</tr>
<tr>
<td>Elbow flexion peak (UAH-BR)</td>
<td>61.7 (29.3)</td>
<td>60.1 (14.0)</td>
<td>0.904</td>
<td>0.07</td>
</tr>
<tr>
<td>Pronation (BR)</td>
<td>-2.1 (3.4)</td>
<td>0.3 (2.4)</td>
<td>0.097</td>
<td>0.82*</td>
</tr>
<tr>
<td>Pronation peak (UAH-BR)</td>
<td>29.2 (13.2)</td>
<td>44.6 (15.9)</td>
<td>0.090</td>
<td>1.05*</td>
</tr>
<tr>
<td>Wrist extension (BR)</td>
<td>-0.5 (4.5)</td>
<td>-0.3 (2.0)</td>
<td>0.889</td>
<td>0.06</td>
</tr>
<tr>
<td>Wrist extension peak (UAH-BR)</td>
<td>-45.0 (13.6)</td>
<td>-66.4 (31.7)</td>
<td>0.102</td>
<td>0.88*</td>
</tr>
<tr>
<td>Radial deviation (BR)</td>
<td>-1.1 (3.3)</td>
<td>-2.1 (4.8)</td>
<td>0.633</td>
<td>0.24</td>
</tr>
<tr>
<td>Radial deviation peak (UAH-BR)</td>
<td>-70.2 (21.1)</td>
<td>-95.0 (22.1)</td>
<td>0.031</td>
<td>1.15*</td>
</tr>
</tbody>
</table>

*Significant ≤0.010 and #Large ES ≥0.80
Table 6.6. Group mean (± standard deviations) for selected anthropometry parameters for elite and pathway wrist-spin bowlers.

<table>
<thead>
<tr>
<th>Variable (cm)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acromiale-radiale length (arm)</td>
<td>33.7 (1.6)</td>
<td>34.3 (1.8)</td>
<td>0.766</td>
<td>0.35</td>
</tr>
<tr>
<td>Radiale–stylion length (forearm)</td>
<td>25.4 (1.4)</td>
<td>26.3 (1.0)</td>
<td>0.229</td>
<td>0.74</td>
</tr>
<tr>
<td>Midstylion–dactyion length (hand)</td>
<td>19.4 (0.9)</td>
<td>20.3 (0.9)</td>
<td>0.044</td>
<td><strong>1.00</strong></td>
</tr>
<tr>
<td>Arm relaxed girth</td>
<td>30.4 (2.6)</td>
<td>31.9 (3.0)</td>
<td>0.252</td>
<td>0.53</td>
</tr>
<tr>
<td>Arm tensed girth</td>
<td>32.6 (2.6)</td>
<td>34.2 (3.1)</td>
<td>0.268</td>
<td>0.56</td>
</tr>
<tr>
<td>Forearm girth</td>
<td>27.7 (1.7)</td>
<td>28.0 (1.4)</td>
<td>0.572</td>
<td>0.19</td>
</tr>
<tr>
<td>Wrist girth</td>
<td>16.6 (0.7)</td>
<td>17.0 (1.1)</td>
<td>0.524</td>
<td>0.43</td>
</tr>
<tr>
<td>Humerus breadth</td>
<td>7.1 (0.3)</td>
<td>7.0 (0.2)</td>
<td>0.380</td>
<td>0.39</td>
</tr>
<tr>
<td>Biacromial breadth</td>
<td>41.8 (3.6)</td>
<td>43.4 (2.6)</td>
<td>0.331</td>
<td>0.51</td>
</tr>
<tr>
<td>Transverse chest breadth</td>
<td>30.8 (2.5)</td>
<td>32.4 (1.7)</td>
<td>0.191</td>
<td>0.75</td>
</tr>
<tr>
<td>Anterior posterior chest depth</td>
<td>19.4 (1.7)</td>
<td>20.1 (0.8)</td>
<td>0.222</td>
<td>0.53</td>
</tr>
<tr>
<td>Sitting height</td>
<td>94.7 (11.3)</td>
<td>94.5 (2.5)</td>
<td>0.921</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*Large ES ≥0.80
Table 6.7. Group mean (± standard deviations) and comparisons of joint ranges of motion for elite and pathway WS bowlers.

<table>
<thead>
<tr>
<th>Variable (°)</th>
<th>Pathway</th>
<th>Elite</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder flexion maximum</td>
<td>178.4 (14.7)</td>
<td>168.9 (13.3)</td>
<td>0.198</td>
<td>0.68</td>
</tr>
<tr>
<td>Shoulder extension maximum</td>
<td>42.8 (11.8)</td>
<td>44.3 (7.2)</td>
<td>0.927</td>
<td>0.15</td>
</tr>
<tr>
<td>Shoulder flexion/extension range</td>
<td>221.7 (22.1)</td>
<td>210.2 (15.5)</td>
<td>0.165</td>
<td>0.60</td>
</tr>
<tr>
<td>Shoulder internal rotation maximum</td>
<td>58.9 (18.5)</td>
<td>54.6 (27.1)</td>
<td>0.688</td>
<td>0.19</td>
</tr>
<tr>
<td>Shoulder external rotation maximum</td>
<td>186.2 (18.2)</td>
<td>177.3 (36.9)</td>
<td>0.578</td>
<td>0.31</td>
</tr>
<tr>
<td>Shoulder internal/external range</td>
<td>245.1 (34.9)</td>
<td>231.9 (54.0)</td>
<td>0.568</td>
<td>0.29</td>
</tr>
<tr>
<td>Shoulder abduction maximum</td>
<td>116.2 (26.0)</td>
<td>125.4 (23.8)</td>
<td>0.403</td>
<td>0.37</td>
</tr>
<tr>
<td>Elbow extension maximum</td>
<td>5.7 (3.3)</td>
<td>3.4 (6.3)</td>
<td>0.530</td>
<td>0.46</td>
</tr>
<tr>
<td>Elbow abduction (carry angle)</td>
<td>9.3 (4.2)</td>
<td>10.0 (2.2)</td>
<td>0.323</td>
<td>0.21</td>
</tr>
<tr>
<td>Wrist flexion maximum</td>
<td>92.4 (11.3)</td>
<td>91.6 (6.0)</td>
<td>0.708</td>
<td>0.09</td>
</tr>
<tr>
<td>Wrist extension maximum</td>
<td>72.3 (12.2)</td>
<td>67.8 (5.7)</td>
<td>0.319</td>
<td>0.47</td>
</tr>
<tr>
<td>Wrist flexion/extension range</td>
<td>164.7 (17.9)</td>
<td>159.4 (9.7)</td>
<td>0.674</td>
<td>0.33</td>
</tr>
<tr>
<td>Radial deviation maximum</td>
<td>27.8 (11.2)</td>
<td>42.3 (13.1)</td>
<td>0.057</td>
<td>1.19*</td>
</tr>
<tr>
<td>Ulna deviation maximum</td>
<td>48.5 (8.3)</td>
<td>43.7 (11.0)</td>
<td>0.337</td>
<td>0.49</td>
</tr>
<tr>
<td>Ulna/radial deviation range</td>
<td>76.3 (9.0)</td>
<td>86.0 (10.0)</td>
<td>0.117</td>
<td>1.02*</td>
</tr>
<tr>
<td>MCP4 flexion maximum</td>
<td>94.5 (9.2)</td>
<td>105.1 (9.7)</td>
<td>0.036</td>
<td>1.18*</td>
</tr>
<tr>
<td>MCP4 extension maximum</td>
<td>16.8 (5.5)</td>
<td>26.1 (7.0)</td>
<td>0.029</td>
<td>1.48*</td>
</tr>
<tr>
<td>MCP4 flexion/extension range</td>
<td>111.2 (11.1)</td>
<td>131.2 (15.8)</td>
<td>0.029</td>
<td>1.46*</td>
</tr>
</tbody>
</table>

*Significant ≤0.010 and "Large ES ≥0.80
Table 6.8. Group mean (± standard deviations) for selected peak isokinetic parameters for elite and pathway wrist-spin bowlers.

<table>
<thead>
<tr>
<th>Variable (Nm/kg)</th>
<th>Pathway 60°.s -'</th>
<th>Pathway 180°.s -'</th>
<th>Elite 60°.s -'</th>
<th>Elite 180°.s -'</th>
<th>p-value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex/abduction peak</td>
<td>0.94 (0.11)</td>
<td>0.74 (0.10)</td>
<td>0.89 (0.16)</td>
<td>0.68 (0.22)</td>
<td>0.552</td>
<td>0.469</td>
</tr>
<tr>
<td>Ext/adduction peak</td>
<td>1.15 (0.08)</td>
<td>1.01 (0.10)</td>
<td>1.33 (0.21)</td>
<td>1.00 (0.35)</td>
<td>0.078</td>
<td>0.951</td>
</tr>
<tr>
<td>Internal rotation peak</td>
<td>0.39 (0.03)</td>
<td>0.33 (0.05)</td>
<td>0.37 (0.13)</td>
<td>0.33 (0.13)</td>
<td>0.729</td>
<td>0.944</td>
</tr>
<tr>
<td>External rotation peak</td>
<td>0.51 (0.10)</td>
<td>0.44 (0.07)</td>
<td>0.49 (0.19)</td>
<td>0.39 (0.13)</td>
<td>0.893</td>
<td>0.343</td>
</tr>
<tr>
<td>Elbow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supination peak</td>
<td>0.11 (0.01)</td>
<td>0.09 (0.01)</td>
<td>0.11 (0.02)</td>
<td>0.08 (0.02)</td>
<td>0.949</td>
<td>0.160</td>
</tr>
<tr>
<td>Pronation peak</td>
<td>0.14 (0.03)</td>
<td>0.12 (0.02)</td>
<td>0.14 (0.05)</td>
<td>0.12 (0.04)</td>
<td>0.920</td>
<td>0.722</td>
</tr>
<tr>
<td>Wrist</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion peak</td>
<td>0.17 (0.09)</td>
<td>0.14 (0.06)</td>
<td>0.20 (0.07)</td>
<td>0.17 (0.07)</td>
<td>0.430</td>
<td>0.425</td>
</tr>
<tr>
<td>Extension peak</td>
<td>0.11 (0.04)</td>
<td>0.10 (0.03)</td>
<td>0.18 (0.05)</td>
<td>0.16 (0.05)</td>
<td>0.001*</td>
<td>0.031</td>
</tr>
<tr>
<td>Radial deviation peak</td>
<td>0.20 (0.04)</td>
<td>0.16 (0.04)</td>
<td>0.26 (0.05)</td>
<td>0.22 (0.05)</td>
<td>0.048</td>
<td>0.050</td>
</tr>
<tr>
<td>Ulna deviation peak</td>
<td>0.18 (0.07)</td>
<td>0.16 (0.03)</td>
<td>0.31 (0.09)</td>
<td>0.23 (0.06)</td>
<td>0.010*</td>
<td>0.034</td>
</tr>
</tbody>
</table>

*Significant ≤0.010 and *Large ES ≥0.80
6.5 Discussion

The purpose of this study was to examine the differences in upper-body bowling mechanics, anthropometry and isokinetic strength across skill levels in WS bowlers and to assess the influence these variables have on bowling performance, as measured by a velocity/revolution index.

Biomechanical differences between elite and pathway bowlers
In order for the WS bowler to deliver the ball with the desired amount of revolutions and velocity, the upper-body undergoes a series of complex and rapid movements between BFI and BR. At BR the pelvis and thorax segments are rotating forward and the shoulder is internally rotating and extending, the elbow flexing and pronating, the wrist extending and moving into ulna deviation. At this point several kinematic and kinetic differences were observed between elite and pathway bowlers.

Elite bowlers exhibited lower pelvis and thorax forward rotation displacements at BR, peak forward thorax rotation and increased pelvis forward rotation angular velocity at BR. The coaching literature makes mention of the need to be side-on at BFI and for the shoulders to turn towards the batsman but is vague on the specific body position at BR (Philpott, 1995; Tyson, 1994; Woolmer et al., 2008). Results from this research suggest, that at the point of BR, WS bowlers deliver the ball with both the pelvis and thorax aligned and in a less front-on position to that reported in chapter five for FS bowlers (between 11-18° lower rotation levels). It also suggests that elite bowlers deliver the ball with a pelvis 21° more front-on, rotate both their thorax and pelvis forward to a lesser degree between BFI and BR and have an increased pelvis rotation angular velocity at BR, indicating that elite bowlers decelerate the pelvis at a lower rate in the BFI-BR phase. Increases in trunk rotational angular velocity have also been reported within the baseball literature when comparing professional with non-professional players, and has been shown to be responsible for velocity dependant torques in the distal segments of the upper-limb, although it must be noted that this was only observed at the pelvis, and not the thorax for elite WS bowlers (Aguinaldo et al., 2007; Hirashima et al., 2008).
Elite bowlers also exhibited a higher peak shoulder internal rotation moment and shoulder internal rotation and extension moments at BR. As mentioned above, trunk angular velocities have been linked to velocity dependant torques in the distal segments of the limb, although the timing of the peak internal rotation moment suggests that elite bowlers may rely more on this in driving the subsequent differences observed in the distal segments of the kinetic chain rather than increases seen at the pelvis. This is due mainly to the peak internal rotation moment occurring early within the UAH-BR phase, as the humerus moves from peak external rotation into internal rotation, as has been reported within the baseball literature (Chu, Fleisig, Simpson, & Andrews, 2009; Fleisig et al., 1996; Fleisig, Chu, Webber, & Andrews, 2008; Vogelpohl & Kollock, 2015). For this reason, the peak shoulder internal rotation moment appears to be a major discriminator between elite and pathway bowlers and is responsible for creating subsequent differences throughout the distal segments of the bowling limb (Escamilla & Andrews, 2009; Fleisig et al., 1996; Naito et al., 2014). The importance of shoulder internal rotation has been regularly cited in the literature as critical to maximising the resultant distal segment velocity in other throwing and hitting activities (Marshall & Elliott, 2000; Martin et al., 2013; Naito & Maruyama, 2008; Naito et al., 2014; Reid et al., 2015).

As suggested above, elite bowlers subsequently displayed differences in the distal bowling limb, with greater elbow pronation moment and angular velocity at BR. They also recorded increased ulna deviation and extension moments at the wrist, along with the corresponding angular velocities and increased displacements of the wrist joint. The general biomechanical movements at the distal limb indicate that the WS bowler must forcefully flex and pronate at the elbow as well as extend and then deviate at the wrist joint up to and through the point of BR. This again supports the theory that elite bowlers make better use of the DoF within the proximal to distal linkage system, which is heavily influenced by the longitudinal rotations of the upper arm and forearm, similar to what has been reported for other overhead striking activities such as tennis serve and squash forehand (Marshall & Elliott, 2000; Martin et al., 2013; Reid et al., 2015).
While the biomechanical results highlight the importance of the musculature responsible for developing internal rotation as well as flexion and pronation at the elbow, it also highlights the potential loading placed on the shoulder joint during WS bowling. Coupled without taking advantage of the centrifugal force to extend the forearm segment (Wixted, Portus, et al., 2011), as well as less assistance from the forward rotating trunk, WS bowlers in comparison with FS and fast bowlers must rely heavily on manipulating the shoulder in order to get the body to the appropriate BR position. While injury surveillance data over a 10 year period in Australia reveals that injury prevalence in spin bowlers is at 4%, a level described within the research as “acceptable”, it fails to differentiate between bowler type (FS or WS) (Orchard et al., 2002; Orchard et al., 2006). It does however report that the greatest proportion of injuries to spin bowlers were to the shoulder tendon (non-defined). Research has also linked decreased range of motion of the bowling arm in comparison with the non-bowling arm in WS bowlers which has been shown to increase the chances of subsequent injuries (Chauhan & Gregory, 2003). During throwing type activities, the glenohumeral joint must resist large distraction and translation forces using the rotator cuff muscles (teres minor, infraspinatus, supraspinatus and subscapularis) and the internal rotators (pectoralis major, lattisimus dorsi, anterior deltoid and teres major) and as such can be prone to injury (Fleisig et al., 1995; Fleisig et al., 1996; Polster et al., 2013). As previously highlighted, there are major biomechanical differences between over-head throwing activities, such as baseball and WS bowling, however, as previously recommended, shoulder injuries in WS bowlers warrant further investigation (Gregory et al., 2002).

**Anthropometry and isokinetic differences between elite and pathway bowlers**

The anthropometry screen revealed that large ES differences were reported for elite compared with pathway WS bowlers. Midstyliion-dactylion length, radial deviation full range and total frontal plane wrist range of motion (radial and ulna deviation), as well as MCP4 flexion, extension and range of motion all differentiated WS bowling level. This provides valuable information that the size of the hand and increased range of motion in the frontal plane (radial and ulna deviation) of the wrist may be of importance and used to form the basis of talent identification measure for this type of spin bowler. From an applied coaching
perspective a larger hand makes the ball easier to hold and ulna deviation during bowling has been shown from this research to be important in discriminating skill level. Measurements of the phalangeal joints were outside the scope of this current research, however, high-speed footage taken during testing revealed that some elite players used their fourth phalange in a similar way to a FS bowler in an endeavour to control the ball at BR, a point briefly mentioned in the coaching text (Bradman, 1969). It is possible that this has been reflected in the anthropometry screen, and as such warrants further investigation. An example of this technique is shown in Figure 6.2.

![Figure 6.2: An elite WS bowler using their fourth phalange through the point of BR.](image)

Isokinetic strength differences were reported at the shoulder and wrist joints with elite bowlers having greater shoulder extension and adduction torque, wrist extension torque as well as radial and ulna deviation torque. There are examples within the literature of increases in torque production at the shoulder (adduction and extension) and wrist (extension) being positively correlated to throwing speed, however this is the first to show that elite WS bowlers exhibit such strength profiles (Bartlett et al., 1989; Pedegana et al., 1982). It also highlights the potential benefit in strength interventions targeting the musculature responsible for these movements.

**Regression analysis**

Understanding the differences between elite and pathway bowlers may assist in progressing bowlers through the development pathway. The results from the regression analysis collapsed across both groups allow variables to be identified that are critical to the performance of high level WS bowling. The results indicated that performance is best explained by peak isokinetic wrist
radial deviation torque, peak shoulder internal rotation moment, shoulder extension moment at BR and the peak elbow pronation moment.

6.6 Conclusion

The results of this study suggest that elite bowlers rotate their trunks to a lesser degree and exhibit less deceleration between BFI-BR resulting in a more front-on position and increased pelvis rotation angular velocity at BR when compared with pathway bowlers. Importantly, elite bowlers display higher peak shoulder internal rotation moments as the upper arm moves from external rotation into internal rotation, and is thought to be responsible for driving subsequent differences in the distal segments of the kinetic chain between bowling groups. The anthropometry screen highlighted variances at the wrist, hand and the fourth phalange, which may be used to form the basis for talent identification programs. The regression analysis for performance further reinforced that the WS bowling technique relies heavily on the bowling limb strength and peak isokinetic strength at the shoulder, elbow and wrist. While it is recommended that strength interventions aimed at improving the musculature responsible for the movement at the shoulder (internal rotation and extension), elbow (pronation) and wrist joints (radial deviation) be implemented, it should not come at a cost to the young bowler learning the correct technique for this complex skill.

6.7 Limitations

The data from this study were collected within a laboratory environment, allowing for sophisticated methodologies to be implemented. This however, came at the detriment to task representation due to the absence of a batsman and the clinical environment. It also only examined stock WS deliveries from each bowler.
Chapter 7: The influence of elbow extension on bowling performance and upper-body mechanics in finger-spin bowling.

7.1 Abstract

With the advancement of technology, scientists have been able to more accurately measure displacements of the elbow joint during the bowling action. This has led to the realisation that the majority of cricket bowlers undergo some degree of elbow extension during the period UAH to BR, thereby obliging the International Cricket Council (ICC) to revise the laws around the ‘straightening’ or ‘extension’ of the elbow joint from the once zero tolerance threshold to the current 15° extension range. However, it is still not understood if bowling with greater than 15° of elbow extension aids performance, or what biomechanical variables other than elbow extension differ between legal and illegal bowlers. Therefore, the purpose of this study was to compare performance measures between a cohort of pathway bowlers who delivered the ball with a bowling action deemed illegal (pathway illegal) with pathway and elite bowlers that used legal actions (pathway and elite legal). Biomechanical variables between elite legal and pathway illegal bowlers were also compared. Data were collected using a 22-camera Vicon motion analysis system. Results indicated that the performance of pathway illegal bowlers reflected the characteristics of elite legal bowlers, suggesting a performance benefit is obtained from elbow extension ranges exceeding 15°. Technique differences also existed with illegal pathway bowlers being more front-on at BFI and BR, forcing this cohort to rely on increased elbow flexion and supination in their pursuit to impart effective ball kinematics at BR. Subsequently, pathway illegal bowlers exhibited increased amounts of elbow extension displacement and wrist flexion angular velocity to the detriment of ulna deviation angular velocity. It is recommended that being more side-on at BFI and rotating the trunk through to the point of BR will assist bowlers in reducing illegal levels of elbow extension.
7.2 Introduction

In 2000, the holder of the laws of cricket, the Marylebone Cricket Club (MCC) clarified the law involving elbow extension during the bowling action. They defined a legal delivery as one that does not see straightening (extension) either partially or completely at the elbow joint during the swing phase from upper arm horizontal (UAH) until the ball had left the hand (BR) (MCC, 2000). In 2002, the world’s governing body; the International Cricket Council (ICC) introduced a tiered system of thresholds for elbow straightening (extension) between UAH and BR depending on bowler type, with tolerances set at $5^\circ$ for spin-bowlers, $7.5^\circ$ for medium pace bowlers and $10^\circ$ for fast bowlers. It is unclear how these thresholds were set as no reference is made to any scientific literature supporting these absolute levels (ICC, 2005; Portus et al., 2006). In 2005 the ICC reviewed testing data from high performance fast, medium-fast and spin bowlers collected from the Australian Institute of Sport (AIS), University of Auckland, University of Western Australia (UWA) as well as an internally funded project. Results showed that the naturally occurring elbow extension values ranged from $3^\circ$ to $26^\circ$ with a mean of $9^\circ$. Subsequently the ICC increased the upper limit to $15^\circ$ of elbow extension during the phase comprising UAH to BR for all bowlers, irrespective of delivery type. Bowlers, who were reported during a match for suspicion of exceeding this threshold were then obliged to follow a specific protocol that required their actions to be independently assessed by an accredited biomechanics laboratory (Portus et al., 2006).

While there has been significant research in the area of illegal actions in cricket, the focus in the main has been on quantifying or exploring better methods of measuring elbow kinematics, as opposed to understanding if any performance benefit exists when the elbow extends by $15^\circ$ or more during the critical phase of the delivery between UAH and BR. This current body of research has included measuring kinematics for bowlers with varying elbow anthropometry (Aginsky & Noakes, 2010; King & Yeadon, 2012), improving kinematic modelling techniques and exploring other potential variables as a measure for illegality (Chin et al., 2010; Elliott et al., 2007; Ferdinands & Kersting, 2007; Wells, Donnelly, et al., 2015; Yeadon & King, 2015), as well as exploring more
task representative means of testing using inertial sensor based technology (Spratford et al., 2014; Wells, Cereatti, et al., 2015; Wixted, Portus, et al., 2011). While these are all important issues, the underlying question is; does a bowler gain a performance benefit from extending the elbow by more than 15° between UAH and BR? It would also be of interest to appreciate what biomechanical variables other than elbow extension differ between bowlers who deliver the ball with an illegal, compared with legal, action. The ability to answer these questions will either reinforce the current law or provide administrators with quantitative data to make more informed decision around subsequent changes. It will also provide support staff with knowledge that will allow them to better coach bowlers, while also permitting better remediation of bowlers with illegal actions.

While attempts have been made to explore potential performance benefits of bowling with an illegal action, limitations in the scientific approach exist. Researchers have attempted to model fixed flexion elbow angles and the subsequent relationship to wrist velocity, inferred as ball speed (Marshall & Ferdinands, 2003) with results suggesting a positive relationship, driven by the increased humeral rotation that occurs when the elbow is flexed. The limitation to this modelling approach is that, in bowlers with average anthropometry, fixed elbow flexion during the delivery phase is generally not reflected in in-vivo bowling due to centrifugal force causing extension at the elbow during the forward swing (Wixted, Portus, et al., 2011). Ferdinands and Kersting (2007) also explored the link between elbow extension angular velocities at the point of BR and its influence on ball release speeds in both legal and illegal fast, medium and spin bowling groups. The limitation to this study was their small illegal cohort, which only consisted of six bowlers, with only one of the sample being the more commonly illegal, finger-spin (FS) bowler, however they suggested that elbow angular velocity measures may be a valid measure of bowling illegality. As such they recommended further research was warranted in this area. Research by Middleton and colleagues (2015) explored the use of an intuitive forward kinematic modelling process that utilised a substantial data set from a sample of fast bowlers, which permitted influences of both elbow flexion/extension and the abduction axis to be altered and the resultant influence on ball release speed estimated. This study’s finding reported elbow
extension and range of motion to be negatively related to wrist velocity and subsequent ball speeds, whereby the elbow extension nearing BR was associated with reduced ball velocity. This can be explained by the relatively planar (sagittal) alignment of the fast bowler’s upper limb near ball release (where elbow extension will cause the wrist joint centre to move in the opposite direction of the ball’s delivery). Although this is an interesting finding at odds with the current law, with respect to performance benefits, the relevance of the result to the more non-planar spin bowling motion is unknown.

While it is important to understand the implications that bowling with an illegal action has on performance for all types of bowlers, it is especially important for FS bowlers, as their basic biomechanical movement includes elbow extension through the point of BR (Chin et al., 2009; Spratford et al., 2014). Researchers also need to move past a simplistic model of using BR velocity as the criterion measure of performance and include other variables such as the ability to place revolutions on the ball, which has been shown in the literature, and in chapter four of this thesis, to distinguish performance (Chin et al., 2009; Justham et al., 2008).

Therefore, the purpose of this study was to compare BR velocity, ball revolutions and velocity/revolution indices between a cohort of pathway bowlers (up to 1st class level), who delivered the ball with a bowling action that exhibited greater than 15° of elbow extension from UAH to BR (i.e. an illegal action (pathway illegal)), with pathway and elite (1st class and above) bowlers that used a legal action (pathway and elite legal). Selected biomechanical variables between illegal pathway and legal elite level bowlers were also compared. It was hypothesised that pathway illegal bowlers produce performance outcomes (BR velocity, revolutions and velocity/revolution index) similar to that of an elite legal cohort, albeit using different biomechanical attributes. This will determine if elbow extension ranges above the 15° threshold impact on performance and give greater insight into how mechanics differ from bowlers who employ a legal action.
7.3 Methods

Forty-eight male FS bowlers participated in this study. Participants were assigned to one of three groups based on their playing level and legality of their bowling actions. Groups consisted of pathway legal, elite legal and pathway illegal bowlers as defined above. The elite cohort included six bowlers, who had played Test cricket (28 games and 89 wickets) and four who had played International 1-day cricket (128 games and 123 wickets) at the time of testing. The pathway cohorts consisted of bowlers from eight countries, who were either national U19 squad members, represented their countries at the U19 Cricket World Cup or played up to and including List A cricket. The physical characteristics of the participants are outlined in Table 7.1

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway legal</td>
<td>24</td>
<td>19.4 ± 2.7</td>
<td>181.8 ± 6.9</td>
<td>74.0 ± 8.2</td>
</tr>
<tr>
<td>Elite legal</td>
<td>12</td>
<td>24.9 ± 6.5</td>
<td>179.6 ± 6.9</td>
<td>76.0 ± 12.2</td>
</tr>
<tr>
<td>Illegal pathway</td>
<td>12</td>
<td>19.4 ± 2.7</td>
<td>173.3 ± 9.8</td>
<td>66.9 ± 12.8</td>
</tr>
</tbody>
</table>

Ethics approval was granted and written informed consent was obtained for each participant before the commencement of the study, in accordance with the requirements of the Human Research Ethics Committees of the Australian Institute of Sport (AIS) and the UWA (Appendices A-E).

**Experimental Design**

Participants warmed up as per their normal pre game routine and then bowled six overs with a timed two minute break between each to replicate match conditions. The six overs consisted of 20 off-spin and 16 self-nominated variation deliveries. Participants were asked to nominate where their usual deliveries would pass a right-handed batsman based on a clear target that consisted of a series of 20 cm x 20 cm grids (accuracy target) (Figure 4.2). Aside from those that struck the target directly, deliveries that impacted a grid directly above, underneath, or horizontally adjacent to the nominated grid on the
off-side (to the batsman’s right) were considered as successful deliveries. Deliveries were bowled in a randomised order.

**Camera and laboratory set-up**

Bowling data collection took place in an indoor motion capture laboratory that was purpose built for cricket analysis and contained a permanent artificial pitch. Trajectory data were captured using a 22-camera (MX 13 and 40) Vicon MX motion analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. The capture volume was approximately 10 m long and 5 m wide allowing for two full strides before the delivery stride and 3 m of ball flight post-BR to be collected. The global reference frame originated at the bowling crease with the y-axis pointing down the pitch, the z-axis upward and the x-axis the right-handed cross product of the previous vectors.

**Data collection and procedures**

Retro-reflective markers were affixed to each participant’s head, torso, upper-limbs and ball according to a customised marker set and model. The set consisted of numerous single and three marker clusters attached to either semi-rigid plastic or lightweight aluminium bases. Participant specific static trials were collected to define joint centres. The shoulder joint centre was calculated using a regression equation based on anatomical landmarks as well as height and weight (Campbell, Lloyd, et al., 2009). The elbow joint centre was estimated using a pointer method based on the location of the lateral and medial aspects of the humeral epicondyles (Chin et al., 2010), and the wrist joint centre as the midpoint of markers placed on the styloid processes of the radius and ulna (Lloyd et al., 2000). Three dynamic hemispherical markers comprised of ultralight foam (<0.1g) affixed in locations that did not impede the bowler’s preferred grip on the ball were used to calculate ball velocities and revolutions (Whiteside et al., 2012). For more in depth descriptions please see chapter three (p. 37)

Two dimensional (2D) data from each of the 22 cameras were reconstructed into three dimensional (3D) marker trajectories and labelled using Vicon Nexus software (Oxford Metrics, Oxford, UK). Trajectories were filtered using a quintic spline Woltring filter at a mean square error (MSE) of 20 after a residual
analysis and visual inspection of the data (Winter, 2005). Data were then modelled using the previously published UWA upper-body and ball model (Campbell, Lloyd, et al., 2009; Chin et al., 2009; Chin et al., 2010; Whiteside et al., 2012).

Biomechanical data were reported at BR, with peak values between BFI-BR for the pelvis and thorax and UAH-BR for the bowling limb also determined. Elbow extension values were calculated as per the existing ICC regulations at the time of testing, as the level of extension occurring from peak flexion post UAH until BR (ICC, 2005). All variables were normalised to 101 points using a cubic spline in a custom MATLAB program (Mathworks Inc; Natick, MA). BR was determined for each bowler based on the movement of the origin of the ball referenced to a marker placed on the carpal. The BR event was defined when the distance between the ball origin and the carpal marker exceeded the manually measured length comprising the distance of the second phalangeal (measured prior) plus the radius of the ball (35 mm) (Spratford et al., 2014).

Variables of interest
Displacement and angular velocity variables for the pelvis, thorax, shoulder, elbow and wrist joints identified as critical to bowling performance for FS bowlers were investigated. Joint angles were determined relative to their adjoining segments, with 0° indicating alignment between segment coordinate systems. Segment angles (pelvis and thorax) were measured relative to the global coordinate system with 0° indicating a pelvis or thorax orthogonal with its defining vector. Therefore a rotation angle of 90° indicated the bowler standing front-on or orthogonal with the pitch. Ball velocity and horizontal ball revolutions were computed using the data collected from the first 30 frames post BR. The ball velocity was measured as the magnitude of the ball’s (centre of the ball) resultant velocity vector with the magnitude of the ball’s angular velocity vector denoting revolutions. The index score was expressed as the relationship ($x$) between ball velocity ($V$) and ball revolutions around the horizontal axis of the global coordinate system ($\omega$) and calculated using the following equation:

$$x = (V + \omega) + \frac{V^2}{\omega} \quad (5)$$
This allowed for increases in BR velocity, relative to revolutions and velocity to be considered and expressed based on evidence that increases in ball revolutions will come at a detriment to ball speed (Sakurai et al., 2013). Representative mean data for all variables was then calculated from the first six valid FS trials where the ball hit the accuracy target.

Statistical analysis

A one-way analysis of variance (ANOVA) with a Bonferroni post-hoc correction was performed to determine ball kinematic differences between the three groups of pathway, elite and pathway illegal bowlers with the alpha level set at 0.05. Subsequent to this, differences were then only explored between pathway illegal and elite bowlers. A statistical parametric mapping (SPM) technique was adopted for continuous waveform comparison and was used to compare flexion-extension elbow angular displacement data across the entire phase from UAH to BR ($\alpha = 0.05$) (Pataky, Robinson, & Vanrenterghem, 2013). Independent group t-tests were performed to establish differences between discrete biomechanical variables. A partial Bonferroni correction was adopted due to the multiple comparisons being made resulting in an amended alpha level of $\alpha \leq 0.01$. Effect sizes (ES) were also reported to functionally differentiate between ball and biomechanical variables, with levels of, 0.2, 0.5 and 0.8 representing and large effect sizes (Cohen, 1992).

7.4 Results

Ball kinematics (performance characteristics)

Elite legal bowlers displayed significantly greater ball velocity and revolutions than pathway legal bowlers ($p = 0.023$ and $p = 0.005$, respectively), while pathway illegal bowlers had significantly greater ball revolutions than pathway legal bowlers ($p = 0.008$). For the velocity/revolution index, elite legal reported a significantly higher value ($p = 0.002$), while a large effect size existed between pathway illegal (higher) than pathway legal (ES = 0.85) (Table 7.2).
Table 7.2. Group mean (± standard deviations) for ball velocity, revolutions and velocity/revolution index pathway legal, elite legal and pathway illegal FS bowlers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pathway legal</th>
<th>Elite legal</th>
<th>Pathway illegal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball velocity (m.s(^{-1}))</td>
<td>19.2 (0.9)*(^a)</td>
<td>20.4 (1.4)*(^a)</td>
<td>19.7 (1.4)</td>
</tr>
<tr>
<td>Revolutions (rev.s(^{-1}))</td>
<td>26.4 (2.7)*(^{abc})</td>
<td>30.0 (2.8)*(^a)</td>
<td>30.1 (3.1)*(^c)</td>
</tr>
<tr>
<td>Velocity/revolution index</td>
<td>59.7 (3.0)*(^{abc})</td>
<td>64.5 (3.7)*(^a)</td>
<td>62.9 (4.4)*(^c)</td>
</tr>
</tbody>
</table>

*Significant \(p < 0.05\) Elite legal to pathway legal
\(^{a}\)Large ES \(\geq 0.80\) Elite legal to pathway legal
\(^{bc}\)Large ES \(\geq 0.80\) Elite legal to Pathway illegal
\(^{c}\)Large ES \(\geq 0.80\) Pathway illegal to Pathway legal

Results indicate that the performance characteristics of the lower level pathway illegal bowlers approximated that of the elite legal FS bowlers. For this reason, selected biomechanical variables will now be presented exploring the differences between elite legal and pathway illegal FS bowlers.

*Flexion-Extension elbow data from UAH-BR*

SPM analysis identified significant differences in the elbow flexion-extension waveform data between 0-79% \((p < 0.001)\) and between 87-100% of the bowling phase \((p = 0.02)\) (Figure 7.1).
Figure 7.1. SPM analysis of elite legal and pathway illegal bowlers. The thin dotted lines indicate the critical random field theory (RFT) thresholds for significance which are set at, $t > 2.50$. The solid horizontal line indicates the difference between the two waveforms. Significance is established when the solid horizontal line falls outside the RFT thresholds, which occurs between 0-79\%, $p = <0.001$ and between 88-100\% $p = 0.02$ of the phase (denoted by grey shading). The area between the two vertical lines (80-87\%) represents the only area that is not significantly different (unshaded). This occurs as the two waveforms cross late within the phase (Figure 7.2).

Figure 7.2 presents the mean and standard deviation of the flexion-extension elbow angle between pathway illegal and elite legal groups between UAH (0\%) and BR (100\%). Note how the non-significant period (80-87\%) occurs when the two waveforms cross, as pathway illegal bowlers rapidly extend from the maximum flexed position to BR.
Angular displacements

While many biomechanical variables were invariant, significant and large ES differences were observed at the pelvis, thorax, elbow and wrist between elite legal and pathway illegal bowlers. At the trunk (pelvis and thorax) elite legal bowlers displayed greater peak pelvic (ES = 1.11) and thorax (ES = 1.02) forward rotation and thorax forward rotation at the key BR event (ES = 0.98). For the bowling limb, pathway illegal bowlers displayed increased levels of elbow flexion at UAH ($p < 0.001$), peak elbow flexion ($p < 0.001$), elbow flexion at BR ($p < 0.001$), elbow extension range ($p < 0.001$), wrist extension at BR ($p = 0.010$) and peak elbow supination (ES = 0.80) (Table 7.3).
Table 7.3. Group mean (± standard deviations) for selected angular displacement parameters for elite and illegal pathway FS bowlers.

<table>
<thead>
<tr>
<th>Variable (°)</th>
<th>Pathway illegal</th>
<th>Elite legal</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis forward rotation (BR)</td>
<td>88.0 (12.3)</td>
<td>87.2 (11.7)</td>
<td>0.856</td>
<td>0.06</td>
</tr>
<tr>
<td>Pelvis forward rotation peak (BFI-BR)</td>
<td>161.2 (9.2)</td>
<td>171.9 (10.0)</td>
<td>0.017</td>
<td>1.11*</td>
</tr>
<tr>
<td>Thorax forward rotation (BR)</td>
<td>81.3 (9.1)</td>
<td>89.8 (8.2)</td>
<td>0.029</td>
<td>0.98*</td>
</tr>
<tr>
<td>Thorax forward rotation peak (BFI-BR)</td>
<td>166.5 (10.7)</td>
<td>176.2 (8.1)</td>
<td>0.024</td>
<td>1.02*</td>
</tr>
<tr>
<td>Shoulder extension (BR)</td>
<td>15.0 (12.4)</td>
<td>11.7 (11.1)</td>
<td>0.400</td>
<td>0.28</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>15.9 (12.4)</td>
<td>11.7 (11.1)</td>
<td>0.398</td>
<td>0.36</td>
</tr>
<tr>
<td>Shoulder abduction (BR)</td>
<td>119.6 (8.0)</td>
<td>115.4 (8.6)</td>
<td>0.250</td>
<td>0.51</td>
</tr>
<tr>
<td>Shoulder external rotation (BR)</td>
<td>-75.1 (29.3)</td>
<td>-60.1 (42.5)</td>
<td>0.332</td>
<td>0.41</td>
</tr>
<tr>
<td>Shoulder external rotation peak (UAH-BR)</td>
<td>-96.9 (21.1)</td>
<td>-80.2 (25.5)</td>
<td>0.149</td>
<td>0.71</td>
</tr>
<tr>
<td>Elbow flexion (UAH)</td>
<td>47.0 (8.8)</td>
<td>24.0 (8.2)</td>
<td>&lt;0.001*</td>
<td>2.70*</td>
</tr>
<tr>
<td>Elbow flexion peak</td>
<td>51.3 (7.8)</td>
<td>29.3 (6.2)</td>
<td>&lt;0.001*</td>
<td>3.12*</td>
</tr>
<tr>
<td>Elbow flexion (BR)</td>
<td>15.8 (7.7)</td>
<td>24.0 (6.9)</td>
<td>&lt;0.001*</td>
<td>1.12*</td>
</tr>
<tr>
<td>Elbow extension range (UAH-BR)</td>
<td>35.9 (9.0)</td>
<td>5.5 (3.5)</td>
<td>&lt;0.001*</td>
<td>4.45*</td>
</tr>
<tr>
<td>Elbow supination (BR)</td>
<td>-100.3 (21.1)</td>
<td>-89.3 (21.7)</td>
<td>0.197</td>
<td>0.51</td>
</tr>
<tr>
<td>Elbow supination peak (UAH-BR)</td>
<td>-130.4 (24.9)</td>
<td>-106.8 (33.5)</td>
<td>0.070</td>
<td>0.80*</td>
</tr>
<tr>
<td>Ulna deviation (BR)</td>
<td>21.4 (5.1)</td>
<td>20.7 (3.4)</td>
<td>0.699</td>
<td>0.16</td>
</tr>
<tr>
<td>Ulna deviation peak (UAH-BR)</td>
<td>21.9 (4.9)</td>
<td>24.2 (4.8)</td>
<td>0.281</td>
<td>0.47</td>
</tr>
<tr>
<td>Wrist extension (BR)</td>
<td>-47.5 (12.2)</td>
<td>-34.2 (10.5)</td>
<td>0.010*</td>
<td>1.17*</td>
</tr>
<tr>
<td>Wrist extension peak (UAH-BR)</td>
<td>-59.7 (25.2)</td>
<td>-67.2 (10.3)</td>
<td>0.998</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*Significant p ≤ 0.010 and # Large ES ≥ 0.80
Angular velocities

Significant and large ESs angular velocity differences were found at the thorax, elbow and wrist, with elite legal bowlers displaying an increase (large ES) in thorax forward rotation at BR (ES = 0.88). Pathway illegal bowlers displayed an increased level of elbow extension at BR ($p = 0.010$), peak elbow extension ($p = 0.004$), peak elbow supination (ES = 0.82), wrist extension at BR (ES = 1.04), peak wrist flexion (ES = 0.87), ulna deviation at BR ($p = 0.004$), and peak ulna deviation (ES = 1.04), when compared with elite legal bowling counterparts (Table 7.4).
Table 7.4. Mean (± standard deviations) for selected angular velocity parameters between elite and illegal pathway FS bowlers.

<table>
<thead>
<tr>
<th>ω Variable (°·s⁻¹)</th>
<th>Pathway illegal</th>
<th>Elite legal</th>
<th>p-value</th>
<th>Effect size (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis forward rotation (BR)</td>
<td>140.8 (57.7)</td>
<td>174.6 (51.2)</td>
<td>0.162</td>
<td>0.62</td>
</tr>
<tr>
<td>Pelvis forward rotation peak (BFI - BR)</td>
<td>436.0 (168.6)</td>
<td>416.1 (154.9)</td>
<td>0.743</td>
<td>0.12</td>
</tr>
<tr>
<td>Thorax forward rotation (BR)</td>
<td>125.5 (75.2)</td>
<td>186.8 (63.4)</td>
<td>0.048</td>
<td>0.88*</td>
</tr>
<tr>
<td>Thorax forward rotation peak (BFI - BR)</td>
<td>497.7 (147.2)</td>
<td>511.4 (70.6)</td>
<td>0.779</td>
<td>0.12</td>
</tr>
<tr>
<td>Shoulder extension (BR)</td>
<td>-500.4 (390.3)</td>
<td>-434.0 (308.6)</td>
<td>0.658</td>
<td>0.19</td>
</tr>
<tr>
<td>Shoulder extension peak (UAH-BR)</td>
<td>-827.6 (258.4)</td>
<td>-842.6 (167.6)</td>
<td>0.870</td>
<td>0.07</td>
</tr>
<tr>
<td>Shoulder external rotation (BR)</td>
<td>-1657.9 (656.6)</td>
<td>-1360.8 (625.0)</td>
<td>0.280</td>
<td>0.46</td>
</tr>
<tr>
<td>Shoulder external rotation peak (UAH-BR)</td>
<td>-1848.8 (665.7)</td>
<td>-1465.8 (620.9)</td>
<td>0.234</td>
<td>0.60</td>
</tr>
<tr>
<td>Elbow extension (BR)</td>
<td>-385.6 (279.9)</td>
<td>-115.6 (99.5)</td>
<td>0.010*</td>
<td>1.29*</td>
</tr>
<tr>
<td>Elbow supination (BR)</td>
<td>257.9 (237.6)</td>
<td>398.7 (259.4)</td>
<td>0.212</td>
<td>0.57</td>
</tr>
<tr>
<td>Elbow supination peak (UAH-BR)</td>
<td>786.0 (283.2)</td>
<td>553.5 (286.7)</td>
<td>0.065</td>
<td>0.82*</td>
</tr>
<tr>
<td>Wrist flexion (BR)</td>
<td>801.1 (366.5)</td>
<td>480.7 (232.3)</td>
<td>0.026</td>
<td>1.04*</td>
</tr>
<tr>
<td>Wrist flexion peak (UAH-BR)</td>
<td>914.0 (322.3)</td>
<td>642.6 (303.4)</td>
<td>0.050</td>
<td>0.87*</td>
</tr>
<tr>
<td>Ulna deviation (BR)</td>
<td>16.3 (242.8)</td>
<td>-250.0 (82.3)</td>
<td>0.004*</td>
<td>1.47*</td>
</tr>
<tr>
<td>Ulna deviation peak (UAH-BR)</td>
<td>-179.1 (91.0)</td>
<td>-289.2 (118.0)</td>
<td>0.023</td>
<td>1.04*</td>
</tr>
</tbody>
</table>

*Significant p ≤ 0.010 and "Large ES ≥ 0.80"
7.5 Discussion

The purpose of this study was to ascertain if the performance measures of BR velocity, ball revolutions and velocity/revolution index differed between pathway legal, elite legal and pathway illegal FS bowlers. It was also our intention to compare selected biomechanical variables between bowlers who deliver the ball with and without an illegal action.

**Performance measure differences between elite legal, pathway legal and pathway illegal bowlers**

When comparing performance, results indicated that pathway illegal bowlers reflected that of the more experienced and higher quality elite legal cohort, with significant differences observed for the three performance measures. This also signified that the same ball kinematic performance variables that differed in chapter four between pathway legal and elite legal bowlers also existed between pathway legal and pathway illegal bowlers. Given that both pathway groups were of a similar playing level and experience, the findings highlight that when a FS bowler delivers the ball with greater than 15° of elbow extension (i.e. an illegal action) it is possible that a performance benefit is observed. In theory, this performance benefit reflects advancement within the development pathway, highlighting a distinct advantage of bowling with an illegal action. These results are also the first to show that a distinct performance advantage is obtained for FS bowlers bowling with more than 15° of elbow extension between UAH-BR, reinforcing the validity of the current law.

**Biomechanical differences between elite legal and pathway illegal bowlers**

While it is evident that bowling with an illegal action has performance benefits, to date no research has explored if biomechanical differences, other than elbow extension, exist between groups of legal and illegal bowlers. As expected, the two groups exhibited variance for flexion-extension elbow mechanics with a SPM analysis identifying that elbow displacement for this degree of freedom (DoF) was significantly different for 92% of the UAH-BR phase (Figure 7.1). Illegal bowlers also displayed significantly higher levels of elbow flexion at UAH and significantly reduced values at BR, subsequently recording higher
extension range levels and peak extension angular velocity rates during the forward swing (Figure 7.2, and Tables 7.3 and 7.4). While it is important to understand how elbow extension mechanics differ between legal and illegal bowlers, a better descriptive understanding of the contribution of other upper-body mechanics in illegal techniques will provide coaching staff with the necessary information to better equip them to identifying suspect bowlers early in development and remediate actions when necessary.

When comparing other upper-body mechanics, significant differences were observed at the pelvis, thorax, elbow and wrist. At the trunk level, illegal bowlers were more front-on at BFI for both the pelvis and thorax, experienced less pelvic rotation between BFI-BR, exhibited lower thorax angular velocity at BR and subsequently displayed a more front-on thorax alignment at BR. Traditional coaching literature stresses the need for a FS bowler to have a “classical side-on” position at BFI and to rotate their trunk through to the point of BR (Woolmer et al., 2008). In theory, increased angular velocity observed at the trunk will lead to increased velocities at the distal segments through the proximal to distal linkage system or kinetic chain. Rotation of the trunk also assists in getting the bowling arm into the appropriate position to release the ball. Results suggest that both groups adopt polarising biomechanical strategies early within the bowling phase, with the illegal group exhibiting similar trunk mechanics to what has been seen when bowlers attempt to deliver a “Doosra” (Chin et al., 2009), a delivery that has constantly been linked to illegality within the cricket community. Attempts have also been made to describe these different techniques within the coaching literature, with Woolmer et al., (2008) classifying them as the ‘javelin’ and ‘discus action’. The ‘javelin action’, described as the traditional side-on approach at BFI, is clearly observed within the legal cohort of this study, with the ‘discus action’ the front-on approach at BFI, observed in the illegal bowlers. Woolmer et al., 2008 suggests that the ‘discus action’ is indeed the technique adopted by the greatest of all FS bowlers, Muttiah Muralitharan. While this research group is not at all suggesting his action was illegal, indeed it is likely his unique anthropometric characteristics (high level of fixed flexion and a large carry angle) served to limit the available degree of elbow extension, as with all great athletes his technique forms the basis for many aspiring young
bowlers which may place them at an increased risk of adopting the more dangerous ‘discus’ posture associated with illegal actions.

Aside from the elbow flexion-extension differences observed, pathway illegal bowlers exhibited increased peak elbow supination displacement, peak elbow supination angular velocity, wrist extension displacement at BR and peak wrist flexion angular velocities. However, decreased peak levels of ulna deviation; together with peak angular velocity at BR was found in the pathway illegal cohort. By BR, the wrist joint of the pathway illegal bowlers was moving into radial deviation, similar to that of a wrist-spin bowler and opposite to the elite legal group’s ulna deviation angular velocity. It would appear that the distal segments of the bowling limb are influenced by the earlier movements of the trunk. Rather than relying on the natural rotation of the trunk to get the hand in a position to release the ball, the illegal group must rely on greater flexion and rapid supination at the elbow joint in order to shorten the delivery arc and get the body into an appropriate position to release the ball (Figure 7.3A, B and C).

![Figure 7.3. An illegal action bowler at UAH (A) and 0.004 (B) and 0.016 (C) seconds later. Note the flexion at the elbow in all images and the subsequent rapid elbow supination that occurs between B and C (786°.s⁻¹).](image)

From this position, the natural centrifugal forces that act along the long axis of the bowling arm, force both the elbow joint into extension and the wrist joint into flexion (Kreighbaum & Barthels, 1996; Wixted, Portus, et al., 2011). This increases the amount of elbow extension observed between UAH and BR and
forces the pathway illegal bowlers to rely on increased wrist flexion movement rather than the traditional ulna deviation movement observed in the elite cohort at the point of BR (Figure 7.4).

![Figure 7.4. BR for an illegal bowler, note the extended elbow and front-on thorax.](image)

This bowling style is in contrast to the traditional or “javelin” technique that sees bowlers use the natural rotations of the trunk, rather than flexion and supination at the elbow joint to attain the appropriate release position (Figure 7.5). This reduces the influence that the centrifugal forces have in causing elbow extension, and places the bowling hand in a position to take advantage of ulna deviation rather than wrist flexion at BR. The abduction/adduction (radial/ulna deviation) movement of the wrist is a common feature within the coaching literature, referred to as “opening the door” or “screwing off the top of a jar” and is seen as critical in applying revolutions to the ball and also as a natural component of the FS bowling technique (Bradman, 1969; Tyson, 1994; Wilkins, 1991; Woolmer et al., 2008). A point reinforced by the results of chapter five of this thesis where it was highlighted as a discriminator of performance between elite and pathway legal bowlers.
These results highlight, that while illegal action bowlers have increased ranges of elbow extension between UAH and BR, it is the initial movements of trunk that are critical in influencing the downstream joint motion of the bowling limb. It would appear that illegal pathway bowlers rely on elbow extension and wrist flexion rather than ulna radial and ulna deviation, to create those all-important ball revolutions.

7.6 Conclusion

This study highlighted that pathway illegal bowlers have the ability to place significantly more revolutions on the ball compared with bowlers of the same level, who bowl with a legal action (30.1 and 26.4 rev.s\(^{-1}\) respectively). It is also identified that pathway illegal bowlers had similar performance measures compared with elite legal level bowlers. When comparing technique differences, pathway illegal bowlers displayed a more front-on delivery technique at BFI and BR, relying on increased flexion and supination at the elbow to get to the point of BR. Subsequently, this increased the amount of elbow extension displacement and wrist flexion angular velocity to the detriment of ulna deviation angular velocity. These results are also the first to show that a performance benefit is obtained when FS bowlers deliver the ball with more than the
allowable 15° of elbow extension, thus reinforcing the validity of the current laws of the game. Controversially however it also highlights that bowlers should endeavour to make use of the 15° threshold when bowling FS. When trying to reduce the amount of elbow extension, coaching and support staff should aim for bowlers to be more side-on at BFI and rotate their trunks through the point of BR. This will help reduce the dependence on flexing and supinating at the elbow to get the body to the appropriate point for BR, thus reducing overall levels of elbow extension. It will also reduce the amount of wrist flexion angular velocity seen at BR and increase ulna deviation angular velocity, a movement critical in discriminating performance in FS bowlers.

7.7 Limitations

The data from this study were collected within a laboratory environment, allowing for sophisticated methodologies to be implemented. This however, came at the detriment to task representation due to the absence of a batsman and the clinical environment. It also only examined stock FS deliveries from each bowler.
Chapter 8: Summary, conclusions and recommendations for future research

8.1 Summary

Thesis aims
This thesis aimed to investigate the influence of skill level on ball kinematics in an attempt to quantify performance in finger spin (FS) and wrist spin (WS) cricket bowlers. It subsequently compared upper-body mechanics, both kinematic and kinetic as well anthropometric and isokinetic differences across skill level and their influence on performance. It also compared cohorts of FS bowlers with legal bowling actions, to bowlers with illegal actions, in an attempt to better understand the performance impact and biomechanical differences that occur when bowling with more than 15° of elbow extension during the delivery phase.

The outputs of this research will provide a more robust measure of performance as well as an understanding of the differences that exist between elite and pathway level FS and WS bowlers. It will also help administrators, coaching staff and scientists understand the performance benefits obtained when bowling with an illegal bowling action, allowing a more global perspective of biomechanical differences that exist between the two cohorts.

The research problem was addressed using four interrelated studies, each addressing unique facets of the research questions. This chapter aims to summarise the findings of each study with respect to the hypotheses developed in chapter 1 of this thesis. It will also make conclusions based on the results of each of these studies and make recommendations for future research.

8.2 Study one (chapter four): The effect of performance level on initial ball flight kinematics in finger and wrist-spin cricket bowlers
The aim of study one was to compare ball kinematics of elite and pathway FS and WS bowlers at ball release (BR) and during early flight to determine if they could be used to discriminate performance level.

### 8.2.1 Hypotheses

**Hypothesis 1a:** At BR FS bowlers will display a significantly higher axis of rotation elevation angle and ball velocity compared with WS bowlers.

FS bowlers displayed significantly increased axis of rotation elevation angles and ball velocities at BR.

*Hypothesis 1a – accepted*

**Hypothesis 1b:** During initial ball flight WS bowlers will exhibit a higher level of ball revolutions compared with FS bowlers.

WS bowlers delivered the ball with significantly more revolutions during initial ball flight.

*Hypothesis 1b – accepted*

**Hypothesis 1c:** Compared with their pathway counterparts elite bowlers will display significantly higher:

i. axis of rotation elevation angle,
ii. seam azimuth angle rotated toward the intended direction of side-spin,
iii. ball velocity,
iv. ball revolutions,
v. relative seam to axis of rotation angle closer to 90° (indicative of a stable seam during initial ball flight).

Both elite FS and WS bowlers displayed a higher axis of rotation angle and ball velocity at BR, as well as increased ball revolutions during early flight in
comparison to their pathway peers. Elite WS bowlers displayed a seam azimuth angle that was rotated more in the direction of the intended direction of spin compared with WS pathway group. No differences were identified for FS bowlers. Elite FS bowlers had a relative seam to axis of rotation angle that was significantly closer to 90° compared with that of the pathway FS group. No difference was observed between WS skill level groups.

*Hypothesis 1c (i), (iii) and (iv) – accepted*
*Hypothesis 1c (ii) and (v) – partially accepted*

### 8.3 Study 2: The influence of performance on upper-body mechanics, anthropometry and isokinetic strength in finger-spin cricket bowling

The aims of the study were to examine the differences in upper-body bowling mechanics, anthropometry and isokinetic strength across skill levels for FS bowling and how these influence ball kinematics.

#### 8.3.1 Hypotheses

**Hypothesis 2a:** *Compared with the pathway cohort, at BR elite bowlers will generate higher linear endpoint velocities of the:*

1. shoulder,
2. elbow,
3. wrist,
4. second metacarpophalangeal (MCP).

Elite level bowlers exhibited increased linear velocity at the wrist joint, with no differences observed at the shoulder, elbow or MCP joints.

*Hypothesis 2a (i), (ii) and (iv) – rejected*
*Hypothesis 2a (iii) – accepted*
Hypothesis 2b: Compared with the pathway cohort, elite bowlers will display an increased MCP flexion and wrist ulna deviation between UAH-BR.

Elite bowlers recorded a higher peak MCP flexion angle between UAH-BR in comparison to pathway bowlers; however no differences were identified in ulna deviation.

Hypothesis 2b (i) – accepted
Hypothesis 2b (ii) – rejected

Hypothesis 2c: Compared with the pathway cohort, elite bowlers will display higher peak angular velocities of the following between BFI-BR and UAH-BR:

  i.  thorax rotation
  ii. shoulder external rotation

Elite bowlers exhibited increased peak angular velocity for thorax forward rotation in comparison to pathway bowlers. No differences existed between elite and pathway bowlers for shoulder external rotation.

Hypothesis 2c (i) – accepted
Hypothesis 2c (ii) – rejected

Hypothesis 2d: Compared with the pathway cohort, elite bowlers will demonstrate higher (i) shoulder external rotation; (ii) elbow supination and (iii) wrist ulna deviation joint angular velocities at BR.

Elite bowlers displayed increased amounts elbow supination and ulna deviation in comparison with pathway bowlers. No differences were in shoulder external rotation levels were found.

Hypothesis 2d (i) – rejected
Hypothesis 2c (ii) and (iii) – accepted
Hypothesis 2e: Compared with the pathway cohort, elite bowlers will demonstrate higher (i) peak elbow supination and (ii) wrist ulna deviation moments.

Elite bowlers recorded an increased peak elbow supination moment in comparison to pathway bowlers. No differences were observed in peak ulna deviation moments.

Hypothesis 2e (i) – accepted
Hypothesis 2e (ii) – rejected

Hypothesis 2f: Compared with the pathway cohort, elite bowlers will display greater (i) wrist ulna deviation and (ii) lower elbow extension ranges of motion.

No differences were identified for ulna deviation range of motion between elite and pathway bowlers; however elite bowlers did display an increased absolute level of full range elbow extension when compared with the pathway bowlers.

Hypothesis 2f (i) – rejected
Hypothesis 2f (ii) – partially accepted

Hypothesis 2g: Compared with the pathway cohort, elite bowlers will exhibit greater peak isokinetic torque in the following movements:

i. shoulder extension/adduction,
ii. elbow joint supination,
iii. wrist ulna deviation.

Elite FS bowlers recorded a higher shoulder extension/adduction peak torque compared with pathway bowlers. No other differences observed between the groups.

Hypothesis 2gh (i) – accepted
Hypothesis 2g (ii) and (iii) – rejected
**Hypothesis 2i:** The following variables will best explain ball kinematics (velocity/revolution index) when used as a dependant variable in a regression analysis:

1. peak thorax rotation angular velocity between BFI-BR,
2. peak shoulder external rotation angular velocity between UAH-BR,
3. elbow supination angular velocity at BR,
4. MCP flexion at BR,
5. wrist ulna deviation at BR,
6. peak wrist ulna deviation between UAH-BR,
7. peak elbow supination between UAH-BR,
8. peak isokinetic ulna deviation torque.

Results of the regression analysis revealed that performance was best explained by peak MCP joint flexion angle, ulna deviation angular velocity and linear velocity of the wrist joint centre at BR, as well as peak shoulder extension/adduction isokinetic torque.

*Hypothesis 2i (viii) - accepted*

*Hypothesis 2i (i), (ii), (iii), (iv), (v), (vi) and (vii) – rejected*

### 8.4 Study 3: The influence of performance on upper-body mechanics, anthropometry and isokinetic strength in wrist-spin cricket bowling

The aims of the study were to examine the differences in upper-body bowling mechanics, anthropometry and isokinetic strength across skill levels for WS bowling and how these influence ball kinematics.

#### 8.4.1 Hypotheses

**Hypothesis 3a:** Compared with the pathway cohort, at BR elite bowlers will generate higher linear endpoint velocities of the:

1. shoulder,
2. elbow,
No differences were identified in linear endpoint velocities between elite and pathway WS bowlers.

_Hypothesis 3a (i), (ii) and (iii) - rejected_

_Hypothesis 3b: Compared with the pathway cohort, elite bowlers will display an increased (i) peak elbow pronation and (ii) wrist radial deviation between UAH-BR._

Elite bowlers had increased peak elbow pronation and wrist radial deviation between UAH-BR compared with the pathway cohort.

_Hypothesis 3b (i) and (ii) – accepted_

_Hypothesis 3c: Compared with the pathway cohort, elite bowlers will display higher peak angular velocities for (i) shoulder internal rotation and (ii) elbow supination between UAH-BR._

Elite WS bowlers displayed higher peak shoulder internal rotation and peak elbow supination angular velocities in comparison with the pathway group.

_Hypothesis 3c (i) and (ii) – accepted_

_Hypothesis 3d: Compared with the pathway cohort, elite bowlers will display higher peak angular velocities of the following at BR:
   i. shoulder internal rotation,
   ii. elbow supination,
   iii. radial deviation._

Elite WS bowlers displayed increased amounts of shoulder internal rotation, elbow supination and radial deviation angular velocities at BR in comparison with the pathway group.
Hypothesis 3d (i), (ii) and (iii) – accepted

**Hypothesis 3e:** Compared with the pathway cohort, elite bowlers will display higher peak (i) shoulder internal rotation and (ii) radial deviation joint moments.

Elite WS bowlers displayed increased peak shoulder internal rotation and radial deviation joint moments in comparison with the pathway group.

*Hypothesis 3e (i) and (ii) – accepted*

**Hypothesis 3f:** Compared with the pathway cohort, elite bowlers will display greater active radial deviation range of motion.

Elite WS bowlers displayed increased range of motion for radial deviation in comparison with pathway bowlers.

*Hypothesis 3f (i) – accepted*

**Hypothesis 3g:** Compared with the pathway cohort elite bowlers will exhibit greater peak isokinetic torque in the following movements:

- i. shoulder internal rotation,
- ii. elbow joint pronation,
- iii. wrist radial deviation.

Elite WS bowlers recorded increased peak isokinetic torque during radial deviation in comparison with the pathway cohort. No strength differences were recorded for the shoulder and elbow joints.

*Hypothesis 3g (i) and (ii) – rejected*

*Hypothesis 3g (iii) – accepted*

**Hypothesis 3h:** The following variables will best explain ball kinematics when used as a dependant variable in a regression analysis:

- i. peak shoulder internal rotation angular velocity between UAH-BR,
- ii. peak elbow supination angular velocity between UAH-BR,
iii. wrist radial deviation angular velocity at BR,
iv. peak shoulder internal rotation moment between UAH-BR,
v. peak wrist radial deviation moment between UAH-BR,
vi. peak isokinetic shoulder internal rotation torque,
vii. peak isokinetic elbow pronation torque.

Results of the regression analysis revealed that performance was best explained by peak isokinetic radial deviation torque, peak shoulder internal rotation moment, shoulder extension moment at BR and peak pronation moment.

_Hypothesis 3h (i), (ii), (iii), (v), (vi) and (vii) – rejected_
_Hypothesis 3h (iv) – accepted_

8.5 Study 4: The influence of elbow extension on bowling performance and upper-body mechanics in finger-spin bowling

The aims of this study were to compare performance variables identified in study one (chapter four) between a cohort of pathway illegal action bowlers to the existing pathway and elite bowlers to identify if a performance benefit existed. Further kinematic measures between the illegal group and elite FS bowlers were compared to ascertain what other than elbow displacement differed between the groups.

8.5.1 Hypotheses

_Hypothesis 4a: Compared with legal elite bowlers, illegal pathway bowlers will deliver the ball with more (i) revolutions and greater (ii) velocity:_

Illegal pathway bowlers had increased amounts of ball revolutions and velocity in comparison to legal pathway bowlers.

_Hypothesis 4a (i) and (ii) – accepted_
**Hypothesis 4b:** Compared with their legal counterparts, illegal bowlers will deliver the ball with a greater range of elbow extension between UAH-BR:

Illegal pathway bowlers had increased elbow extension between UAH-BR in comparison to elite level FS bowlers.

*Hypothesis 4b (i) – accepted*

**Hypothesis 4c:** Bowlers with an illegal action will have decreased displacements of the following joints and segments at BR:

i. wrist ulna deviation,  
ii. elbow extension,  
iii. thorax forward rotation,  
iv. pelvis forward rotation.

Illegal pathway bowlers displayed decreased levels of elbow extension, thorax forward rotation and pelvis forward rotation at BR.

*Hypothesis 4c (i) – rejected  
Hypothesis 4c (ii), (iii) and (iv) – accepted*

**Hypothesis 4d:** Compared with their legal counterparts, illegal bowlers will have decreased (i) peak thorax forward rotation and (ii) peak pelvis forward rotation between BFI-BR.

Illegal pathway bowlers exhibited decreased peak displacements for both the thorax and pelvis compared with elite legal FS bowlers.

*Hypothesis 4d (i) and (ii) – accepted*

**Hypothesis 4e:** Compared with their legal counterparts, illegal bowlers will display significantly greater (i) peak elbow extension angular velocity and (ii) peak wrist extension angular velocity between UAH-BR.
Illegal action pathway bowlers displayed greater peak elbow extension and wrist extension angular velocities when compared with elite legal bowlers.

*Hypothesis 4e (i) and (ii) – accepted*

**Hypothesis 4f:** Compared with their legal counterparts, illegal bowlers will display decreased (i) peak elbow supination angular velocity and (ii) peak wrist ulna deviation angular velocity between UAH-BR.

Pathway illegal bowlers exhibited increased peak elbow supination and decreased peak ulna deviation angular velocities when compared with elite legal bowlers.

*Hypothesis 4f (i) – rejected*
*Hypothesis 4f (ii) – accepted*

**Hypothesis 4g:** Compared with their legal counterparts, illegal bowlers will have increased (i) elbow extension angular velocity and (ii) wrist extension angular velocity at BR.

Pathway illegal bowlers had increased elbow and wrist extension at BR compared to elite legal FS bowlers.

*Hypothesis 4g (i) and (ii) – accepted*

**Hypothesis 4h:** Compared with their legal counterparts, illegal bowlers will have decreased (i) elbow pronation and (ii) wrist ulna deviation at BR.

Illegal pathway bowlers exhibited lower levels of ulna deviation angular velocity at BR when compared to elite legal bowlers; however, no differences were observed in the elbow pronation data.

*Hypothesis 4h (i) – rejected*
*Hypothesis 4h (ii) – accepted*
8.6 Conclusions and recommendations for future research

The four experimental studies contained within this thesis shared the common goal of improving the current limited scientific knowledge related to both FS and WS cricket bowlers. Chapter four focussed on defining performance measures based on cricket ball kinematic variables, with chapters five and six subsequently using these performance variables to explore biomechanical differences between elite and pathway FS and WS bowlers. Chapter seven investigated the differences in performance and kinematics between groups of illegal and legal action FS bowlers.

The initial study described in chapter four, aimed to investigate if ball kinematics that included; BR velocity, ball revolutions as well as orientation of the spin axis and seam, could be used to differentiate between skill level in both FS and WS bowling cohorts. The key findings from this study were, ball kinematics could be used to differentiate skill level. The movements of the seam, at and post BR, were a critical component of both FS and WS bowling. It is recommended that future research investigate coaching interventions aimed at improving variables that distinguish performance such as ball revolutions, BR velocity and seam azimuth angle. Spin bowling, as well as all types of cricket bowling would benefit from the instrumentation of a cricket ball, robust enough to be used in training and have the capacity to calculate revolutions at a rate of 50 revolutions per second and that concurrently quantifies the orientation of both the spin axis and seam.

The purposes of chapters five (FS) and six (WS) were to compare upper-body kinematics and kinetics, isokinetic strength and anthropometrical variables between elite and pathway bowlers, and to identify any differences that exist in the development pathway. Subsequently these variables were compared with the velocity/revolution index, a performance measure identified in chapter four as being important for both FS and WS bowlers. This enabled the identification of variables that best explained performance. The key findings from study two (FS) was the importance of bowlers in rotating their trunks and extending at the elbow joint through BR, as well the possible gains that may be made in optimising the strength of the musculature responsible for shoulder extension.
and adduction. It is recommended that future research investigate strength based interventions aimed at increasing the musculature responsible for shoulder extension and adduction in an attempt to improve the velocity/revolution index. The key findings from study three was the identified importance of bowling limb long axis rotations, particularly internal rotation at the shoulder and pronation at the elbow, combined with the musculature responsible for producing these movements. It is recommended that future research investigate strength based interventions aimed at increasing the musculature responsible for the long axis rotations of the bowling arm, as well as attempting to better understand the role the 4th phalangeal and lower body play in WS bowling. Improved injury surveillance data may also facilitate a better understanding of the injury rates and prevalence of shoulder injuries in WS bowlers.

Finally, the aim of study four was to use the performance variables identified in study one to understand if a performance benefit existed when a cohort of bowlers delivered the ball with an illegal bowling action. Further it was intended to provide a better understanding of the biomechanical variables that may differ in legal and illegal actions. The key findings from study four were, that when a pathway FS cohort with an illegal action delivered the ball, their performance variables reflected that of an elite or higher level bowler, suggesting that a performance benefit does indeed exist. Pathway illegal bowlers also exhibited a more front-on delivery technique at both BFI and BR and subsequently had to rely on increased amounts of flexion and supination at the elbow to position the upper-limb for BR by increasing wrist flexion angular velocity to the detriment of ulna deviation angular velocity. Coaching staff should encourage a more side-on approach at BFI and for bowlers to rotate their trunks through the point of BR when attempting to remediate illegal bowling actions. It is recommended that future research should investigate interventions aimed at remediating illegal actions based on altering the orientation of the trunk at BFI and BR and its impact on elbow extension values. This substantial data set also offers the opportunity for a forward kinematic modelling approach that may help further explain biomechanical influences on rates of elbow extension.
It is also hoped that this thesis has broken ground for ongoing biomechanical monitoring off all spin bowlers, both developing and elite, much the same way that fast bowlers are prospectively monitored. This will not only give more information about performance, but the ability to link technique to injury.
Appendix A: Approval to undertake research involving human subjects

(AIS)

Australian Institute of Sport

MINUTE

TO: Mr Wayne Stratford
FROM: Ms Helene Kay
CC:

SUBJECT: Approval from AIS Ethics Committee  DATE: 14th December 2009

At the last meeting of the AIS Ethics Committee held out of session in December 2009, the Committee gave consideration to your submission titled "The influence of technique and selected physical factors on elite spin bowling." The Committee saw no ethical reason why your project should not proceed.

The approval number for this project remains as 20091201.

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

- any proposed changes to the research design,
- any adverse events that may occur,

Researchers are required to submit annual status reports to the secretary of the AIS Ethics Committee until completion of the project. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

Failure to comply with the above will render ethics approval null and void.

If you have any questions regarding this matter, please don’t hesitate to contact me on (02) 6214 1577.

Sincerely,
Helene Kay
Assistant Secretary, AIS EC
Appendix B: Approval to undertake research involving human subjects (UWA)

Graduate Research School
Hackett Hall - M358
55 Stirling Highway,
CRAWLEY WA 6009
+61 8 6488 2966 Phone
+61 8 6488 1515 Fax
katherine.webster@uwa.edu.au Email
http://www.postgraduate.uwa.edu.au/Website

Ref: 20763899

3 November 2011

Mr W Spraford
22 Croton Street
Fyshwick
ACT 2011

Dear Mr Spraford

RESEARCH PROPOSAL - DOCTOR OF PHILOSOPHY

I am pleased to inform you that the Board of the Graduate Research School has considered your Research Proposal and, it is accepted without the requirement for changes or clarification.

Your proposal indicates that approval from UWA Human Research Ethics Committee is currently being sought in relation to your research. Until you provide us with notification that you have approval, or otherwise, from the UWA Human Research Ethics Committee the status of your research proposal will be marked as provisional. Please note that approval is required from the appropriate UWA committee notwithstanding that the project might have been approved by an external agency (e.g. hospital) or another university.

The supervisors for your research are recorded as being:
- Coordinating supervisor: Associate Professor J Alderson (55%)
- Co-supervisor: Winthrop Professor B Elliott (15%)
- External supervisor: Doctor N Brown (15%)
- External supervisor: Doctor M Pena (15%)

On behalf of the Board please accept my best wishes for the remainder of your candidature.

Yours sincerely

Katherine Webster
Administrative Officer, Candidate

cc: Professor A Gordon (Graduate Research Coordinator)
    Associate Professor J Alderson
    Winthrop Professor B Elliott
    SCHOOL OF SPORT SCIENCE, EXERCISE AND HEALTH

Students please note:
- Please activate your UWA student email account and check it regularly. http://www.uwa.edu.au/student\email
- You can check your milestones on Student Connect: http://www.studentadmin.uwa.edu.au/academic/student_connect
  Click on the “Course and Unit” link in the left column of the page, and you should see your current and previous courses displayed. For the course in which you are enrolled currently, click on the “Milestones” link under the course details. You will see your list of milestones and the current status of each. There is a description of what each milestone status means. If you believe that there is an error in the list, please contact katherine.webster@uwa.edu.au.
  Please note that your enrolment each year is dependent on all your milestones being up to date.

T&F 4ET Updated 300011
THE CONTRIBUTION OF THE UPPER-LIMB TO BALL REVOLUTIONS IN FINGER AND WRIST SPIN BOWLERS.

Researchers
Mr Wayne Spratford (Australian Institute of Sport)
Dr Jacque Alderson (University of Western Australia)
Dr Nick Brown (Australian Institute of Sport)
Professor Bruce Elliot (University of Western Australia)
Dr Marc Portus (Cricket Australia)

Background
Spin bowling is an important component of the bowling attack within the game of cricket. This is reinforced by the fact that the all-time three leading wicket takers in World Test cricket are spin bowlers (wrist and finger). As yet very little is understood about the mechanics of the action or the characteristics of the ball post release in spin bowlers at any level.

Aim of the study

Therefore the aim of this research is to identify the link between technique (grip, kinematics, kinetics) selected physical factors, (strength, hand dimensions, joint ranges of movement) and ball flight characteristics (revolutions, seam stability, seam position, speed and angle of release) relative to the amount the ball spins (we may find that revolutions and seam position dictate turn) in wrist and finger spinners.

The main aim can be divided into the following parts:

a. Designing a methodology to accurately measure ball revolutions, seam stability, seam position, angle of release, side spin as well as collecting kinematic and kinetic data of the athlete.
b. Comprehensive analysis of ball revolutions, seam stability, seam position, angle of release (relative to the ground), side spin, joint strength and ranges of movement in a cross sectional cohort (International, first class, pathway and juniors). The aim being to collect data on all our first class and talented (pathway) junior spin bowlers.

c. Examine relationship between technique (kinematics, kinetics, strength and ranges of movement) and ball dynamics (revolutions, seam stability, seam position, angle of release, speed and turn).

Participants
Your participation in this project is voluntary. If you do agree to participate, you can withdraw from participation at any time during the project without comment or penalty. Your decision to participate will in no way impact upon your current or future relationship with the Australian Institute of Sport or with Cricket Australia (for example team selection). By signing the informed consent you are indicating that the tests and procedures of this study have been explained to you and understood by you.

Study protocols
As a subject in this study you will be asked to perform a six over bowling spell which incorporates your stock delivery and any variations you bowl within AIS Biomechanics laboratory. Video recordings from multiple cameras will be made to analyse movement dynamics. The system used involves a set of reflective markers which are fixed to body landmarks using a mild adhesive tape. Only the motion of the markers is picked up by the camera system. Anthropometrical, range of motion and strength measures will also be taken by experienced practitioners. Testing will be concluded within a single day (5 hours per session).

Potential discomforts and risks
Potential for discomfort or risk during data collection is no greater than anything encountered during normal training.
Confidentiality
All aspects of the testing, including the results will be strictly confidential. To protect the anonymity of the participant only researchers involved in the study will know the identity of the participant. All data will be de-identified and stored on a password protected hard drive.

Enquiries
If you have any further questions regarding requirements and procedures please do not hesitate to contact the investigator.

Ethics Committee Clearance
This project has been approved by the Human Research Ethics Committee at the Australian Institute of Sport, approval number 20091201.

Queries and Concerns
If you have any further queries and concerns about the research then contact Wayne Spratford:

Wayne Spratford
(02) 6214 7873
(02) 6214 1593
wayne.spratford@ausport.gov.au

If you have any concerns with respect to the conduct of this study, you may contact the Secretary of the AIS Ethics Committee (Ms Helene Kay on (02) 6214 1577
Appendix D: Participant consent forms for adults

‘INFORMED CONSENT’ FORM (Adult)

The creation of ball dynamics in finger and wrist spin bowlers across the development pathway

Principal Researchers: Wayne Spratford (AIS Biomechanics Dept), Jacque Alderson (University of Western Australia), Nick Brown (AIS Biomechanics Dept) and Marc Portus (Praxis Sport)

This is to certify that I, hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Wayne Spratford.

The investigation and my part in the investigation have been defined and fully explained to me by Wayne Spratford and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

• I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.

• I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.

• I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.

• I understand that I am free to withdraw my data from analysis without disadvantage to myself.
• I understand that any data or answers to questions will remain confidential with regard to my identity.

• I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.

• I am participating in this project of my (his/her) own free will and I have not been coerced in any way to participate.

Signature of Subject: _______________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: _____________________________ Date: ___/___/___
Appendix E: Participant consent forms for minors

‘INFORMED CONSENT’ FORM (Minor)

Project Title: The Influence of technique and selected physical factors on elite spin bowling

Principal Researchers: Wayne Spratford (AIS Biomechanics Dept), Jacque Alderson (University of Western Australia), Nick Brown (AIS Biomechanics Dept) and Marc Portus (Cricket Australia)

This is to certify that I, hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Wayne Spratford.

The investigation and my child’s part in the investigation have been defined and fully explained to me by Wayne Spratford and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.

- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.

- I understand that my child is free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.

- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
• I understand that any data or answers to questions will remain confidential with regard to my child’s identity.

• I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to me (him/her) of participating in this investigation.

• My child is participating in this project of my (his/her) own free will and My child has) not been coerced in any way to participate.

Signature of Participant: _______________________________ Date: ___/___/___

Signature of Parent or Guardian of minor: (under 18 years) ______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: _______________________________ Date: ___/___/___
Reference list


Campbell, A., Alderson, J., Lloyd, D., & Elliott, B. (2009). Effects of different technical coordinate system definitions on three dimensional
representation of the glenohumeral joint centre. *Medical and Biological Engineering and Computing, 47*(5).


ICC. (2005). *Regulations for the review of bowlers reported with suspected illegal bowling action*. Retrieved from


