The Determinants and Development of Fast Bowling Performance in Cricket

Simon A. Feros

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School of Health Sciences

Federation University Australia

P.O. Box 663

University Drive, Mount Helen

Ballarat Victoria 3353

Australia

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Abstract

This thesis sought to reveal the physical and kinematic determinants of pace bowling performance. After drawing on these determinants, a secondary aim was to investigate whether pace bowling performance could be enhanced with chronic resistance training and warm-up strategies. However, before the physical and kinematic determinants of pace bowling performance could be identified, and the effects of two training interventions and warm-ups on pace bowling performance, a new pace bowling test was created, and the test-retest reliability of its performance and kinematic measures were evaluated.

Knowledge of a variables' test-retest reliability is important for interpreting the validity of correlations, but also for the determination of a meaningful change following a training intervention. Only one published study to date has explored the test-retest reliability of a pace bowling assessment, and this test only measured bowling accuracy (1). Previous research has not comprehensively examined the relationships between physical qualities and pace bowling performance. Several important physical qualities (e.g., power, speed-acceleration, flexibility, repeat-sprint ability) have been excluded in correlational research, which may be crucial for optimal pace bowling performance. Furthermore, there is only one published training intervention study on pace bowling research (2). Consequently there is scant evidence for coaches to design training programs proven to enhance pace bowling performance. Baseball pitching studies have trialled the effects of heavy-ball throwing in the warm-up on subsequent throwing velocity and accuracy, but this approach has not been studied in cricket pace bowling, especially after several weeks of training. Therefore, four studies were conducted in this PhD project to address these deficiencies in the literature.

The purpose of Study 1 (Chapter 3) was to ascertain the test-retest reliability of bowling performance measures (i.e., bowling speed, bowling accuracy, consistency of bowling speed, and consistency of bowling accuracy) and selected bowling kinematics (i.e., approach speed, step length, step-length phase duration, power phase duration, and knee extension angle at front-foot contact and at ball release) in a novel eight-over test, and for the first four overs of this test. The intraclass correlation coefficient (ICC), standard error of measurement (SEM), and coefficient of variation (CV) were used as measures of test-retest reliability (3). Following a three week familiarisation period of bowling, 13 participants completed a novel eight-over bowling test on two separate days

with 4–7 days apart. The most reliable performance measures in the bowling test were peak bowling speed (ICC = 0.948–0.975, CV = 1.3–1.9%) and mean bowling speed (ICC = 0.981–0.987, CV = 1.0–1.3%). Perceived effort was partially reliable (ICC = 0.650–0.659, CV = 3.8–3.9%). However, mean bowling accuracy (ICC = 0.491–0.685, CV = 12.5–16.8%) and consistency of bowling accuracy failed to meet the pre-set standard for acceptable reliability (ICC = 0.434–0.454, CV = 15.3–19.3%). All bowling kinematic variables except approach speed exhibited acceptable reliability (i.e., ICC > 0.8, CV < 10%). The first four overs of the bowling test exhibited slightly poorer test-retest reliability for all measures, compared to the entire eight-over test. There were no systematic biases (i.e., $p > 0.05$) detected with all variables between bowling tests, indicating there was no learning or fatigue effects. The smallest worthwhile change was established for all bowling performance and kinematic variables, by multiplying the SEM by 1.5 (4). It is recommended that the eight-over pace bowling test be used as a more comprehensive measure of consistency of bowling speed and consistency of bowling accuracy, as bowlers are more likely to be fatigued. However, if coaches seek to assess pace bowlers in shorter time, delimiting the test to the first four overs is recommended. Both versions of the pace bowling test are only capable of reliably measuring bowling performance outcomes such as peak and mean bowling speed, and perceived effort.

The second study of this PhD project examined the relationships between selected physical qualities, bowling kinematics, and bowling performance measures. Another purpose of this novel study was to determine if delivery instructions (i.e., maximal-effort, match-intensity, slower-ball) influenced the strength of the relationships between physical qualities and bowling performance measures. Given that there were three delivery instructions in the bowling test, an objective of this study was to explore the relationship between bowling speed and bowling accuracy (i.e., speed-accuracy trade-off). Thirty-one participants completed an eight-over bowling test in the first session, and a series of physical tests, spread over two separate sessions. Each session was separated by four to seven days. Mean bowling speed (of all pooled deliveries) was significantly correlated to 1-RM pull-up strength (r_s [24] = 0.55, $p = 0.01$) and 20-m sprint time (r_s [30] = -0.37, $p = 0.04$), but the correlations marginally increased as delivery effort increased (i.e., maximal-effort ball). Greater hamstring flexibility was associated with a better consistency of bowling speed, but only for a match-intensity delivery (r_s [29] = -0.49, $p = 0.01$). Repeat-sprint ability (i.e., percent decrement on 10 × 20-m sprints, on every 20 s) displayed a stronger correlation to consistency of bowling speed (r_s [21] = -0.42, p =

0.06) than for mean bowling speed (r_s [21] = 0.15, $p = 0.53$). Bench press strength was moderately related to bowling accuracy for a maximal-effort delivery (r_s [26] = -0.42, $p = 0.03$), with weaker but non-significant ($p > 0.05$) correlations for match-intensity and slower-ball deliveries. Bowling accuracy was also significantly related to peak concentric countermovement jump power (r_s [28] = -0.41, $p = 0.03$) and mean peak concentric countermovement jump power (r_s [27] = -0.45, $p = 0.02$), with both physical qualities displaying stronger correlations as delivery effort increased. Greater reactive strength was negatively associated with mean bowling accuracy (r_s [30] = 0.38, $p = 0.04$) and consistency of bowling accuracy (r_s [30] = 0.43, $p = 0.02$) for maximal-effort deliveries only.

Faster bowling speeds were correlated to a longer step length (r_s [31] = 0.51, $p < 0.01$) and quicker power phase duration (r_s [31] = -0.45, $p = 0.01$). A better consistency of bowling accuracy was associated with a faster approach speed (r_s [31] = -0.36, $p = 0.05$) and greater knee flexion angle at ball release (r_s [27] = -0.42, $p = 0.03$). No speed-accuracy trade-off was observed for the group (r_s [31] = -0.28, $p = 0.12$), indicating that most bowlers could be instructed to train at maximal-effort without compromising bowling accuracy. Pull-up strength training and speed-acceleration training were chosen for the “evidence-based” training program (Study 3). Heavy-ball bowling was also considered as part of the evidence-based training program, as it is a specific form of training used previously, and because there was a shortage of significant relationships ($p < 0.05$) between physical qualities and bowling performance measures in Study 2.

The third investigation of this PhD project compared the effects of an eight-week evidence-based training program or normal training program (not a control group) on pace bowling performance, approach speed, speed-acceleration, and pull-up strength. Participants were matched for bowling speed and then randomly split into two training groups, with six participants in each group. After an initial two-week familiarisation period of bowling training, sprint training, and pull-up training, participants completed two training sessions per week, and were tested before and after the training intervention. Testing comprised the four-over pace bowling test (Study 1), 20-m sprint test (Study 2), and 1-RM pull-up test (Study 2). In training, the volume of bowling and sprinting was constant between both groups; the only differences were that the evidence-based training group bowled with heavy balls (250 g and 300 g) as well as a regular ball (156 g), sprinted with a weighted-vest (15% and 20% body mass) and without a weighted-vest, and performed pull-up training. Participants were instructed to deliver each ball with maximal effort in training, as no speed-accuracy trade-off was observed for the sample in Study 2. The evidence-based training group bowled with poorer accuracy and consistency of accuracy, with only a small improvement in peak and mean bowling speed. Heavy-ball bowling may have had a negative transfer to regular-ball bowling. Although speculative, a longer evidence-based program may have significantly enhanced bowling speed. Coaches could use both training programs to develop performance but should be aware that bowling accuracy may suffer with the evidence-based program.

The evidence-based training group displayed slower 20-m sprint times following training (0.08 ± 0.05 s). However, the normal training group was also slower (0.10 ± 0.09 s), indicating the potential for speed-acceleration improvement is compromised if speed training is performed immediately after bowling training; most likely due to residual fatigue. Consequently it is recommended that speed-acceleration training be conducted when bowlers are not fatigued, in a separate session, or at the beginning of a session.

The evidence-based training group improved their 1-RM pull-up strength by 5.8 ± 6.8 kg ($d = 0.68$), compared to the normal training group of 0.2 ± 1.7 kg ($d = 0.01$). The difference between training groups is due to the fact that the normal training group were not prescribed pull-up training. As many participants could not complete the pull-up exercise due to insufficient strength, the dumbbell pullover may be a suitable alternative that is more specific to the motion of the bowling arm (i.e., extended arm).

The fourth study of this PhD project explored the acute effects of a heavy-ball bowling warm-up on pace bowling performance, and determined if these acute effects could be enhanced or negated following an evidence-based training program. This study involved the same participants who completed the evidence-based training program in Study 3. These participants were required to perform two different bowling warm-ups (heavy-ball or regular-ball) in pre and post-test period, followed by the four-over pace bowling test (Study 1). In pre-test period, bowling accuracy was 8.8 ± 7.4 cm worse for the heavy-ball warm-up compared to the regular-ball warm-up ($d = 1.19$). In post-test period however, bowling accuracy was 5.5 ± 6.4 cm better in the heavy-ball warm-up compared to the regular-ball warm-up ($d = -0.90$). A similar trend was observed for consistency of bowling accuracy. These findings indicate that pace bowlers adapt to heavy-ball bowling, and bowl more accurately with a regular ball if they warm-up with a heavy ball first (but only after eight weeks of heavy-ball training). Coaches could employ a heavy-ball warm-up prior to training or a match, but only after eight weeks of evidence-

based training. It is hypothesised that a less biomechanically similar exercise to the pace bowling motion such as resisted push-ups / bench press throws could be more effective in eliciting potentiation by activating higher order motor units without negatively transferring to bowling performance.

From the studies presented in this thesis, it is concluded that peak and mean bowling speed are the most reliable bowling performance measures, and all kinematic variables apart from approach speed possess excellent reliability. Furthermore, 1-RM pull-up strength and 20-m speed are significantly correlated to bowling speed. An evidence-based training program can develop peak and mean bowling speed, but the cost to bowling accuracy and consistency of bowling accuracy does not make this training program worthwhile in enhancing pace bowling performance. A heavy-ball warm-up impairs bowling accuracy and consistency of bowling accuracy compared to the regular-ball warm-up, but only prior to training with the heavier balls. Pace bowlers adapt to heavy-ball bowling after eight weeks of training, but must use the heavy balls in the warm-up to bowl more accurately with a regular ball, otherwise pace bowling performance is below optimal.

Statement of Authorship

Except where explicit reference is made in the text of this thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgement in the main text and bibliography of this thesis.

Signed: Simon Feros	Signed: ____________________________
Dated: *14/09/2015*	Dated: ____________________________
Simon A. Feros	Associate Professor Warren Young
Candidate	Principal Supervisor

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Dedication

I dedicate this thesis to my parents Beth and John, my brother Chris, my mentor Johnny, my fiancée Julia, and my daughter Penelope. This thesis would not have been possible without your unconditional love and unwavering support.

Table of Contents

List of Tables

List of Figures

List of Equations

Publications and Conference Presentations Arising from PhD research

Peer Reviewed Publications

Feros, S. A., Young, W. B., O'Brien, B. J., & Bradshaw, R. J. (2012). Physically preparing the fast bowler in cricket: A review of the literature. *Journal of Australian Strength and Conditioning Research, 20*(S1), 117-122.

Feros, S. A., Young, W. B., & O'Brien, B. J. (2013). The acute effects of heavy-ball bowling on fast bowling performance in cricket. *Journal of Australian Strength and Conditioning Research, 21*(S2), 41-44.

Feros, S. A., Young, W. B., & O'Brien, B. J. (in press). The relationships between selected physical qualities and bowling performance, with "match-intensity" and "maximal-effort" deliveries in cricket pace-bowlers. *Journal of Australian Strength and Conditioning Research.*

Conference Presentations

Feros, S. A., Young, W. B., & O'Brien, B. J. The physical determinants of fast bowling performance in community-level pace bowlers. Podium presentation at the 2013 University of Ballarat - Annual Research Conference, Ballarat, November 7, 2013.

Feros, S. A., Young, W. B., & O'Brien, B. J. The differences between "match intensity" and "maximal effort" instructions on bowling speed, accuracy, and selected bowling kinematics in cricket pace-bowlers. Podium presentation at the 2014 Federation University Australia - Annual Research Conference, Ballarat, November 6, 2014.

Feros, S. A., Young, W. B., & O'Brien, B. J. The reliability of a novel fast bowling test in cricket. Poster presentation at the 6th Exercise & Sports Science Australia Conference and Sports Dieticians Update: Research to Practice, Adelaide Convention Centre, April 10-12, 2014.

Chapter 1:
Introduction

1.1 Background

Cricket is an international sport that attracts many people to either play or spectate. In Australia, 951,993 people formally participated in indoor and outdoor cricket during 2012-13 (5). Fifty-two percent of these people played club and community-based cricket, and 48% participated in school-based cricket (5). In 2012-13, 577 cricket associations and 3,737 registered cricket clubs existed in Australia (5). Cricket is regarded as Australia's most popular summer sport, and is thus a strong part of Australian culture (5).

Although three forms of cricket exist (i.e., Test, One-Day International, Twenty/20) with slightly different rules, the fundamentals of the game remain the same. In competitive cricket, two teams of eleven players showcase their batting, bowling, and fielding abilities. As one team is bowling and fielding, the other is batting. After the opposition batting team is dismissed, or when all overs have been bowled for the innings, both teams swap roles. The objective of batting is to score as many runs possible, without losing wickets. The purpose of bowling and fielding, however, is to restrict runs, and dismiss ten batsmen (wickets). The team that scores the most runs wins the game.

Bowling in cricket comprises two forms: spin and pace. Spin bowlers deceive batsmen by causing the cricket-ball to deviate off the pitch, following the bounce. These types of bowlers aim to impart many revolutions on the ball, which due to the Magnus Effect; can cause the ball to "drift" or "drop" in the air, to ultimately mislead the batsman. Pace bowlers, however, primarily use their bowling speed to dismiss batsmen. Pace bowlers too, can "swing" the ball in the air, and affect a lateral deviation after bounce (seam), to deceive the batsman. Pace bowlers can be classed by their speed as: slow, medium, medium-fast, fast-medium, fast, and express (6).

Faster bowlers, due to their speed, are typically of more danger to batsmen than slower bowlers (i.e., more risk of being dismissed). Very few fast bowlers have delivered the cricket-ball at 44.4 $m \cdot s^{-1}$ (7). In fact, a ball delivered at this velocity approaches a batsman in just 0.44 s (8). The batsman's reaction time, perception time, and movement time are thus reduced (9), and the probability of their dismissal increases. Additionally, the ability of fast bowlers to maintain their speed (consistency) throughout a bowling spell, or on consecutive days, does not allow a batsman to settle into their innings, and increases the likelihood of their dismissal. The determinants of bowling speed, therefore, have been a major focus in cricket-performance research (10-13). The consistency of bowling speed, however, has been disregarded. This gap is problematic, as some physical capacities or kinematic variables may relate to the ability to maintain bowling speed, and therefore should be developed to improve this performance measure.

Both spin and pace bowlers require a great level of accuracy to minimise runs scored against them, but to also place “scoreboard” pressure on the batsman. Furthermore, accurate bowling forces the batsman to play at a higher percentage of deliveries (14), which enhances the chances of their dismissal. An accurate bowler is more capable of controlling the play, by bowling to a batsman’s weaknesses. Additionally, the ability of a bowler to maintain their accuracy (consistency) throughout a bowling spell, or on consecutive days, is imperative for enforcing pressure, taking wickets, and not allowing a batsman to control the game by freely scoring runs. Also, a bowler may be fast, but possess poor bowling accuracy; a fast but inaccurate delivery can be struck to the boundary quicker. Nevertheless, a dearth of literature exists on the determinants of bowling accuracy, and the consistency of bowling accuracy. This rather large gap in the literature needs to be addressed, so sport scientists and coaches know what physical qualities to develop, if their goal is to enhance a bowler’s accuracy or consistency of bowling accuracy.

Australian fast bowler Mitchell Johnson recently dismissed 37 batsmen in the 2013-14 Ashes series (15). Each of Johnson’s wickets came at a very-low cost of 14 runs on average (15). Additionally, his bowling speed peaked at 43.3 $m{\cdot}s^{-1}$ in the Boxing Day Test (16). The English batsmen found Johnson’s bowling speed and accuracy tough to encounter. For most of the 2013-14 Ashes series, Johnson was able to maintain his speed and accuracy throughout each day of bowling, displaying an excellent standard of consistency. He was awarded man of the series (17); possibly due to his fast, accurate, and consistent bowling, which allowed him to take so many wickets at little expense.

Although literature on the biomechanical determinants of bowling speed is prevalent (6, 11, 13, 18, 19), the associations between physical qualities and bowling speed is not (10, 19, 20). Furthermore, the interaction between physical qualities, bowling kinematics, and bowling performance measures has rarely been studied (10, 21). This approach may reveal greater information for the development of pace bowlers. For example, a straight front-leg technique relates to bowling speed (10, 13, 19, 22-24), but its association with lower-body strength is not understood. Greater leg strength may permit a straight front-leg technique, and thus be important for enhancing bowling speed. Similar interactions may exist, but have not been explored previously. Knowledge of these interactions would allow sport scientists and coaches to understand the effects of developing a physical quality on bowling kinematics, and thus pace bowling performance.

Of interest to pace bowling coaches is the speed-accuracy trade-off. This phenomenon implies that when bowlers attempt to increase their delivery speed, their accuracy will suffer, and consequently may need to slow down to bowl more accurately (25). Previous research has reported no trade-off between bowling speed and accuracy when bowlers were instructed to deliver at “match-intensity” (25, 26). Pace bowlers sometimes deliver slower-balls and maximal-effort balls, and the speed-accuracy trade-off has not been assessed with a combination of delivery types. Knowledge of the relationships between bowling speed and accuracy would influence the instruction given to pace bowlers in training and a match, to achieve optimal bowling performance.

Research on the development of pace bowling performance is also in its infancy. Remarkably, only one published study has explored the effects of a training intervention on bowling speed and accuracy (2). This study employed a heavy-, light-, and regular-ball bowling intervention to develop speed-strength specific to the pace bowling motion. This intervention was designed from a successful baseball pitching intervention (27), which is meant to elicit post-activation potentiation to enhance performance with regular-ball bowling. However, Petersen, Wilson (2) did not evaluate the acute effects of heavy- and light-ball bowling on regular-ball bowling performance. If heavy- and light-ball bowling is effective in acutely enhancing bowling performance, then it could be employed in the warm-up prior to training or a match. But given the shortage of research on training interventions in pace bowling performance, coaches and sport scientists do not have sufficient evidence to develop efficacious training interventions. This thesis aims to address these shortcomings by examining the effects of an evidence-based training program and normal cricket training program on pace bowling performance, but also explore the acute effects of a heavy-ball warm-up on pace bowling performance.

To evaluate the efficacy of a training intervention, the smallest worthwhile change (i.e., minimal difference) can be calculated for each performance measure (28). For bowling speed, the smallest worthwhile change has been arbitrarily set to 1.4 $m{\cdot}s^{-1}$ (2). The smallest worthwhile change should be determined, however, by evaluating the standard error of measurement, obtained from a test-retest reliability investigation (4). Although a large variety of pace bowling assessments exist (1, 26, 29, 30), the test-retest reliability of the performance / kinematic measures have not been adequately reported. Consequently, the efficacy of a training intervention cannot be properly determined. This thesis will address this gap, so that sport scientists and coaches can determine the efficacy of future physical or skill-based training interventions.

1.2 Purposes

Study 1:

1. To establish the test-retest reliability of selected pace bowling performance components and kinematic measures in a novel eight-over pace bowling test, and in the first four overs of this test.

Study 2:

1. To determine the relationships between selected physical qualities and bowling performance measures (bowling speed, bowling accuracy, consistency of bowling speed, consistency of bowling accuracy) with various delivery instructions (i.e., match-intensity, maximal-effort, slower-ball).
2. To investigate the relationships between selected bowling kinematics (e.g., approach speed), and bowling performance measures, irrespective of delivery instruction.
3. To explore the relationships between selected physical qualities and bowling kinematics, irrespective of delivery instruction.
4. To ascertain the relationship between bowling speed and bowling accuracy with all delivery instructions pooled together, across the group, and within each bowler.

Study 3:

1. To compare the effects of an evidence-based training program with a normal training program on bowling performance, approach speed, speed-acceleration performance, and pull-up strength.

Study 4:

1. To evaluate the acute effects of heavy-ball bowling on pace bowling performance, and if these acute effects are of greater magnitude following an evidence-based training program.

1.3 Theoretical framework

This research has adopted a positivist approach (i.e., epistemology) (31). Furthermore, the investigations in this thesis are classified as applied and explanatory. That is, these studies are concerned with assessing relationships between variables (e.g., physical qualities, bowling kinematics, and bowling performance measures). Explanatory research requires a theoretical framework and permits a discussion of findings gathered from the data.

Although there is no theoretical framework underpinning this research, the applied research model for the sport sciences has been chosen (32). This model is directed towards enhancing sports performance, and comprises eight phases: 1) definition of the problem, 2) descriptive research, 3) predictors of performance, 4) experimental testing of predictors, 5) determinants of key performance predictors, 6) controlled laboratory or field efficacy studies, 7) barriers to the uptake of the program, and 8) implementation studies into a real sporting setting. This thesis will address stages one to six of the model. Stages seven and eight are beyond the scope of this thesis, and should be addressed with future research.

1.4 Delimitations

1. Community-standard male pace bowlers will be used in these investigations, ranging between 16 and 39 years old.
2. The physical testing battery will be limited to tests considered important for bowling performance and certain kinematic measures that have been previously linked to bowling speed.
3. Basic two-dimensional bowling kinematic measures will be explored.

1.5 Limitations

1. To reduce the scope of biomechanical analysis, a two-dimensional analysis of bowling kinematics was performed. This approach has been used previously to assess sagittal plane kinematics in pace bowling (10).
2. Small sample sizes in these investigations resulted from recruiting a specific population (i.e., pace bowlers), attrition rate, motivation, and injuries external to this research.
3. The results from this research can only be applied to community-standard male pace bowlers, and not to an elite cohort.
4. The relationships between physical qualities and unreliable bowling performance / kinematic variables are presented, but are less valid than the correlations conducted on reliable variables, and should be interpreted with caution.
5. Post-activation potentiation and fatigue were assessed by acute changes in bowling or sprint performance, and not through electromyography or ultrasonography.
6. There was a lack of control / monitoring over the activities that bowlers participated in outside of the PhD project.

1.6 Assumptions

1. The test-retest reliability of maximal-effort, match-intensity, and slower-ball deliveries will be acceptable for bowling performance / kinematic measures if the combination of these deliveries presents acceptable test-retest reliability, regardless of test duration (eight overs, or first four overs).
2. Participants will perform each investigation to the best of their ability, with minimal but consistent physical and psychological fatigue levels.
3. Learning effects on the pace bowling and physical tests can be discounted following three weeks of practice.
4. The physical tests present acceptable test-retest reliability.
5. Kinematic analysis of sagittal-plane bowling technique is a valid approach.
6. Participants will not deliberately change their bowling technique throughout the course of all investigations.
7. Acute improvements or detriments in bowling performance and speed-acceleration performance following a warm-up will be due to post-activation potentiation or fatigue respectively, and not the result of a warm-up effect.

1.7 Thesis format and significance

The literature review (Chapter 2) seeks to critically synthesise research in: pace bowling biomechanics, physiology, training interventions, post-activation potentiation, assessments of pace bowling performance, and the speed-accuracy trade-off. This chapter aims to present the most relevant information for a sport scientist or coach.

Study 1 (Chapter 3) explores the test-retest reliability of a novel pace bowling performance assessment. To date, only one pace bowling study has reported its test-retest reliability, but only for bowling accuracy (1). Unfortunately a Pearson's correlation coefficient was used, which does not detect systematic error (3). This chapter therefore, includes more comprehensive reliability measures (i.e., intraclass correlation coefficient, coefficient of variation, standard error of measurement), and data on the smallest worthwhile change, for selected bowling performance and kinematic measures. This information will enable sport scientists and cricket coaches to evaluate the efficacy of various types of training interventions (e.g., physical, skill-based). Additionally, this chapter also aims to add a new pace bowling performance test that is more ecologically valid than its predecessors (1, 21, 26). Coaches will be able to comprehensively assess pace bowling performance using this novel test, which will inform them and pace bowlers of strengths and weaknesses in their bowling performance.

The interplay between selected physical qualities, bowling kinematics, and bowling performance measures are covered in Study 2 of this thesis (Chapter 4). Although this approach has been used previously (10, 19), bowling speed has been the sole bowling performance measure, and not all important physical qualities have been assessed (e.g., speed, repeat-sprint ability, flexibility, power-endurance). Although physical preparation is considered important for pace bowling (14, 33, 34), the associations between physical qualities and bowling performance measures with various delivery instructions (i.e., match-intensity, maximal-effort, slower-ball) has never been explored. Furthermore, the relationship between bowling speed and accuracy has been examined with match-intensity deliveries, but not with a combination of various delivery instructions (i.e., match-intensity, maximal-effort, slower-ball). This chapter reflects the 'determinants' component of the applied research model for the sport sciences (32). The physical determinants of pace bowling performance will be considered in the development of an evidence-based training intervention in Study 3 (Chapter 5). Coaches will understand what physical qualities are related to bowling performance measures and bowling-kinematic variables, which will assist the design of training programs. Furthermore, coaches will understand if the speed-accuracy trade-off exists, which will influence the type of instructions given to pace bowlers at training and in a match situation.

The comparison of an eight-week evidence-based training program with a normal training program on pace bowling performance, approach speed, speed-acceleration performance, and pull-up strength is presented in Study 3 (Chapter 5). Although the normal training program does not represent a typical control group, this investigation is concerned with comparing an evidence-based approach with what would typically be conducted at a community cricket club ("normal" training). This chapter represents the 'controlled laboratory study' component of the applied research model for the sport sciences (32). Coaches will be able to compare both training programs and use either to develop pace bowling performance. More importantly, they may gain an appreciation for an evidence-based approach to the design of training programs, which at a community-standard cricket club, could be of great benefit to their pace bowlers.

Study 4 (Chapter 6) explores the acute effects of heavy-ball bowling on pace bowling performance, and if these acute effects are of greater magnitude following an evidence-based training program. Coaches will see how effective a heavy-ball warm-up is on subsequent pace bowling performance, and may be able to implement this warm-up prior to training or a match.

Finally, a summary and conclusions of all three experimental studies, their practical applications, and future research directions are presented in Chapter 7. This thesis will adopt the *Vancouver* referencing style, where references in the bibliography are listed in order of appearance in text. This referencing style has been selected because it is concise and clear to follow.

Chapter 2:
Review of Literature

2.1 Purpose

The purpose of this chapter is to synthesise, interpret, critique, and identify shortcomings to provide the basis for the experimental work to follow. This review of literature will explore the biomechanics (Section 2.1) and physical qualities (Section 2.2) pertaining to pace bowling. These sections serve as the "needs analysis" of the pace bowling motion (35). This review will assist in the selection of appropriate physical tests, which are presented in Study 2. The efficacy of pace bowling training interventions on pace bowling performance are assessed in Section 2.3, as well as the efficacy of training interventions on their respective performance measures in related sports to pace bowling (i.e., baseball, handball, water polo). Additionally, the post-activation potentiation phenomenon and its exploitation in sprinting and throwing motions are appraised in Section 2.4. An overview of the design of various pace bowling performance tests and the speed-accuracy trade-off are presented in Section 2.5 and 2.6 respectively.

2.2 Biomechanics of pace bowling

Pace bowling in cricket involves the delivery of a 156 g ball at speeds of 18.0 $m{\cdot}s^{-1}$ to >40.5 $m{\cdot}s^{-1}$ at the moment of release (36). This section provides a detailed analysis on the key-phases and biomechanics of the "general" pace bowling technique. As pace bowling techniques vary from side-on, semi-open, front-on, and mixed (37), this section is based on literature that does not distinguish between these techniques. Although published reviews on pace bowling biomechanics exist (38-40), they are not written from the perspective of a sport scientist or coach. The biomechanical qualities presented in this section, therefore, are those thought to be influenced with physical training, and should be considered in the design of an evidence-based training program. This section will commence with the run-up, and conclude with the follow-through.

2.2.1 The run-up phase

The run-up is deemed a very important phase of the pace bowling motion (Figure 2.1) (41). A gradual linear or curvilinear acceleration during the run-up creates kinetic energy that can be imparted to the cricket-ball upon release, which can be used to enhance bowling speed. The run-up should be long enough to permit a gradual acceleration. A run-up of 17.7 m ± 4.1 m is sufficient for Australian medium-fast bowlers to bowl at 125.7 km$\cdot$h^{-1} ± 5.1 km$\cdot$h^{-1} (25). Faster bowlers generally use a slightly longer run-up than slower bowlers (42).

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Figure 2.1. The run-up phase of the pace bowling motion.

The speed of the run-up, typically reported to be 5.3–6.3 m$\cdot$s^{-1}, displays a positive relationship to bowling speed (6, 12, 25, 43). This relationship could be mediated by bowling technique. For example, Jeff Thomson, who bowled at nearly 44.4 m$\cdot$s^{-1} (8), approached the crease at 3.8 m$\cdot$s^{-1} (44) and used a “slingshot” bowling technique. Dennis Lille, ran up at 5.4 m$\cdot$s^{-1} (45), bowled at 38.3 m$\cdot$s^{-1}, but employed a conventional bowling technique. Thomson released the ball with an extended front-leg, while Lillee collapsed his front-leg (44). An “optimal” run-up speed, therefore, has been recommended (38), perhaps so bowlers can achieve a stable body position at the crease (25). A balanced position at the crease may assist bowlers to optimally coordinate each segment to bowl quickly and accurately.

Centre of mass kinematics (6), reveals the run-up only contributes 11.7% to bowling speed. Bowlers with a greater peak run-up velocity typically decelerate more in the delivery stride, and in-turn, relates to bowling speed (6). A faster run-up increases kinetic energy, and thus the deceleration in the step-length phase and power phase. The magnitude of kinetic energy, however, could be too large for the execution of an extended front-leg technique. Consequently, some of the kinetic energy is absorbed by collapsing the front-leg, where less is transferred to the ball for the generation of ball speed.

2.2.2 *The take-off step phase*

The take-off step separates the run-up from the delivery step (Figure 2.2). For a right hand bowler, it commences with a jump from the left foot, and ends on back-foot contact. A powerful take-off step is suggested to increase “hang-time”, allowing greater control of the bowling action (46). Faster bowlers jump 22% further than slower bowlers during the delivery step (42), which represents 112% of their standing height on average (19). A longer jump is likely to increase delivery step length and thus braking force on landing, which could develop bowling speed, providing an extended front-leg is employed and maintained. A jump that is too long may lengthen the delivery step, and consequently a collapsed front-leg (47). Therefore, an optimal jump-length, and run-up speed, probably exists for pace bowlers, and these kinematic variables may be influenced by physical qualities such as lower-body strength, power, and power-endurance.

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A B C

Figure 2.2. Take-off (A), hang-time (B), and just prior to landing (C).

2.2.3 *The step-length phase*

The step-length phase represents the duration between back- and front-foot ground-contact (Figure 2.3) (6, 48), and typically lasts 0.12–0.24 s for a pace bowler (11). A pace bowler’s spine is slightly extended at back-foot contact, where it flexes until ball release (48). Trunk flexion is speculated to increase the acceleration path of the cricket ball (38). Consequently, a greater impulse may be applied to the ball, thereby enhancing bowling speed. Fast bowlers could thus use more of their maximal strength to bowl faster.

The back leg absorbs peak vertical and horizontal forces of 2.0–2.9 BWs and 0.5–1.7 BWs respectively, when landing from the take-off step (22, 49-52). Additionally, peak vertical loading rates range from 30–85 $BW \cdot s^{-1}$ and occur 53 ms following back-foot contact (51). Consequently, many pace bowlers flex their back leg by 40° on landing (22), but re-extend it at ball release (18). The faster bowlers typically flex and extend their back leg more (22), and with greater angular velocity (18), than slower bowlers. This “whip-like” motion, however, is not actuated by concentric back leg knee-extensor contraction (53), but possibly contralateral trunk-rotation.

Figure 2.3. The step-length phase of the bowling action.

The front leg is “kicked-out” following back-foot landing to form the delivery step (Figure 2.4), which varies between 70–80% of standing height (19, 33). Furthermore, front-foot “slamming” in the step-length phase is thought to enhance bowling speed (42). In fact, quicker bowlers slam their front foot faster (downswing), and through a greater angular displacement, than slower bowlers (19, 42). The front leg downswing therefore, is likely to increase angular acceleration and kinetic energy at the front-leg hip, and assist with back leg hip rotation. Consequently, greater hip-extensor mobility would permit a longer acceleration path for front leg downswing. The hip-extensor mobility of the front leg and its connection to bowling speed has not been studied.

Figure 2.4. The delivery step in the bowling motion.

The “plant angle”, similar to delivery step length, is defined as the angle from the downwards-vertical, to a linear line connecting the hip and ankle joint centres of the front leg (Figure 2.5) (54). The plant angle ranges from 27–43° at the instant of front-foot contact (55). The plant angle relates to front leg horizontal impulse and bowling speed (54). As bowling speed is also associated to front leg horizontal impulse (54), a greater plant angle may enhance bowling speed. In support, normalised delivery step length is largely related to the centre of mass velocity at back-foot contact ($r = 0.57$, $p < 0.01$) (6). An optimised run-up therefore, is likely to create an optimum plant angle, and develop sufficient horizontal impulse to enhance bowling speed.

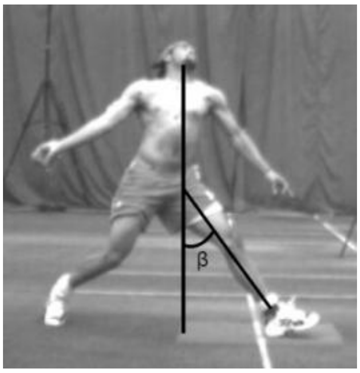

Figure 2.5. The plant angle measurement (54).

The lumbar spine rotates, flexes, extends, and laterally flexes during the step-length phase (Tables 2.1–2.3) (48). Most trunk muscles are activated eccentrically or concentrically (48), and thus should be developed in a training program. Training trunk stability and strength enhances throwing velocity in junior handball throwers (56), and reduces low-back pain in pace bowlers (57). The relationships between trunk strength-endurance and pace bowling performance have not been explored.

Table 2.1. Lumbar spine flexion and extension in the step-length phase, adapted from Ferdinands, Kersting (48).

Phase (%)	Contraction / motion	Trunk muscles activated
0	Eccentric flexion	Erector spinae, transversospinalis, interspinales, quadratus lumborum, multifidus
10 20	Concentric flexion	Abdominals, external obliques, internal obliques
30 40 50 60 70	Eccentric extension	Abdominals, external obliques, internal obliques
80 90 100	Concentric extension	Erector spinae, transversospinalis, interspinales, quadratus lumborum, multifidus

Table 2.2. Lumbar spine rotation in the step-length phase, adapted from Ferdinands, Kersting (48).

Phase (%)	Contraction / motion	Trunk muscles activated
0 10 20 30	Eccentric counter-rotation	L internal obliques, R external obliques, R transversospinalis
40 50 60 70	Concentric anti-clockwise rotation	L internal obliques, R external obliques, R transversospinalis
80 90 100	Eccentric anti-clockwise rotation	R internal obliques, L external obliques, L transversospinalis

R, right side; L, left side

Table 2.3. Lumbar spine lateral flexion in the step-length phase, adapted from Ferdinands, Kersting (48).

Phase (%)	Contraction / motion	Trunk muscles activated
0 10 20 30 40 50 60 70 80 90 100	Eccentric L lateral flexion	R quadratus lumborum, R external obliques, R internal obliques

R, right side; L, left side

The front arm (i.e., non-bowling arm) should be vertical, and extended, at back-foot contact (14, 41, 58, 59). Faster bowlers not only delay front-arm adduction, but thrust the front-arm quicker into their ribs with a more vertical trajectory, compared to slower bowlers (42). A vertical and extended front-arm could develop greater angular velocity and rotational energy by covering a greater angular distance. The rotational energy from this segment could transfer to the ball to enhance bowling speed. In fact, front-arm angular velocity ranges between $818.2\text{–}1300.6^\circ \cdot s^{-1}$ (19), and correlates with bowling speed in elite pace bowlers ($r = 0.45$, $p < 0.05$) (60). Developing the strength and power of the front arm and upper-back muscles may enhance the angular velocity or torque generated in front-arm adduction, and contribute to bowling speed.

2.2.4 The power phase

The power phase occurs between front-foot contact and ball release (6, 48) and typically lasts 80–120 ms for a pace bowler (11). An extended front leg on landing and at ball release is advocated (61), as it maximises tangential end-point velocity (Figure 2.6 B) (23, 33), and enhances bowling speed. The extended front leg technique would also assist in decelerating the front leg, and increase angular momentum about the pelvis. In fact, an extended front-leg at front-foot contact (10, 62), and at ball release (10, 13, 19, 22-24) is positively related to bowling speed. Flexibility, mobility, and eccentric strength may influence the ability to execute an extended front-leg technique. However, the relationships between these physical qualities and knee kinematics are not understood.

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A B

Figure 2.6. The power phase of the bowling motion (A, B). An extended front-leg technique (B) increases tangential velocity (Vt).

The front-leg experiences peak vertical and horizontal ground reaction forces of 3–9 BWs and 1.4–4.5 BWs respectively (22, 33, 43-45, 49-52, 55, 62-65). Peak vertical ground-reaction forces occur 26 ms following front-foot contact (51). Faster bowlers develop peak vertical and horizontal forces quicker than slower bowlers (62). Bowlers who adopt an “extender” or “flexor-extender” front-knee technique display shorter times to peak vertical and horizontal force, and greater peak vertical and horizontal forces, compared to bowlers who use a “flexor” front-knee technique (62). Portus, Mason (62) suggested the extender and flexor-extender front-knee techniques reduce the time to peak force. In contrast, Worthington, King (55) reported greater front-knee flexion with a shorter time to peak force. In the latter investigation, the time to peak force was reduced by employing a smaller plant angle and a greater plantar-flexion angle at front-foot contact (55). Front-knee flexion in the power phase therefore, appears to not be influenced by the time to peak force, but vice versa. A heel-strike technique would delay the time to peak force, and enable an extended front-leg, in pursuit of maximising bowling speed. Reactive strength, which is defined as the ability to quickly change from an eccentric to concentric contraction (66), may relate to an “extender” or “flexor-extender” front-knee technique, and contribute to bowling speed. Greater front-knee flexion can result from quadriceps fatigue, and ultimately slower bowling speeds (24). The association between lower-body power-endurance and bowling speed however, is not known.

The lumbar spine flexes, laterally flexes, and rotates in the power phase (Tables 2.4–2.6) (48). The angular velocity of these motions peak at approximately the same time when horizontal and vertical ground reaction forces are maximal (48). Faster bowlers counter-rotate their trunk segment more at front-foot contact, and cover a greater angular displacement up to ball release, compared to slower bowlers (67, 68). Furthermore, a vigorous conscious trunk flexion enhances bowling speed, but at the decrement of bowling accuracy (69). The relationship between trunk strength-endurance and pace bowling performance however, has not been investigated.

Table 2.4. Lumbar spine flexion and extension in the power phase, adapted from Ferdinands, Kersting (48).

Phase (%)	Contraction / motion	Trunk muscles activated
0	Concentric flexion	Abdominals, external obliques, internal obliques
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		

Table 2.5. Lumbar spine rotation in the power phase, adapted from Ferdinands, Kersting (48).

Phase (%)	Contraction / motion	Trunk muscles activated
0	Eccentric anti-clockwise rotation	R internal obliques, L external obliques, L transversospinalis
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		

R, right side; L, left side

Table 2.6. Lumbar spine lateral flexion in the power phase, adapted from Ferdinands, Kersting (48).

Phase (%)	Contraction / motion	Trunk muscles activated
0	Eccentric L lateral flexion	R quadratus lumborum, R external obliques, R internal obliques
10	Concentric L lateral flexion	L quadratus lumborum, L external obliques, L internal obliques
20		
30		
40		
50		
60		
70		
80		
90	Concentric R lateral flexion	R quadratus lumborum, R external obliques, R internal obliques
100		

R, right side; L, left side

The bowling-arm shoulder is one of the last segments to contribute to bowling speed. Faster bowlers move their bowling-arm through a greater angular distance than slower bowlers (68). For example, Jeff Thomson covered a 120° arc with his “slingshot” technique (44), and bowled at nearly 160 km·h^{-1} (8). A greater impulse could be applied to the ball if the bowling-arm shoulder covers a greater angular displacement; a possible mechanism for enhancing bowling speed.

Surprisingly, bowling speed relates poorly to the angular velocity of the bowling-arm humerus (12). Bowling-arm torque therefore, might be more important in generating bowling speed. Faster bowlers create greater shoulder horizontal adduction power, whereas slower bowlers develop more shoulder vertical adduction power (70). Consequently, faster bowlers might use the stretch-shortening cycle more effectively in their chest musculature (6, 71), by delaying the onset of bowling-arm circumduction (13, 71), and releasing the ball with a more “round arm” technique. Chest flexibility might therefore permit a greater horizontal abduction motion, to increase the acceleration path of the ball, and ultimately enhance bowling speed. However, the relationship between chest flexibility and bowling speed is not understood.

The bowling-arm wrist contributes a small amount to bowling speed (38, 59). Faster bowlers cover greater angular displacement in the sagittal and transverse planes, and produce greater angular velocity in the transverse plane (72). Additionally, faster bowlers delay the onset of wrist flexion (42), but use the stretch-shortening cycle to produce a wrist “snap” to develop bowling speed (70).

2.2.5 Follow-through

The follow-through commences from ball release and concludes when the bowler is stationary (Figure 2.7). As the follow-through occurs after ball release, it does not directly influence bowling performance. The follow-through however, may affect injury risk, and be representative of actions occurring earlier in the bowling motion. A short follow-through is typically characteristic of slower bowlers (33), as they have less forward momentum to negate. During the first step of the follow-through, vertical and horizontal ground reaction forces peak at 4.9 BWs and 1.3 BWs respectively (73). Although these forces are considerable, the pace bowler experiences greater vertical and horizontal forces at front-foot contact (38).

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Figure 2.7. The follow-through phase of the bowling motion.

2.2.6 Conclusions

A fast approach speed generates kinetic energy that can be transferred to the bowling hand to increase bowling speed. The transfer of kinetic energy is maximised with an “extender” or “flexor-extender” front-leg technique. Furthermore, the ability to decelerate quickly in the step-length phase and power phase is associated with delivery step-length, which both positively relate to bowling speed. Although there are many kinematic and kinetic variables that correlate to bowling speed, shoulder counter-rotation is the only kinematic variable that is negatively associated with bowling accuracy. A dearth of kinematic correlational research exists on bowling accuracy, consistency of bowling speed, and consistency of accuracy. This thesis addresses these gaps.

2.3 Physical qualities in pace bowling

2.3.1 Time-motion analysis of match play for pace bowlers

The physiological demands of pace bowling are influenced by the rules of each match format. For example, a 10- and 4-over limit exists for pace bowlers in One-Day International and Twenty/20 cricket respectively. Unlimited overs can be bowled however, in multi-day (e.g., Test) cricket. Time-motion data of pace bowlers in 4-day (74), One-Day International (74-76), and Twenty/20 cricket (76-78) has been investigated, and has included fielding activities between overs (Table 2.7).

Pace bowlers perform at a higher intensity in Twenty/20 cricket, compared to one-day or multi-day cricket. Additionally, they perform more sprints per hour, with less recovery, and cover greater distances at faster running speeds in Twenty/20 cricket (76). Multi-day cricket however, is a greater test of endurance, as pace bowlers may be required to bowl each day, and multiple spells within each day.

Pace bowling is the only activity in cricket that requires well-developed repeat-sprint ability. Repeat-sprint ability is defined as a cluster of three or more sprints, with less than 60 s recovery between each (76). Furthermore, each sprint must be greater than 5.0 $m.s^{-1}$ for one second to be counted in the repeat-sprint definition (76). An application of the repeat-sprint definition would reveal that some bowlers could be classified as “sprinting” in each delivery during the run-up, while some bowlers would not run-up as fast to deliver the ball.

The clusters of repeat-sprints vary between match formats: Twenty/20 (3.3 ± 1.5 clusters), one-day (6.2 ± 2.9 clusters), and 3-day (5.5 ± 4.0 clusters) (76). Additionally, the number of sprints within each cluster also differs between formats: Twenty/20 (4.8 ± 1.4 sprints), one-day (5.0 ± 1.4 sprints), and 3-day (4.9 ± 0.7 sprints). The interplay between repeat-sprint ability, bowling kinematics, and pace bowling performance however, has never been explored.

Table 2.7. Time-motion analysis data of combined pace bowling and fielding in Twenty/20, One-Day, and multi-day cricket (74, 76).

	National Twenty/20 (*n* = 18)	**State One-Day (*n* = 8)**	**Nat One-Day (*n* = 24)**	**International One-Day (*n* = 21)**	**State 4-Day (*n* = 80)**	**National 3-Day (*n* = 10)**
Distance (m·hr^{-1})						
Walking (0–2.0 m·s^{-1})	2,634 ± 268	2,626 ± 297	2,520 ± 362	**2,936 ± 539**	2,810 ± 487	2,512 ± 258
Jogging (2.01–3.5 m·s^{-1})	**718 ± 276**	684 ± 158	618 ± 217	648 ± 220	574 ± 185	614 ± 173
Running (3.51–4.0 m·s^{-1})	164 ± 76	154 ± 40	157 ± 58	145 ± 39	118 ± 42	**185 ± 89**
Striding (4.01–5.0 m·s^{-1})	**249 ± 121**	216 ± 47	220 ± 81	208 ± 53	187 ± 65	233 ± 133
Sprinting (>5.01 m·s^{-1})	**406 ± 230**	344 ± 93	316 ± 121	341 ± 76	334 ± 134	230 ± 149
Total distance		4,026 ± 496		**4,279 ± 677**	4,024 ± 716	
Time						
Walking & jogging (s)		3,414 ± 40		3,444 ± 36	**3,448 ± 104**	
Running, striding & sprinting (s)		**149 ± 22**		143 ± 27	132 ± 40	
Sprint						
Number per hour (#)	**23 ± 10**	20 ± 3	18 ± 5	19 ± 4	20 ± 7	17 ± 11
Mean sprint distance (m)	17 ± 4	17 ± 3	**18 ± 3**	**18 ± 3**	17 ± 3	13 ± 1
Maximum sprint distance (m)	35 ± 13	42 ± 13	46 ± 12	**49 ± 17**	44 ± 12	28 ± 5
Maximum sprinting speed (m·s^{-1})		8.1 ± 0.5		8.2 ± 0.8	**8.4 ± 0.7**	
High Intensity Efforts						
Number per hour (#)	**61 ± 25**	53 ± 8	54 ± 14	52 ± 11	50 ± 22	56 ± 29
Recovery ratio (1 : x)	**25 ± 18**		**25 ± 7**			38 ± 31
Mean effort duration (s)		**2.8 ± 0.2**		**2.8 ± 0.2**	2.7 ± 0.4	
Recovery between (s)		**69 ± 10**		73 ± 21	83 ± 35	

Bold numbers reflect the largest recorded across all formats. Numbers reported as mean ± *SD*. High intensity effort defined as running, striding, or sprinting. Low intensity effort included walking and jogging. The recovery ratio is "high intensity effort : low intensity effort'. A sprint is defined as a movement above 5 m·s^{-1} for at least 1 s.

Time-motion analysis data has been captured during laboratory pace bowling, where bowling was designed to replicate match demands (Table 2.8) (79, 80). The laboratory pace bowling testing included fielding drills between overs. The fielding drills comprised a 10-m walk-in for each delivery bowled by a partner, and a 20-m sprint on the second and fourth ball of their over.

Table 2.8. Time-motion analysis data of combined pace bowling and fielding drills for a 10- and 6-over spell in laboratory conditions (79, 80).

	10-over spell (79)	**6-over spell** (80)
Distance (m)		
Total	8676 ± 1295 m	4328 ± 707 m
Very-high-intensity activity (>5.5 $m\cdot s^{-1}$)	738 ± 550 m	442 ± 287 m
High-intensity activity (4.0–5.5 $m\cdot s^{-1}$)	1656 ± 427 m	888 ± 230 m
Moderate-intensity activity (1.9–4.0 $m\cdot s^{-1}$)	1019 ± 379 m	461 ± 75 m
Low-intensity activity (<1.9 $m\cdot s^{-1}$)	5263 ± 649 m	2537 ± 411 m
Speed ($m\cdot s^{-1}$)		
Very-high-intensity activity (>5.5 $m\cdot s^{-1}$)	5.8 ± 0.9 $m\cdot s^{-1}$	5.8 ± 0.5 $m\cdot s^{-1}$
High-intensity activity (4.0–5.5 $m\cdot s^{-1}$)	5.3 ± 0.6 $m\cdot s^{-1}$	5.2 ± 0.6 $m\cdot s^{-1}$
Moderate-intensity activity (1.9–4.0 $m\cdot s^{-1}$)	3.0 ± 0.2 $m\cdot s^{-1}$	3.1 ± 0.1 $m\cdot s^{-1}$
Low-intensity activity (<1.9 $m\cdot s^{-1}$)	1.0 ± 0.1 $m\cdot s^{-1}$	1.0 ± 0.1 $m\cdot s^{-1}$

Numbers reported as mean ± *SD*.

Although the speed classifications in these studies (79, 80) differ from previous research (74, 76), low-intensity activity such as walking, predominates in pace bowling, and would serve as an active recovery between deliveries and sprints in the field. These studies support the notion that pace bowling is an explosive intermittent activity, irrespective of match formats.

2.3.2 Physiology of laboratory-based pace bowling

Throughout a 12-over pace bowling spell conducted in a controlled environment designed to simulate match conditions indoors (i.e., laboratory-based pace bowling), a bowler's heart rate ranges from 163–172 $beats\cdot min^{-1}$, while blood lactate peaks at 5.1 $mmol\cdot L^{-1}$ (81). Additionally, these bowlers (state-standard) exhibited a $\dot{V}O_{2peak}$ of 54.2 ± 6.2 $mL\cdot kg^{-1}\cdot min^{-1}$ and a peak heart rate of 193 ± 14 $beats\cdot min^{-1}$ during a graded treadmill test (81). In the pace bowling spell (conducted in 28.1°C ± 0.8°C), the bowlers attained 84.7% of their peak heart rate, but were able to maintain their bowling speed. Fast bowlers are therefore capable of performing at a high intensity for a long spell in warm–hot conditions, without reducing bowling speed (81). Pace bowlers must remain hydrated, as hypohydration may not affect anaerobic performance (e.g., bowling speed), but it influences the execution of fine motor skills and coordination (e.g., bowling accuracy) (82). The relationship between the $\dot{V}O_{2peak}$ and consistency of bowling speed or consistency of bowling accuracy however, has not been investigated.

When elite medium-fast bowlers perform two 6-over spells in milder ambient conditions (22°C), slight changes in: blood lactate (0.3 $mmol{\cdot}L^{-1}$ increase), blood pH (0.01 increase), blood glucose (0.7 $mmol{\cdot}L^{-1}$ increase), heart rate (7 $beats{\cdot}min^{-1}$ increase), core temperature (0.5°C increase), vertical jump (1 cm improvement), mean running speed (0.11 $m{\cdot}s^{-1}$ decrease), bowling speed (0.08 $m{\cdot}s^{-1}$ decrement), and bowling accuracy (1.2 arbitrary units better) occur between spells (25). Larger but insignificant differences however, in nude mass (2.7 kg loss), perceived exertion (1 point increase), and muscle soreness (1 point increase) are also evident between spells (25). These data indicate that elite medium-fast bowlers can sufficiently repeat a 6-over spell without adversely affecting many physiological measures, indicating the demands of fast bowling in mild conditions are relatively low–moderate for national-standard pace bowlers.

2.3.3 Anthropometrics

The anthropometric profile of former Australian fast bowler Dennis Lillee was assessed in 1978 and 1984 (45). Lillee's body-mass dropped from 90.0 kg to 86.5 kg, and his skinfold thickness reduced by 11.3 mm. Lillee stood 183 cm tall, consistent with current elite pace bowlers (83). Height is thought to be important for a pace bowler, because the ball is released from a greater height, and has extra bounce off the pitch (84). The reach height of the bowler, a dynamic motion involving shoulder flexion in standing, has not been assessed or related to bowling performance.

Theoretically, a longer bowling arm increases the acceleration path of the ball, which could increase tangential velocity and thus ball speed (12). Glazier, Paradisis (12) estimated that bowling speed could increase by 3.1 $m{\cdot}s^{-1}$ if bowling-arm angular velocity was fixed at 40.6 $r{\cdot}s^{-1}$, but with a 10-cm longer bowling arm. Faster bowlers typically have long arms (usually 86 ± 3 cm) (12), possibly because they are normally taller than slower bowlers.

Skinfold and limb-length measures have been used to calculate body fat, residual tissue, muscle, and bone mass, in senior and junior pace bowlers (Table 2.9) (20). Pyne, Duthie (20) reported no disparities in body mass and stature between senior and junior pace bowlers. Body mass however, was a positive predictor of bowling speed for junior pace bowlers, whereas bowling-arm length and a greater anterior-posterior chest depth positively related to bowling speed for senior pace bowlers (20). These findings were in agreement with Portus, Sinclair (21), who showed ball release speed to be related with chest composition and chest girth in senior pace bowlers. Building muscle size in the upper body region may therefore be important in bowling fast. The relationship between upper body strength and bowling speed however, has not been ascertained.

Table 2.9. The anthropometric profile of senior and junior pace bowlers (20).

Anthropometric measure	**Senior fast bowlers (*n* = 24)**	**Junior fast bowlers (*n* = 48)**
Height (cm)	187.4 ± 4.8	175.7 ± 9.8
Body mass (kg)	87.3 ± 8.4	65.8 ± 12.9
Fat mass (kg)	8.3 ± 2.2	7.5 ± 2.3
- % body mass	9.5	11.4
Bone mass (kg)	14.0 ± 1.4	12.1 ± 2.0
- % body mass	16.0	18.4
Residual mass (kg)	23.0 ± 2.4	16.9 ± 2.8
- % body mass	26.3	25.7
Muscle mass (kg)	40.0 ± 3.9	28.3 ± 5.6
- % body mass	45.8	43.0
Sum of seven skinfolds (mm)	62.5 ± 19.2	63.2 ± 21.5
Arm length (cm)	82.0 ± 4.8	75.8 ± 4.7
- % height	43.8	43.1
Anterior-posterior chest depth (cm)	21.3 ± 1.9	17.8 ± 1.7

Data presented as mean ± *SD*.

2.3.4 Physical qualities

A great level of muscular power, strength-endurance, flexibility, aerobic capacity, and anaerobic power is suggested to be important for bowling speed (14, 33). Although data was published on these physical qualities (33, 34, 45), their relationships to pace bowling performance were not examined. In 2005 however, the interplay between selected physical capacities, bowling kinematics, and bowling speed was investigated (10). Isokinetic knee flexion and extension, and isokinetic shoulder internal and external rotation were the only strength tests employed in this study. The bowling kinematic measures included the front-knee extension angle at front-foot contact and at ball release. Bowling speed was not significantly related to any strength tests ($p > 0.05$); possibly due to the lack of postural specificity of the tests, and the nature of isokinetic testing (i.e., constant velocity and accommodating resistance). An extended front knee at front-foot contact however, correlated with a greater knee-extension angle for peak-torque production in the isokinetic knee-flexion test ($r = 0.58$, $p < 0.05$). Hamstring strength may therefore enable a bowler to adopt a straight front-leg technique, which is known to be associated with faster bowling speeds (10, 13, 19, 21).

Table 2.10. Physical tests and results from early investigations (33, 34, 45).

Physical capacity	Test	15 Fast bowlers Mean ± *SD* (33)	Dennis Lillee 1975 (34)	Dennis Lillee 1978, 1984 (45)
Mobility / Flexibility	Trunk flexion	39.4 ± 6.6°	NC	NC
	Trunk extension	7.1 ± 3.0°	NC	NC
	Sit and reach	+ 11.0 ± 3.4 cm	+ 2.0 cm, + 9.0 cm	+ 1.0 cm, + 10.0 cm
	Lateral flexion	34.0 ± 4.6 cm* 34.0 ± 5.5 cm^	NC	NC
	Trunk rotation	79.3 ± 13.1°* 80.1 ± 12.1°^	NC	NC
	Lower limb raise	84.1 ± 7.5°* 82.3 ± 7.5°^	NC	NC
	Upper limb elevation	204.5 ± 10.5°* 198.9 ± 21.7°^	NC	NC
	Shoulder internal rotation	78.4 ± 9.5°* 79.0 ± 8.4°^	NC	NC
	Shoulder external rotation	100.3 ± 11.8°* 96.9 ± 10.4°^	NC	NC
Muscular Strength	Shoulder extension	74.0 ± 12.2 kgf* 96.9 ± 10.4 kgf^	71.8 kg, 82.3 kg	NC
	Hand flexion	NC	25.9 kg, 27.7 kg	NC
Muscular Power	Shoulder extension	NC	199 kg·m·s^{-1}, 245 kg·m·s^{-1}	NC
Muscular Strength-Endurance	Sit-ups in 60 s	43.0 ± 2.9 reps	NC	40 reps, 52 reps
	Max push-ups	NC	NC	45 reps, 95 reps
ATP-PC Energy System	40 m sprint	5.7 ± 0.3 s	NC	5.7 s, 5.6 s
All 3 Energy Systems	400 m sprint	61.0 ± 1.4 s	NC	60.2 s, 57.4 s
Aerobic Energy System	15 min run	3750 ± 150.2 m	NC	3550 m, 3900 m
	$\dot{V}O_{2max}$		50.5 mL·kg^{-1}·min^{-1}, 55.2 mL·kg^{-1}·min^{-1}	
Ball Release Speed		**30.6 ± 2.0 m·s^{-1}**	**NR, 39.5 m·s^{-1}**	**34.8 m·s^{-1}, NR**

*, preferred side; ^, non-preferred side; NC, not conducted; NR, not reported; Kgf, kilograms of force; Kg·m·s^{-1}, kilogram metres per second; reps, repetitions; min, minutes; ATP, adenosine tri-phosphate. Data presented for column “Dennis Lillee 1975” consists of results before and after a nine week training intervention on former Australian pace bowler Dennis Lillee (34).

Fatigue during pace bowling is possibly best explained by the biomechanical model of exercise performance (85). This model infers that repeated eccentric contractions alter muscle function, resulting in a loss of stored elastic energy (86). In a pace-bowling spell, excessive lower-body decelerations during the step-length and power phases may eventually alter muscle function (i.e., contractibility, extensibility, and elasticity), which may result in less energy transfer to the ball for the generation of ball speed. In fact, pre-fatiguing the quadriceps causes greater front-knee flexion during the power phase, especially for bowlers who adopt an extended front-leg technique (24). Also, a greater eccentric to concentric quadriceps strength ratio (not reported) results in less front-leg flexion at front-foot contact (87). Eccentric strengthening of the quadriceps is therefore recommended for pace bowlers (85, 87, 88), even though one study revealed a non-significant relationship between bowling speed and eccentric isokinetic quadriceps strength (19).

Isokinetic strength testing is non-specific to the pace bowling motion (10, 19). Isokinetic strength tests typically involve a single joint, and therefore do not assess inter-muscular activation. Isokinetic strength tests comprise accommodating resistance or a constant movement velocity, whereas pace bowling is a "ballistic" motion that requires a burst of muscle activation followed by an acceleration of each segment, in attempt to maximise end-point velocity. To address the limitations with isokinetic strength testing, the single-leg concentric-only jump (i.e., no prior countermovement) and single-leg countermovement jump were performed by senior and junior fast bowlers (20). Surprisingly, faster bowlers jumped lower on the countermovement jump test, but higher on the concentric-only jump test. This finding suggests that concentric peak power is important for bowling fast, and the stretch-shortening cycle is not as essential. A slow stretch-shortening cycle movement (i.e., ground contact time of >0.25 s) such as the countermovement jump was argued to be important from the moment of back-foot contact to ball release (89); as this typically lasts 0.29 s (11). However, a faster stretch-shortening cycle movement (< 0.25 s) such as the drop jump may be a better and more specific test to the pace bowling motion, as the step-length phase and power phase durations are relatively short (0.19 s and 0.10 s respectively) (11). Furthermore, Pyne, Duthie (20) acknowledged that both tests possessed moderate to large typical error, rendering them less reliable. A bilateral jump test, therefore, might be a more reliable and easier test to perform. Unfortunately, this study did not explore the relationship between lower-body strength and bowling speed.

Upper-body power tests, such as the concentric-only bench press throw (i.e., no prior countermovement) and concentric-only deltoid throw (i.e., no prior countermovement) were also completed by senior and junior pace bowlers (20). The concentric-only bench press throw partially predicted the variance in bowling speed for juniors. The concentric-only deltoid throw however, negatively related to bowling speed for senior pace bowlers (*r* not reported). These upper-body power tests did not incorporate a stretch-shortening cycle component, which may have resulted in stronger relationships to bowling speed.

Ferdinands, Kersting (71) suggested the bowling arm experiences an inertial lag when circumduction is delayed, and the anterior chest musculature is consequently stretched and then shortened as the bowling arm circumducts. As the bowling motion is repeated intermittently throughout a spell, an upper-body power-endurance test may relate to the consistency of bowling speed or consistency of bowling accuracy, but these relationships have not been explored.

Tests of upper-body strength, such as the 1-RM bench press and barbell pullover are strongly related to bowling speed (90). Stewart (90) employed a stretch-shortening cycle component to both upper-body strength tests. Greater correlations were observed with the 1-RM bench press ($r = 0.58$, $p = 0.03$) and barbell pullover tests ($r = 0.66$, $p = 0.01$) to bowling speed, than isokinetic internal- external-rotator strength tests of the shoulder (not statistically significant, but not reported) (19). Furthermore, the advantage of using the pullover test is that it permits little elbow flexion (90, 91), and is thus more specific to the pace bowling motion (92).

Tests of trunk strength and stability, such as the seven-stage abdominal sit-up, and the single-leg lowering, do not relate to bowling speed or accuracy (21). Greater performance on the single-leg lowering test however, correlated to a larger front knee-flexion at front-foot impact. Pace bowlers with greater trunk stability may therefore use their trunk as a rigid lever instead of their front-leg (21). The use of the trunk as a rigid lever however, would compromise bowling speed, as faster bowlers flex their upper-trunk more in the power phase than slower bowlers (13). Conversely, the faster bowlers in the study of Portus, Sinclair (21) could have possessed poorer lower-body strength, but excellent trunk stability. Although trunk strength and stability do not relate to bowling speed, trunk strength-endurance was not assessed, and could be important.

2.3.5 Conclusions

Pace bowling is an intermittent ballistic activity, which requires repeat-sprint efforts interspersed with walking recoveries. The shorter game formats (Twenty/20 and One Day cricket) are played at a higher intensity than longer game formats (4-day cricket). The physiological demand of pace bowling is moderate to high, but is probably influenced by spell length, aerobic capacity, anaerobic power, and environmental conditions. Pace bowlers require a great level of strength-endurance to endure the rigours of 4-day cricket.

Fatigue during fast bowling is possibly best explained by the biomechanical model of exercise performance, where repeated eccentric contractions are likely to alter muscle function and storage of elastic energy. A great level of muscular power, strength-endurance, flexibility, aerobic capacity, and anaerobic power is suggested to be important for bowling speed. The relationships between some relevant physical qualities (e.g., speed, repeat-sprint ability, strength, and flexibility) and bowling performance however, has not been studied.

2.4 Resistance training interventions

2.4.1 Training intervention classification

Resistance training exercises can be categorised as general, special, or specific (93). A general training exercise develops basic strength or maximal strength, whereas a special training exercise targets power development through non-specific exercises. A specific training exercise however, is powerful but is strongly related to the athlete’s movement pattern. Three trainable qualities such as hypertrophy, intra-muscular coordination, and inter-muscular coordination are suggested to enhance athletic performance (94). These three qualities can be applied to the general, special, or specific classification system to enhance pace bowling performance (Table 2.11).

Table 2.11. An integrated training philosophy model (93, 94), with an example to develop bowling speed.

Physical quality	**Type of exercise (93)**	**Physiological adaptation (94, p. 80)**	**Race-car analogy (94, p. 80)**	**Example exercises for pace bowlers**	**Hypothesised transfer to bowling performance for beginner at RT**	**Hypothesised transfer to bowling performance for advanced at RT**
Functional Hypertrophy	General	↑ muscle cross-sectional area	↑ engine capacity	Squat, deadlift, lunge, bench press, pull-up	Low	Low
Strength	General	↑ motor-unit recruitment, firing rates, synchronisation, reflex potentiation	↑ engine power output E.g., optimal timing of all cylinders	Squat, deadlift, lunge bench press, pull-up	Low–medium	Low
Power	Special	↑ motor-unit recruitment, firing rates, synchronisation, reflex potentiation	↑ engine power output E.g., optimal timing of all cylinders	Jump squat, bench press throw, split squat jump, medicine ball throw	Low–medium	Medium
Power	Specific	↑ activation of synergists, ↓ co-contraction of antagonists	↑ conversion of power from engine to road E.g., effective transmission	Heavy- and light-ball bowling, sprinting	Low–medium	High

RT, resistance training; ↑, increase; ↓, decrease; Beginner, 0 years of structured resistance training experience; Advanced, more than 2 years of structured resistance training experience.

2.4.2 Pace bowling training interventions

Surprisingly, only one pace bowling training intervention has been published (2). Petersen, Wilson (2) recruited 20 senior club-standard pace bowlers, and divided them into two training groups (intervention or control) matched for bowling speed. A specific type of training, comprising heavy-, light-, and regular-ball bowling was employed for the intervention group. The control group bowled only with a regular-ball (156 g). Training was conducted three times per week for 10 weeks, where bowling volume was constant for both groups. The intervention group used a 2:1 ratio of heavy- and light-ball bowling compared to regular-ball bowling. This ratio was reported to be the most efficacious for developing shot put throwing velocity (95), and has been adopted in power-dominant sports (2, 27). The mass of the heavy-ball was progressively increased, and the mass of the light-ball was progressively reduced; both by 3.2–16% throughout the training intervention (Table 2.12) (2).

Table 2.12. The specific pace bowling training program for both groups (2).

Training weeks	**Deliveries per session**	**Deliveries per week**	**Ball weight (g) R-H-L-R**	**Delivery sequence of weighted balls**
Intervention group				
1-2	18	54	156-161-151-156	3-6-6-3
3-4	24	72	156-166-146-156	4-8-8-4
5-6	30	90	156-171-141-156	5-10-10-5
7-8	36	108	156-176-136-156	6-12-12-6
9-10	36	108	156-181-131-156	6-12-12-6
Control group				
1-2	18	54	156	NA
3-4	24	72	156	NA
5-6	30	90	156	NA
7-8	36	108	156	NA
9-10	36	108	156	NA

R, regular cricket ball (156g); H, heavy cricket ball; L, light cricket ball; NA, not applicable.

Following the training program, bowling accuracy diminished by 13% in the intervention group, but improved by 3% in the controls (2). The probability the intervention program was beneficial, trivial, or harmful for bowling accuracy was 1/48/51% (2) Although both groups improved bowling speed, a disparity of 0.75 $m{\cdot}s^{-1}$ (or 2.4%), was reported in favour of the intervention group. For a smallest worthwhile change (arbitrarily set) of 1.38 $m{\cdot}s^{-1}$ for bowling speed, the chances the intervention program was beneficial, trivial, or harmful for bowling speed was 1.0/99/<0.1% (2).

The gains in bowling speed reported with the intervention group was inferior to those reported in baseball pitching studies (4.4–6.7%) using a similar design (27, 96). The disparities between studies may be attributable to weekly throwing / bowling volume. For example, the baseball training intervention employed 198 throws per week (27), exceeding the 54–108 deliveries bowled per week in the pace bowling training intervention (2). Another reason for the discrepancy in speed may have been due to the lower intensity employed in the pace bowling intervention. The baseball pitching studies increased and decreased the mass of heavy- and light-balls by 20% respectively (27, 96), which was larger than the 3.2–16% employed in the pace bowling training intervention (2).

In an unpublished Master's thesis, the effects of a general / special pace bowling training intervention on bowling speed was investigated (90). Two groups performed the same training program, but the intervention group performed the concentric phase of each upper-body exercise with the intent to lift explosively. The training program comprised primarily of upper-body exercises, with some exercises for the lower-body and trunk region. The pace bowlers completed three sessions a week for eight weeks. The program included four mesocycles in attempt to maximise gains in bowling speed (Table 2.13).

Table 2.13. Periodised training program to enhance bowling speed (90).

Training weeks	**Phase / cycle**	**Intensity**	**Volume**
1-2	Conditioning	60-70% of 10 RM	3-4 sets x 10-15 reps
2-5	Base strength	80-90% of 10 RM	3-4 sets x 8-12 reps
5-7	Strength & power	≥ 90% of 1 RM	2-3 sets x 2-3 reps
7-8	Competitive	70-90% of 3 RM	2-3 sets x 5-7 reps

RM, repetition maximum; ≥, greater than or equal to; reps, repetitions.

A 0.69 $m\cdot s^{-1}$ improvement in bowling speed was reported for the intervention group (2.4%, small effect size = 0.284) while there was no change in the control group (0%). The increase in bowling speed could be considered small, and probably not noticeable to an elite batsman (2). It is likely however, that a longer training intervention would produce greater gains in bowling speed. Nevertheless, the intent to lift explosively during a strength-training exercise should be considered in future pace bowling training programs. Furthermore, this investigation supports the notion that strength and power gains are dependent upon the velocity of the exercise (97). The effects of this program on bowling accuracy, consistency of bowling speed, and consistency of bowling accuracy however, were not explored in this unpublished research.

2.4.3 Training interventions in other related sports

Throwing in baseball, handball, and javelin is similar to the pace bowling motion. In cricket, it is illegal to flex or extend the bowling-arm elbow by more than 15°, from when the arm is horizontally behind the bowler (98). Nevertheless, a general proximal-to-distal sequencing has been established in pace bowling (71, 99), baseball (100-103), javelin (104-109), and handball (110-112). The muscles activated in throwing and pace bowling could therefore be similar. Consequently, an investigation into the training interventions in throwing sports may reveal efficacious programs, which can be used in designing pace bowling training programs.

On review of the specific training interventions (Table 2.14), it appears that weekly throwing volume, irrespective of an increase or decrease in ball mass, is critical to improving throwing velocity. For example, no improvement in throwing velocity is observed when there is 54–75 throws per week with either a 20% increase (113), or 40–240% increase (114-116) in regular-ball mass (of a baseball). If the weekly throwing workload is raised to 120–216 throws per week however, then a larger ball mass appears to increase throwing velocity (96, 117, 118). For example, a 20% increase in ball mass enhances throwing velocity by 5.3% (96), but a 40–140% increase in ball mass augments throwing velocity by 14.6% (118). When lighter balls are employed however, throwing velocity develops by 2.0–6.7%, with a 20–25% reduction in ball mass (113, 119). A shortage of research currently exists on the training effects of bowling with a very heavy ball on pace bowling performance.

General resistance exercises combined with skills training appears to be efficacious for handball throwing performance (Table 2.15). For example, an eight-week training intervention comprising strength training and handball throwing improved throwing velocity in the standing throw by 33.3%, and in the 3-step running-throw by 42.5% (120). The control group however, only performed handball training and improved these throws by only 8.8% and 9.0% respectively. Therefore, adding strength exercises to skills practice is effective for enhancing throwing velocity. The effect of combining strength training with bowling training on pace bowling performance is not understood.

Table 2.14. The effects of specific resisted, assisted, and combined training interventions on throwing velocity in baseball and handball. Studies were included a control group was used, and between-group comparisons were made. The control group had to have also maintained throwing practice throughout the training intervention.

Studies	**Sport**	**Sex**	***n***	**Age**	**Standard**	**Length (wk.)**	**Throws per week**	**Ball mass (% of regular balls)**	**Intervention group ↑ or ↓ relative to control group**
Specific Resisted Training									
(96)	Baseball	M	10	16–18	HSV	10	150	5–6 oz. (20%)	↑ 4.0%*
(115)	Baseball	M	11	15.8 ± 1.0	HS	8	54–72	7 oz. (40%)	NR^{-}
(116)	Baseball	M	7	18–19	CF	6	75	10 oz. (100%)	NR^{-}
(114)	Baseball	M	36	14–19	HS	6	60	7–17 oz. (40–240%)	NR^{-}
Specific Assisted Training									
(96)	Baseball	M	10	16–18	HSV	10	150	5–4 oz. (20%)	↑ 5.5%*
(119)	Baseball	M	22	16–18	HS	10	187	4 oz. (20%)	↑ 3.3%*
(121)	Baseball	M	12	14.1 ± 0.9	HS	10	126–198	4.4 oz. (12%)	↑ 2.5%*
Specific Combined Training									
(27)	Baseball	M	150	16.6 ± 0.5	HS	10	198 (162–234)	6–5 oz. (5 wks.) (+20%) 4–5 oz. (5 wks.) (-20%)	↑ 4.4–6%*
(27)	Baseball	M	150	16.6 ± 0.5	HS	10	198 (162–234)	5–6–4–5 oz. (+20%, -20%)	↑ 4.4–6%*
(122)	Handball	F	7	18.3 ± 2.1	National	8	258	288 g (-20%) 432 g (+20%)	↓ 2.8%$^{-}$

NR, not reported; M, male; F, female; Wks., weeks; HSV, high school varsity; HS, high school; NS, not stated; CF, college freshmen; ↑, increase; ↓, decrease; ↔, no change; *, significant between-group difference ($p < 0.05$); $^{-}$, non-significant between-group difference ($p > 0.05$). Age reported as mean ± *SD*.

Table 2.15. The effects of general and special resistance training interventions on throwing velocity in baseball, handball, and water-polo. Studies were included if an active control group was used (structured or unstructured training), and between-group comparisons were made.

Studies	**Sport**	**Sex**	***n***	**Age**	**Standard**	**Length (wk.)**	**Type of RT sets × reps**	**Sessions per week**	**Load**	**Intervention group ↑ or ↓ relative to control group**
(123)	Handball	M	9	20.1 ± 0.6	Elite	10	General – 2 exercises Bench press, pull-over 2–3 × 2–6	2	80–95% 1-RM	Throw: RU ↑ 33.7%* Throw: no RU ↑ 24.3%$^{-}$
(122)	Handball	F	7	18.3 ± 2.1	STC	8	General – pulleys 3 × 6	3	85% 1-RM	↓ 5.0%$^{-}$
(124)	Handball	F	6	19.8 ± 2.0	STC	9	General – 1 exercise Bench press 3 × 5–6	3	85% 1-RM	Throw: RU ↑ 8.1%* Throw: standing ↑ 3.6%$^{-}$
(125)	Water polo	M	12	18.5	NS	8	General – 8 exercises 1 × 15: 50–60% 8-RM 1 × 15: 70–80% 8-RM 1 × 8–12-RM	3	Variable	↓ 2.1%$^{-}$
(123)	Handball	M	9	20.0 ± 0.7	Elite	10	General – 2 exercises Bench press, pull-over 2–4 × 3–6	2	55–75% 1-RM	Throw: RU ↑ 28.9%* Throw: no RU ↑ 19.5%$^{-}$
(116)	Baseball	M	7	18–19	CF	6	Special - pulleys 25 throws	3	10 lb	NR^{-}
(126)	Baseball	M	13	19.7 ± 1.3	College	8	Special & General 6 plyometric exercises 3 × 10–20	3	NS	↑ 1.9%*
(127)	Baseball	M	9	24.0 ± 4.0	NL	10	Special Bench press throws 3 × 6-8	1.5	30–50% 1-RM	↑ 2.4%*

NR, not reported; RU, run-up; RT, resistance training; RM, repetition maximum; M, male; F, female; STC, strength-training classes; NL, national league; HS, high school; CF, college freshmen; VC, varsity college; ↑, increase; ↓, decrease; ↔, no change; *, significant between-group difference ($p < 0.05$); $^{-}$, non-significant between-group difference ($p > 0.05$). Age reported as mean ± *SD*.

Similar improvements in throwing velocity occur when special and general baseball training interventions are matched by program length (Table 2.15). These gains in throwing velocity are less than those from specific training interventions (Table 2.14). In contrast, general training interventions in handball (Table 2.14) are superior in developing throwing velocity than specific training approaches (Table 2.15). Although a general proximal-to-distal sequencing exists in both baseball (100-103) and handball (110-112), a disparity would exist in their force-velocity profile (128), as the mass of the baseball (141.8 g) and handball (400 g) differ. Consequently, the baseball can be thrown with greater velocity, whereas the handball requires more force, and would thus travel slower. It would be more important therefore, to develop power for baseball throwing, and strength for handball throwing.

Although javelin throwing closely resembles the biomechanics of pace bowling, the mass of the men's javelin is 644 g heavier (≈4 × heavier) than the cricket ball. The baseball however, is 15 g lighter than the cricket ball, and is a closer match with pace bowling on the force-velocity spectrum. Pace bowling training interventions therefore, may be designed from efficacious baseball training programs. Of one concern is the ability of a pace bowler to match the number of throws exhibited by a baseball pitcher. Pace bowlers experience greater peak ground reaction forces in the delivery step than baseball pitchers (129), and this repetitive microtrauma is likely to be a cause of musculoskeletal injury (45). Most successful baseball-specific training interventions have prescribed 162–234 throws per week (Table 2.14). State-standard pace bowlers are at greater injury risk if they bowl less than 123 deliveries per week, and more than 188 deliveries per week (130). These pace bowlers therefore, could adopt a baseball-specific training intervention, but deliver 123–188 deliveries per week to remain in a 'safe workload zone'.

2.4.4 Training interventions on sprint performance

A positive relationship typically exists between bowling speed and run-up velocity (6, 12, 25, 43). Elite medium-fast bowlers reach 89% of their peak 30-m sprint speed during the final 5 m of their run-up (25), but employ a short run-up of 17.7 ± 4.1 m. Pace bowlers use their run-up to gradually accelerate to an optimal speed. Theoretically, a greater speed capacity would allow a bowler to run-up with a greater speed reserve (i.e., using less of their maximal speed), and bowl with less effort, and possibly greater control. This section, therefore, investigates the effectiveness of general, special, and specific resisted training interventions on maximum speed performance (Table 2.16).

Deane, Chow (131) showed that a hip-flexor training program can significantly reduce 36.6-m sprint time by 4.8% in physically active untrained individuals ($p < 0.05$). Improved hip-flexor strength may have developed hip-flexion range of motion and velocity, which may have increased stride length and stride frequency respectively. Deane, Chow (131) discovered the improvements in hip-flexion torque occurred in the first five weeks in the eight week program, and suggested that sprint-specific training could have been employed to realise further gains in maximum speed.

Upton (132) prescribed sprint-specific training in the form of sled towing, which significantly enhanced 36.6-m sprint velocity by 0.8%, relative to an active control group ($p < 0.05$). Conversely, Clark, Stearne (133) reported that weighted-vest and sled-sprint training reduced average velocity over 18.3–54.9-m by 0.8% and 1.1% respectively, albeit not significant ($p > 0.05$). The disparities in both studies could be attributed to gender (females vs. males), sessions per week (three vs. two), training duration (four weeks vs. seven weeks), and training distance (13.7 m vs. 18.3–54.9 m).

Sled sprinting enhances 10-m sprint velocity by 4.1%, but is ineffective over 20–40 m, and 40–50 m (134). Un-resisted sprint training is ineffective over 10–20 m, but is effective over longer distances of 20–40 m, and 40–50 m (134), although not all are in agreement (132). The disparity between studies (132, 134) may be explained by the sled load (5 kg vs. 12.6% body mass), sprint length (20–50 m vs. 13.7 m), and the sample (male students vs. female soccer athletes).

Sprinting with a weighted-vest induces slightly greater gains in maximum speed to a sled, but both remain slightly inferior to un-resisted sprint training (133). A more upright trunk angle occurs with weighted-vest sprinting, and is suggested to increase the braking force by a longer foot-strike from the athlete’s centre of mass (133). Weighted-vest sprinting therefore could be beneficial to for pace bowlers, as they encounter large vertical and horizontal ground reaction forces. Furthermore, developing this braking capacity could enhance the magnitude and rate of kinetic energy transfer to the bowling hand, and therefore develop bowling speed.

Table 2.16. The effects of general, special, and specific resistance training interventions on maximum speed performance (0–30 m +). Studies were included if an active control group was employed (structured or unstructured training), and between-group comparisons were made.

Studies	**Sex**	***n***	**Age**	**Standard**	**Length (wks.)**	**Type of RT**	**Sessions per week**	**Sets × reps load (RM)**	**Intervention group ↑ or ↓ relative to control group**
(131)	M F	13 11	21.1 ± 1.9 22.2 ± 3.9	PA	8	General – hip flexor strengthening	3	2 × 10, 1 × failure	36.6 m T ↓ 4.8%* – M 36.6 m T ↓ 2.8%* – F
(135)	M	22	18–22	PE students	9	General – 11 exercises and one sprint session per week	2	3 × 10–15 → 6–3 10 → 3-RM Some ex's fixed at 10-RM and 15-RM	100 m T ↓ 0.9%$^-$
(135)	M	21	18–22	PE students	9	General & Special – 10 exercises, mostly plyometric. One sprint session per week	2	1–4 × 5–20 BW	100 m T ↓ 2.4%$^-$
(133)	M	7	19.7 ± 1.0	Lacrosse	7	Specific – weighted sled sprint training	2	2–4 × 18.3–54.9 m 10.2% BW	18.3–54.9 m V ↓ 1.1%$^-$
(133)	M	6	19.8 ± 0.9	Lacrosse	7	Specific – weighted vest sprint training	2	2–4 × 18.3–54.9 m 18.5% BW	18.3–54.9 m V ↓ 0.8%$^-$
(132)	F	9	19.6 ± 0.9	College Soccer	4	Specific – weighted sled sprint training	3	10 × 13.7 m 12.6% BW	36.6 m V ↑ 0.8%*

PA, physically active; PE, physical education; RT, resistance training; wks., weeks; M, male; F, female, RM; repetition maximum; BW, bodyweight; max, maximum; T, time; V, velocity; ↑, increase; ↓, decrease; →, progressed to; *, significant between-group difference ($p < 0.05$); $^-$, non-significant between-group difference ($p > 0.05$). Age reported as mean ± *SD*.

2.4.5 Conclusions

Only one published study to date has investigated the effects of a specific pace bowling training intervention on bowling speed and accuracy. This intervention employed heavy-, light-, and regular-ball bowling, with mean improvements in bowling speed to be 0.75 $m \cdot s^{-1}$ (or 2.4%), but at the expense of poorer bowling accuracy. The training effect of using a heavier ball on bowling performance has not been explored. Heavy-ball bowling could enhance power (via an improvement in strength) to a greater extent than regular-ball bowling. An unpublished Master's thesis discovered that lifting explosively in the concentric phase of each strength and power exercise improves bowling speed by 0.69 $m \cdot s^{-1}$.

Due to the paucity of pace bowling training interventions, an examination of training interventions of related sports motions (e.g., baseball pitching, handball, javelin, sprinting) is useful. These interventions can be categorised as general, special, and specific. Specific baseball training interventions (i.e., heavy-, light-, and regular-ball pitching) appear to be more efficacious for developing throwing velocity than general or special training interventions. Moreover, baseball pitching is the closest match to pace bowling on the force-velocity curve. Future pace bowling training programs therefore, could adopt successful specific baseball pitching programs to enhance bowling speed, but be mindful of bowling volume.

Developing maximum speed may allow bowlers to run-up with less effort, and bowl with greater control. Strengthening the hip flexors appears to develop maximum speed, along with short sled sprints. Weighted-vest sprinting may be beneficial for pace bowlers, as they may train their ability to decelerate during the step-length phase, which is related to bowling speed. The effect of a sprint training intervention on pace bowling performance and approach speed however, has not been studied.

2.5 Post-activation potentiation

Post-activation potentiation (PAP) refers to the acute enhancement of the neuromuscular system following a conditioning contraction (136, 137). Post-activation potentiation enables muscles to produce greater peak torque and to reach peak torque faster (138). This phenomenon has been exploited in attempt to acutely enhance sprinting (139-148) and throwing (114, 149, 150) performance, through the adoption of general, special, or specific conditioning contraction protocols. The PAP phenomenon could be exploited in the warm-up to enhance pace bowling performance, or be used in complex or contrast training interventions to develop power output (151). For example, heavy- or light-ball bowling could be used to acutely develop power in the bowling-arm and trunk muscles prior to training or a match. However, this has not been investigated.

Potentiation protocols could acutely enhance a bowler's speed capacity, and thereby allow a bowler to run-up with less effort and bowl with greater control. Section 2.4 covered specific training interventions that involved some studies exploiting the PAP. This section however, briefly explains the mechanisms of PAP, and its acute effects on sprinting and throwing performance; as these activities relate to pace bowling.

2.5.1 Mechanisms of post-activation potentiation

Myosin regulatory-light-chain phosphorylation is proposed as the primary mechanism of PAP (152, 153). The regulatory-light-chain is located at the hinge region of the myosin cross-bridge (Figure 2.8). An action potential permits regulatory-light-chain phosphorylation, and causes calcium to discharge from the sarcoplasmic reticulum (154). Twitch peak torque increases with greater phosphate accumulation at the regulatory-light-chain binding site (Figure 2.9) (152). Phosphorylation is therefore suggested to move the myosin head closer to the actin binding site (155), which permits faster cross-bridge attachment. Consequently, twitch peak torque increases during submaximal calcium concentrations (156).

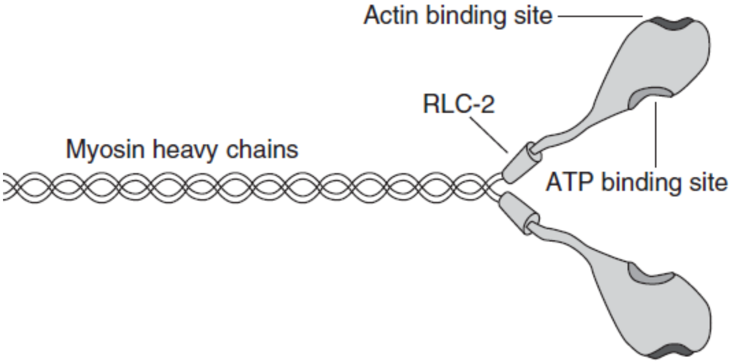

Figure 2.8. The regulatory-light-chain branches from the heavy chain, and has the capacity to join with a phosphate molecule, thus causing the myosin head to change shape (137).

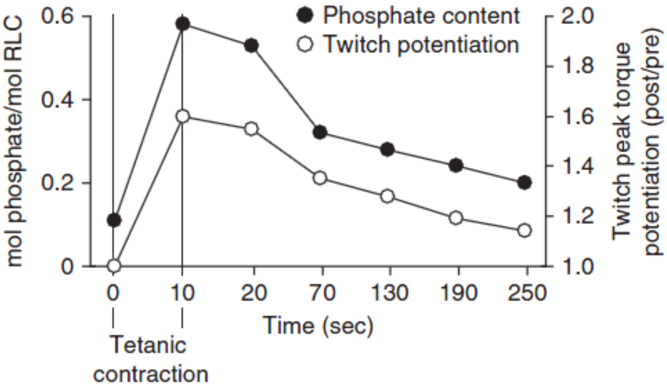

Figure 2.9. Phosphate content per regulatory-light-chain unit is elevated immediately after a 10-s pre-conditioning tetanus, and thus augments twitch peak torque (152).

The increased recruitment of higher order motor units is another mechanism of PAP (137), and is measured by the H-wave (157). The H-wave represents the signal from the Ia afferents to the spinal cord, where it is transmitted to the homonymous efferent fibres towards the muscle (137). Post-activation potentiation in this sense occurs through an increased synaptic efficiency between Ia terminals and α-motoneurons of the homonymous muscle (158). That is, for the same pre-synaptic potential there is an increased post-synaptic potential (137). Furthermore, H-wave amplitude is resultant of the number and size of recruited motor units, and is affected by: motoneuron excitability, variation in the intrinsic properties of the motoneurons, and the volume of neurotransmitter release (157).

2.5.2 Potentiation of sprinting performance

Most PAP research in sprinting has employed general conditioning contraction protocols (Table 2.17). These investigations have produced conflicting results, as five of the 10 general protocols significantly enhanced maximum speed performance by 1.1–2.9% ($p < 0.05$) (139, 141). The larger the intensity of the general conditioning contraction protocol, the greater the maximum speed performance (141). Conversely, special and specific conditioning contraction protocols do not significantly enhance maximum speed performance ($p > 0.05$) (145, 148). Although sled sprints with a load equivalent to 20% or 30% body mass is superior in potentiating maximal-sprint velocity compared to 10% load, these loads produce similar gains in maximal velocity to un-resisted sprinting (148).

Table 2.17. The acute effects of general, special, and specific potentiation protocols on maximum speed performance (>30 m). Studies were only included if a within-condition or between-condition comparison was made.

Studies	**Sex**	***n***	**Age**	**Standard**	**Relative strength**	**CCP type**	**Design#**	**Control supplement$**	**EC ↑ or ↓ relative to CC**
(139)	F	12	20.8 ± 1.9	PA	1.1 × BW 4-RM half squat	General	Warm-up of 4-min 4-min active rest 100-m sprint 4-min active rest *1 × 4 at 4-RM half squat* *9-min active rest* 100-m sprint		100-m T ↓ 1.1%*
(141)	M	12	22.4 ± 1.0	Elite soccer	NR	General	Warm-up of 5-min cycling and 4-min walking *2 × 4 at 60% 1-RM parallel back squat* *2-min rest between sets* *4-min walking* 40-m sprint		40-m T ↓ 1.1%*
(141)	M	12	22.4 ± 1.0	Elite soccer	NR	General	Warm-up of 5-min cycling and 4-min walking *2 × 4 at 70% 1-RM parallel back squat* *2-min rest between sets* *4-min walking* 40-m sprint		40-m T ↓ 1.8%*
(141)	M	12	22.4 ± 1.0	Elite soccer	NR	General	Warm-up of 5-min cycling and 4-min walking *2 × 4 at 85% 1-RM parallel back squat* *2-min rest between sets* *4-min walking* 40-m sprint		40-m T ↓ 2.9%*
(144)	M	12	22.4 ± 3.2	Trained track athletes	1.8 × BW 1-RM back squat	General	Warm-up of 5-min cycling and dynamic stretches *3 × 3 s – MVIC knee extension at 90°* *2-min rest between sets* *4-min rest* 30-m sprint	*8-min rest*	30-m T ↑ 0.7%-

(144)	M	12	22.4 ± 3.2	Trained track athletes	1.8 × BW 1-RM back squat	General	Warm-up of 5-min cycling and dynamic stretches *3 × 3 s – MVIC squat at 120–130° knee flexion* *2-min rest between sets* *4-min rest* 30-m sprint	*8-min rest*	30-m T ↑ 1.2%$^{-}$
(144)	M	12	22.4 ± 3.2	Trained track athletes	1.8 × BW 1-RM back squat	General	Warm-up of 5-min cycling and dynamic stretches *1 warm-up set of 10-RM* *1 warm-up set of 5-RM* *1 × 3 at 3 RM - back squat (depth NR)* *4-min rest* 30-m sprint	*8-min rest*	30-m T ↑ 0.7%$^{-}$
(145)	M	15	20.8 ± 1.0	NCAA Division III football	Strongest (*n* = 7) = 2.0 × BW for 1-RM back squat Weakest (*n* = 8) = 1.7 × BW for 1-RM back squat (depth NR)	General	Warm-up of 5-min cycling *4-min walk* *1 × 3 at 90% of 1-RM back squat (depth NR)* 4-min walk 40-m sprint		30-m T ↓ 0.5%$^{-}$ 40-m T ↓ 0.9%*
(147)	M	10	22.3 ± 0.8	Football, weightlifting, track and field	1.6 × BW for 1-RM parallel back squat	General	Warm-up of 5-min cycling *4-min walk* *1 × 5 at 30% of 1-RM parallel back squat* *2-min rest* *1 × 4 at 50% 1-RM parallel back squat* *2-min rest* *1 × 3 at 70% 1-RM parallel back squat* 4-min walk 3 × 40-m sprint 3-min rest between sprints		30–40-m V ↑ 2.3%*

(147)	M	10	22.3 ± 0.8	Football, weightlifting, track and field	1.6 × BW for 1-RM parallel back squat 1-RM parallel front squat was estimated from 1-RM parallel back squat.	General	Warm-up of 5-min cycling *4-min walk* *1 × 5 at 30% of 1-RM parallel front squat* *2 min rest* *1 × 4 at 50% 1-RM parallel front squat* *2 min rest* *1 × 3 at 70% 1-RM parallel front squat* 4-min walk 3 × 40-m sprint 3-min rest between sprints		30–40-m V ↓ 0.7%$^{-}$
(145)	M	15	20.8 ± 1.0	NCAA Division III football	Strongest (*n* = 7) = 2.0 × BW for 1-RM back squat Weakest (*n* = 8) = 1.7 × BW for 1-RM back squat (depth NR)	Special	Warm-up consisting of 5 mins cycling *4-min walk* *1 × 3 at 30% of 1-RM back squat – jump squat* 4-min walk 40-m sprint		30-m T ↓ 0.3%$^{-}$ 40-m T ↓ 0.6%$^{-}$
(148)	M F	22	23.0 ± 5.0	AF	NM	Specific	Standard bike warm-up (time NR) 4-min walk 36.6-m sprint 4-min walk *18.3-m sled sprint – 10% BW load* 4-min walk 36.6-m sprint	*18.3-m sprint – BW*	36.6-m T ↑ 41.7%$^{-}$

(148)	M F	22	23.0 ± 5.0	AF	NM	Specific	Standard bike warm-up (time NR) 4-min walk 36.6-m sprint 4 min walk *18.3-m sled sprint – 20% BW load* 4-min walk 36.6-m sprint	*18.3-m sprint – BW*	36.6-m T ↔$^{-}$
(148)	M F	22	23.0 ± 5.0	AF	NM	Specific	Standard bike warm-up (time NR) 4-min walk 36.6-m sprint 4-min walk *18.3-m sled sprint – 30% BW load* 4-min walk 36.6-m sprint	*18.3-m sprint – BW*	36.6-m T ↓ 8.3%$^{-}$

$^{\#}$, experimental condition performed everything in the design column but the control condition did not perform what was written in italics; $^{\&}$, the control condition might have supplemented the activity (written in italics) in the design column; CCP, conditioning contraction protocol; EC, experimental condition; CC, control condition; NCAA, national collegiate athletic association; MVIC, maximal voluntary isometric contraction; AF, anaerobically fit; PA, physically active; NR, not reported, NM; not measured; M, male; F, female; RM, repetition maximum; BW, bodyweight; min, minutes; CMJ, countermovement jump; T, time; V, velocity; ↑, increase; ↓, decrease; ↔, no change; *, significant between-condition interaction ($p < 0.05$); $^{-}$, non-significant between-condition interaction ($p > 0.05$). Age reported as mean ± *SD*.

2.5.3 Potentiation of throwing performance

The potentiation research in throwing has comprised specific conditioning contraction protocols in attempt to acutely enhance throwing velocity (114, 149, 150). One study recruited 50 university baseball pitchers to trial an overloaded throwing warm-up protocol (149). This study employed a repeated measures design, where 10 participants acted as their own controls, and warmed-up exclusively with a regular-mass baseball (149). Both conditions involved 10 maximal-effort throws with a regular baseball (5 oz.) prior to a warm-up, and after the conditioning contraction protocol. The warm-up comprised 15 throws with a progressive increase in intensity. Ten maximal-effort throws immediately followed, with an 11-oz baseball (experimental condition) or a 5-oz baseball (control condition). There was an immediate improvement in throwing velocity, but throwing accuracy was compromised for the experimental condition. Furthermore, a significant group × throw interaction was observed for throwing accuracy ($p < 0.05$), but not for velocity ($p > 0.05$). That is, heavy-ball throwing acutely impaired accuracy, but did not actually enhance throwing speed.

The findings from Van Huss, Albrecht (149) are similar to Straub (114), who recruited 60 male high school students. In this investigation, subjects were divided into three groups, and performed 20 maximal-effort throws with a 10-oz (group 1), 15-oz (group 2), or 5-oz (group 3) baseball, following a warm-up. Afterwards, 30 maximal-effort throws were performed with a 5-oz baseball, and velocity and accuracy were measured. This study presented no disparities in throwing velocity and accuracy between groups. The overloaded groups however, displayed an initial impairment in throwing accuracy. The negative effects of overloaded throwing on accuracy, reported in both studies (114, 149), may be due to fatigue or negative transfer between throwing with heavy and regular baseballs. Negative transfer occurs when the two performance situations are similar, but movement characteristics differ (159, 160). Negative transfer could have occurred due to a change in segmental sequencing coordination / timing of movement (159, 160), which is quite likely when throwing a ball that is overloaded in mass by 100% (10 oz. ball) and 200% (15 oz. ball) respectively.

A more in-depth investigation was conducted with only eight university baseball pitchers (150). This study comprised eight randomised warm-up conditions in a repeated-measures design. These conditions involved six or 18 maximal-effort throws, with a 5-oz baseball (145 g), lighter baseball (130.5 g), heavy baseball (159.5 g), or a combination of all three. Immediately after the warm-up, five maximal-effort throws were performed with the regular baseball. This study indicated that six or 18 throws with a lighter baseball were most effective in acutely enhancing throwing velocity by 1.27 $m \cdot s^{-1}$, than the other conditions. There were no differences in throwing accuracy across all conditions.

2.5.4 Conclusions

Post-activation potentiation has been exploited to acutely enhance maximum-speed and throwing performance. Most of these studies have inferred PAP, without directly measuring it through electromyography or ultrasonography. Nevertheless, general conditioning contraction protocols of higher intensity are more effective at augmenting maximum speed than lower intensities. Specific conditioning contraction protocols however, are not effective in acutely potentiating maximum speed. This observation might be due to the use of a sled, which is designed to develop speed-acceleration, and not maximum speed. To date, there is no research on the acute effects of weighted-vest sprinting on speed-acceleration or maximum speed.

Warming-up with a heavy-ball does not enhance throwing velocity but impairs throwing accuracy. Throwing with a 10% lighter ball however, can significantly increase throwing velocity by 1.27 $m \cdot s^{-1}$ ($p < 0.05$), without impairing throwing accuracy. These findings suggest that strategies that maximise the velocity of the throwing-arm may be more beneficial than those that maximise strength development. Throwing a heavier ball (i.e., greater than 20% increase in ball mass) may result in negative transfer to throwing accuracy by altering segmental sequencing coordination. The acute effects of heavy-ball bowling on pace bowling performance have not been investigated.

2.6 Pace bowling performance assessments

The first published pace bowling assessment was part of a cricket skills test-battery, designed to evaluate cricket ability for juniors (1). The pace bowling test only measured bowling accuracy, by comprising a rectangular scoring system on the pitch (Figure 2.10). One hundred and fifty-five junior cricketers performed the bowling assessment. The participants were required to deliver 10 balls, aiming for a perfect score of 100 points in total. The results of this study indicated the junior cricketers averaged 57 points on this test. Additionally, this test was deemed reliable ($r = 0.85$, $p < 0.05$), with a 19.8% coefficient of variation, and a slight learning effect between the first two trials. The Pearson’s correlation coefficient was used to determine test-retest reliability, but it cannot detect systematic error (3). Furthermore, ecological validity of the pace bowling test is questionable. That is, a target on the cricket pitch does not account for any deviations that may occur to a cricket ball during flight (swing) or after bounce from the pitch (seam) (21). This assessment of bowling accuracy implies that a “good” delivery in the assessment could in fact be “poor” in a match. Furthermore, the rectangular targets are centred on the pitch, which does not account for left or right hand batsmen. Including more deliveries would have physically tested the bowlers, and provided a better measurement of their bowling accuracy. Although novel, this pace bowling test did not measure bowling speed; a quality that reduces the reaction time of the batsman (161), and separates junior bowlers of different standards (30).

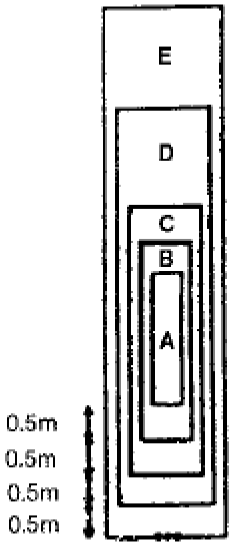

Figure 2.10. The rectangular zones in the pace bowling assessment (1).

A more comprehensive pace bowling test was devised upon recognition of previously discussed limitations (21). Fourteen premier-grade bowlers performed eight overs, and were assessed on their bowling speed and accuracy. Bowling accuracy was measured through use of three white rectangular scoring zones on a black cotton sheet suspended overhead, 30 cm in-front of the batsman’s stumps (Figure 2.11). A rectangular target on the pitch was used for a full length delivery (i.e., “yorker”). A scoring system was employed, and scores of 100, 50, 25, and 0 points were given per delivery, dependent on ball strike. Although a “live” batsman was not employed, this test assessed the bowler’s accuracy to a right-hand batsman. The results indicated that bowling speed and accuracy were constant throughout the test. This test may have been improved if targets to a left-hand batsman were included, as well as a slower-ball delivery, and a short pitched delivery (i.e., “bouncer”). The test-retest reliability of bowling speed and accuracy was not examined.

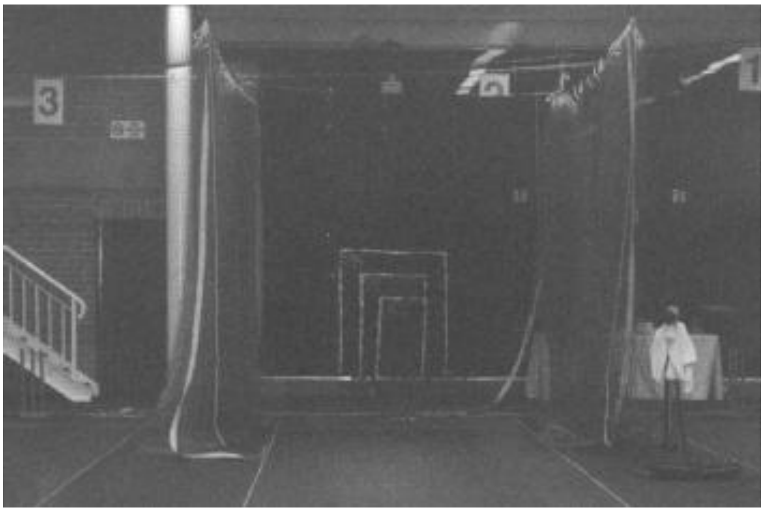

Figure 2.11. The accuracy set-up in the pace bowling test (21).

A pace bowling test comprising six targets was developed to account for right- and left-hand batsmen, and included a bouncer and yorker target (29). A grid-based vertical target sheet was used, positioned at the batting crease (Figure 2.12). Each square of the grid was allocated points in relation to a particular target, and scores varied from 100, 90, 75, 50, 25, and 0 points, depending on the location of ball strike. Bowlers delivered four balls at each target type, but never to the same target consecutively. This study calculated the consistency of accuracy by determining the spread of pitched deliveries on the wicket. This methodology however, was not applied to the grid-based vertical target sheet. The authors acknowledged the scoring system was not sensitive enough for the measurement of bowling accuracy. This test possessed strong predictive validity, as it was capable of revealing differences in bowling speed, accuracy, and consistency of accuracy between bowlers of various standards (i.e., international, first class, and non-first class) (Table 2.18).

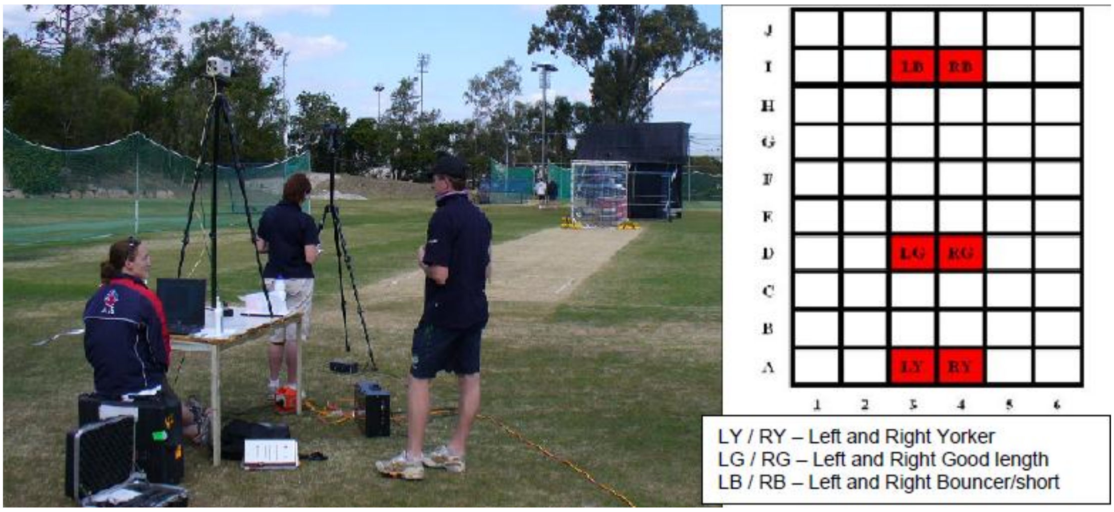

Figure 2.12. Vertical target sheet and overall set-up of the pace bowling test (29).

Table 2.18. Bowling performance data across different playing standards (162).

	International (*n* = 6)	**First class (*n* = 12)**	**Non-first class (*n* = 24)**
Bowling speed ($km{\cdot}h^{-1}$)	124.9	123.8	116.0
Bowling accuracy (%)	52.6	47.2	36.6
Consistency of accuracy (cm)	77.5	85.9	106.3

Although the previous test included six targets, only four deliveries were bowled to each, thereby reducing the precision of the bowling accuracy score. To counter this limitation, the previous test was modified to include only three targets, but 10 deliveries bowled at each (26). Furthermore, a rear-projected two-dimensional image of a right handed batsman was superimposed onto the target sheet (Figure 2.13). Although this test measured bowling accuracy through a points-system, it included more precise measures such as: radial error (bowling accuracy), centroid error (bias), and bivariate variable error (consistency of accuracy). Radial error was defined as the absolute distance from ball strike to the centre of the target. Centroid error was calculated by obtaining the mean *x* and *y* coordinates for each ball strike. Bivariate variable error however, was computed as the absolute distance to a bowler's own midpoint for each target, averaged across all deliveries. These data on bowling accuracy measures were calculated from digitised footage, collected at 25 frames per second. A low frame rate could have reduced the likelihood of detecting ball strike, especially with faster bowlers. Nevertheless, this bowling test was capable of distinguishing elite fast bowlers from junior pace bowlers, with reference to bowling speed (5.6 km$\cdot$h^{-1}), bowling accuracy score (points system), and centroid error. Although this test possessed good level of construct validity, the test-retest reliability of each measure was not reported. The "noise" of each performance measure is therefore obscure, and the efficacy of a training program cannot be properly determined.

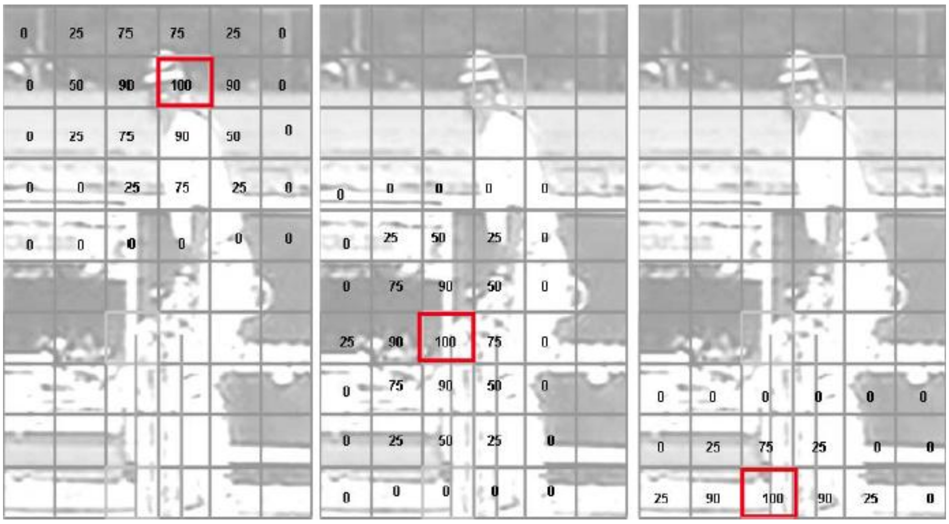

Figure 2.13. The vertical grid-based scoring sheet, with a superimposed two-dimensional right-hand batsman. The points and red squares were invisible to the bowler (26).

Recently in an unpublished investigation, O'Grady (30) explored the predictive validity and test-retest reliability of a novel four-over pace bowling test. A vertical target sheet was positioned at the batsman's end similar to previous pace tests (26, 29), but instead of a grid-based scoring system, five circular targets were employed. The frequency of deliveries at each target was altered to better replicate a traditional match scenario. For example, more deliveries were directed towards off stump, with less bouncers and yorkers than previously prescribed (162). A slower-ball delivery however, was incorporated into the test for the first time. A "live" batsman was also used, which was also a major improvement on previous pace bowling tests, and enhanced the ecological validity of the test. The batsman was instructed to evade the delivery after it was released. More deliveries were bowled to a right-hand batsman than a left-hand batsman, as it was suggested the former were more common in cricket. The footage collected for digitisation was sampled at 125 frames per second, another improvement from previous research (26). Although this fast bowling test was deemed reliable (Table 2.19), it was conducted with low numbers (n = 7). Furthermore, the consistency of bowling accuracy was calculated as the *SD* of bowling accuracy, which is less precise than the bivariate variable error measurement (26).

Table 2.19. Test-retest reliability of the performance measures in seven community-standard pace bowlers (30).

	Mean ± *SD* trial 1	**Mean ± *SD* trial 2**	**ICC**	**CV (%)**
Bowling speed (km·h^{-1})	100.6 ± 11.4	100.2 ± 12.0	0.995	0.9
Bowling accuracy (cm)	47.4 ± 8.0	46.3 ± 10.2	0.814	8.1
Consistency of bowling accuracy (cm)	28.8 ± 7.0	26.5 ± 6.5	0.920	5.7

ICC, intraclass correlation coefficient; CV, coefficient of variation.

The pace bowling test was considered valid, as it was capable of distinguishing between high-performance (n = 8) and low-performance (n = 10) pace bowlers in terms of bowling speed, but not bowling accuracy or consistency of bowling accuracy (Table 2.20).

Table 2.20. Differences between elite and sub-elite junior pace bowlers in performance measures (30).

	EJ (n = 8) Mean ± *SD*	**SEJ (n = 10) Mean ± *SD***	**Difference from EJ (%)**	***p* Value**	***d***
Bowling speed (km·h^{-1})	115.0 ± 4.4	106.6 ± 6.9	-7.8	0.009*	1.45
Bowling accuracy (cm)	44.0 ± 10.1	46.6 ± 9.2	5.6	0.580	0.27
Consistency of bowling accuracy (cm)	24.3 ± 6.7	26.4 ± 3.5	7.9	0.403	0.39

EJ, elite-junior; SEJ, sub-elite junior; *p* Value, determined from independent samples *t*-test; *d*, Cohen's effect size; *, significance was set at $p < 0.05$.

2.6.1 Conclusions

Pace bowling tests have varied in design and have measured different components of bowling performance. Regardless, it appears that bowling speed separates high performing pace bowlers from low performing pace bowlers. The ability to bowl consistently fast however, has not been assessed before. Bowling accuracy and the consistency of bowling accuracy have often been neglected in bowling assessments. Only one published study to date has investigated the test-retest reliability, but only for bowling accuracy. The evaluation of test-retest reliability comprised a Pearson’s correlation coefficient and coefficient of variation; the former cannot detect systematic error and the intraclass correlation coefficient should have been used. Future pace bowling tests therefore, should assess bowling speed, consistency of bowling speed, bowling accuracy, and consistency of bowling accuracy, and report the test-retest reliability of each measure using the intraclass correlation coefficient, coefficient of variation, and standard error of measurement.

2.7 The speed-accuracy trade-off

The speed-accuracy trade-off, described by Fitts (163), states that movement time will increase with greater distance between two targets, or when the width of the two targets are narrower. In a sports setting, the speed-accuracy trade-off indicates that an increase in speed of movement results in a loss of accuracy or vice versa. For example, bowlers may strive to bowl a maximal-effort delivery, but compromise bowling accuracy. In cricket practice, pace bowlers are sometimes coached to “slow down, [and] bowl a line and length” (164, p. 16), to ensure bowling accuracy is not neglected at the importance of bowling speed.

Although Fitts’ law applies to skills requiring the hand to move from one position to another (e.g., reciprocal tapping, disc and pin transfers) (163), it does not apply to throwing-related motions. When a projectile is thrown, the performer cannot control its direction or velocity (165). Therefore, a modification of Fitts’ Law, known as the impulse-variability theory, was proposed (166). This theory suggests that the final spatial location of the throwing-limb depends on the variability in accelerative forces, which act perpendicular to the intended movement direction (167).

Sherwood and Schmidt (168) discovered an inverted-U function between force variability and force magnitude. That is, the maximum variability in dynamic and isometric force production occurred at 65% of a subject’s capacity; but was considerably smaller at 92% of maximal force (168). These findings might at first indicate that throwing with maximal force results in less impulse-variability, which may improve throwing accuracy. Unfortunately though, a temporal limit on force production was not enforced by Sherwood and Schmidt (168). To account for this limitation, Newell and Carlton (169) reported a negatively-accelerated function existed between force magnitude and variability during an isometric contraction (169).

To observe if a similar trend existed with dynamic contractions, the effects of force variability in six various loads with constant dynamic peak force were investigated (170). The greatest variability in force occurred in the lowest four loads, while the largest two loads displayed less variability. Others have observed that when movement speed increases (or movement time decreases), there is lower variability in force production (171-174). Additionally, Urbin, Stodden (167) identified the greatest variability in throwing velocity occurred at 40–60% of perceived maximal-effort, and was less variable as effort approached maximum. Note, there was no speed-accuracy trade-off present in this study (167), which is in agreement with pace bowling research that measured both speed and accuracy (Table 2.21) (25, 26). In these studies (25, 26) however, bowlers were instructed to deliver at “match intensity”, where speed and accuracy received equal importance. With this instruction, it is unlikely that a trade-off between speed and accuracy (i.e., a negative correlation) would exist, as bowlers place equal importance on both performance measures.

Brees (175) discovered when bowlers were instructed to run-up faster than usual; they bowled faster, but at the cost of bowling accuracy. Conversely, when bowlers were instructed to slow their run-up below their self-selected intensity, they bowled more accurately, but slower. Although bowling speed improved with a faster than optimal run-up, it does not necessarily indicate an improvement in pace bowling performance, as accuracy diminished. Therefore, it appears the “match intensity” delivery instruction could be important for ensuring both speed and accuracy is optimised.

The speed-accuracy trade-off has not been assessed when bowlers have been instructed to deliver a variety of deliveries (i.e., match-intensity, maximal-effort, slower-ball) (11, 13). This gap is noteworthy, as a speed-accuracy trade-off could be present, and the maximal-effort delivery instruction might be counterproductive for developing bowling accuracy. Conversely, if there is no speed-accuracy trade-off when delivering with maximal-effort, then this implies that bowlers should be instructed to bowl with maximal-effort to best develop bowling speed, whilst not impairing bowling accuracy.

Table 2.21. The speed-accuracy trade-off examined in fast bowling research.

Author	**Sex**	***n***	**Age**	**Standard**	**Correlation between speed and accuracy**	**Conclusion**
(175) as cited in (38)	M	7	NR	College	Accuracy measured as scoring based system (1) Run-up velocity was manipulated so that bowlers ran-up at 1) normal speed, 2) fast, and 3) slow. A positive correlation was revealed between run-up speed and ball speed (*r* NR, $p < 0.05$). A negative correlation was revealed between run-up speed and bowling accuracy (*r* NR, $p < 0.05$).	A trade-off might be present between speed and accuracy, but only when a bowler chooses a faster run-up
(25)	M	6	23.0 ± 3.0	National	Trivial insignificant relationship ($r = 0.05$) between ball speed and accuracy, across short, good, and full length deliveries. Accuracy measured through points system on grid based target	No speed-accuracy trade-off present
(30)	M	25	15–26	State and regional junior s	Accuracy measured as radial error Consistency of accuracy measured as the *SD* of accuracy. Small negative relationship ($r = -0.25$, $p = 0.22$) between speed and accuracy across entire group.	No speed-accuracy trade-off present
(26)	M M M	8 12 12	29.1 ± 3.2 21.2 ± 3.3 17.3 ± 0.7	National Emerging Junior	Accuracy measured as radial error No significant difference ($p = 0.87$) between groups and the speed-accuracy relationship $r = -0.11$ ($p = 0.28$) – Short length delivery $r = 0.37$ ($p = 0.06$) – Good length delivery $r = -0.09$ ($p = 0.31$) – Full length delivery	No speed-accuracy trade-off present, irrespective of playing standard and delivery type

NR, not reported.

2.7.1 Conclusions

The speed-accuracy trade-off implies that as bowlers attempt to increase their delivery speed, their bowling accuracy will be poorer. Most pace bowling assessments have instructed bowlers to deliver at match-intensity, and no speed-accuracy trade-off has been reported (11, 13). Bowlers in this instance may place equal importance on speed and accuracy, and therefore no trade-off is observed. In cricket, pace bowlers sometimes perform maximal-effort and slower-ball deliveries. Furthermore, it appears that an artificial increase or decrease in approach speed can result in worse and better bowling accuracy respectively. There may be less force variability with a maximal-effort delivery, and therefore greater precision of the moment of ball release. If true, then bowlers could be instructed to bowl at maximal-effort without compromising bowling accuracy. The speed-accuracy trade-off however, has not been explored across a variety of delivery instructions. This thesis will aim to explore this gap.

2.8 Summary

There are many bowling kinematic variables that relate to bowling speed, such as: run-up velocity, delivery step length, and front-knee extension angle at front-foot contact and at ball release. These variables may be influenced by lower-body strength, reactive strength, power, and flexibility. Pace bowling is an intermittent ballistic activity involving moderate to high work rates, and modest lactate production. It is obvious that physical fitness is important to the pace bowler. The literature however, has not thoroughly investigated the interplay between physical qualities, bowling kinematics, and bowling performance measures. Determining these relationships will assist sport scientists and coaches to develop evidence-based pace bowling training interventions.

Surprisingly, only one pace bowling training intervention study has been published. This intervention employed heavy-, light-, and regular-ball bowling, and observed small improvements in bowling speed, but compromised bowling accuracy. The training program was designed from a successful baseball pitching intervention. This specific form of training exploits the post-activation potentiation phenomenon, where the heavy- or light-ball bowling is employed to improve motor unit recruitment and thus power production with a regular ball. If prescribed correctly, heavy- and light-ball bowling may acutely enhance performance with a regular-ball, which could manifest to greater training adaptations in performance. If prescribed incorrectly, a negative transfer to performance may occur. Regardless, the acute effects of heavy-ball bowling on pace bowling performance, and the magnitude of this acute change following a training program is not understood.

Pace bowling assessments have evolved in design, but not all performance measures have been evaluated. Bowling accuracy has typically been calculated by a points system, which is practical for coaches and bowlers, but is not precise. Although a recent investigation included radial error, centroid error, and bivariate variable error as more precise bowling accuracy measures, the test-retest reliability of these were not reported, similar to other pace bowling assessments. The efficacy of a training intervention cannot be determined unless the “noise” of each measure is known.

Instructing pace bowlers to bowl at “match intensity” could be the safest option to maintain or improve performance. However, further research is required to investigate the speed-accuracy trade-off when bowlers are instructed to perform a variety of balls at different delivery instructions.

Chapter 3 – Study 1:
The Test-Retest Reliability of a Novel Pace-Bowling Test

3.1 Background

In cricket, pace bowlers use their bowling speed, accuracy, and consistency to assist in dismissing a batsman. The faster a bowler can deliver the ball, the less time a batsman has to react and play an appropriate shot (9). Note, that a ball delivered at 44.4 $m{\cdot}s^{-1}$ reaches the batsman in ≈0.44 s (8). If fast bowlers maintain their bowling speed for long periods (consistency), then batsmen do not get an opportunity to settle into their innings by taking advantage of a drop in pace. Although it is imperative for fast bowlers to bowl quickly, they must also bowl accurately, as batsmen can use the pace to assist with run scoring if a ball is inaccurate. Moreover, accurate bowling places pressure on batsmen to score runs; forcing them to play more deliveries (14). However, the ability to maintain accuracy for long periods (consistency) is imperative for enforcing pressure, taking wickets, and not allowing a batsman to control the match.

Some of these performance measures have been assessed in laboratory conditions (Section 2.6). These pace bowling tests have markedly improved in design and evaluation of performance measures since their conception (1, 21, 26). The most recent published pace bowling assessment (26) included more precise measurements of bowling accuracy (radial error) and consistency of accuracy (bivariate variable error), but did not evaluate consistency of bowling speed. Radial error is the absolute distance of ball strike to the centre of the target (26). Bivariate variable error is the variability of delivery locations about the centroid (average x and y coordinates) in relation to the centre of a particular target (176).

A few studies have reported relationships between selected bowling kinematic variables (e.g., approach speed, front-leg knee angles) and bowling speed (10, 12, 21). Most pace bowling tests (21, 29, 162), and studies investigating bowling kinematics (10, 12, 21) however, have not reported the test-retest reliability of their performance or kinematic measures. The “noise” of each measure is therefore obscure, and inferences regarding the efficacy of a training program cannot be made (4).

Nevertheless, the first published pace bowling test reported its test-retest reliability (1), although bowling accuracy was the only performance measure. However, a Pearson’s correlation coefficient was used to measure test-retest reliability instead of the preferred intraclass correlation coefficient (3, 4). Other meaningful measures such as the intraclass correlation coefficient, coefficient of variation, and standard error of measurement (3) have rarely been reported in studies assessing bowling performance or kinematics.

Furthermore, the smallest worthwhile change is a practical measure for coaches and sport scientists to use in determining the effectiveness of a program, and can be calculated by multiplying the coefficient of variation by 0.3 (28). Therefore, this study had two purposes: 1) to determine the test-retest reliability of bowling performance measures and selected bowling-kinematic variables in a novel eight-over test, and 2) to ascertain if the first four overs of this test presents acceptable test-retest reliability. If the first four overs are deemed reliable, then not only could coaches and sport scientists assess pace bowlers in less time, but the shorter test would be more specific to specialist Twenty/20 cricket bowlers; as a maximum of four overs can be delivered in this game format.

3.2 Methods

3.2.1 Experimental approach to the problem

This investigation comprised a within-subjects repeated-measures design, to ascertain the test-retest reliability of pace bowling performance measures, and selected bowling kinematics in a novel eight-over test. Pace bowling performance measures encompassed: bowling speed, consistency of bowling speed, bowling accuracy (radial error), and consistency of accuracy (bivariate variable error). Bias (centroid error) was not included because it is calculated as the absolute distance of mean *x* and *y* coordinates to the target centre, and technically provides no direction of bias (26). Furthermore, rating of perceived exertion was included not as a bowling performance measure, but as a means to monitor a bowler’s intensity throughout the bowling test.

Selected bowling kinematics comprised: approach velocity, delivery step length, step-length phase duration (back-foot contact to front-foot contact), power phase duration (front-foot contact to ball release), and front-leg knee extension angle at front-foot contact and at ball release. These bowling-kinematic variables were included as previous research has indicated a majority of these to relate with bowling speed (6, 10, 11, 13).

The pace bowling test is considered novel as it provides a more comprehensive evaluation of bowling performance (bowling speed, bowling accuracy, consistency of bowling speed, consistency of bowling accuracy), but involves a “live” batsman (explained further on), various delivery speeds (match-intensity, maximal-effort, slower-ball), and a variety of targets (outside off-stump, top of middle stump, bouncer, yorker). This test was adapted from a bowling test documented in an unpublished Honours thesis (30). O'Grady (30) reported the bowling test to possess acceptable test-retest reliability (albeit low sample size), and was capable of distinguishing between high-performance (*n* = 8) and low-performance (*n* = 10) pace bowlers in terms of bowling speed, but not bowling accuracy or consistency of bowling accuracy. The current investigation seeks to improve this pace bowling test by doubling its length (4 overs to 8 overs), and by correctly measuring the consistency of bowling accuracy (26), and by including an equal amount of deliveries to a right and left handed batsman.

3.2.2 Participants

Since it is desirable to apply the results of this investigation to elite-standard pace bowlers, a high-performance sample would ideally be assessed. However, due to the difficulty in recruiting such athletes for comprehensive testing, a community-standard group was recruited from the city of Ballarat. As this study was conducted in the cricket off-season, most prospective participants were playing local AFL football and were not able to participate. Therefore, only thirteen male pace bowlers of community-standard (i.e., local club cricket, A and B grade) volunteered for this study. Participants were on average 22.8 ± 5.6 years old (mean ± *SD*), and had been pace bowling for 8.4 ± 4.2 seasons (mean ± *SD*) of outdoor cricket. Their body-mass was 80.2 ± 11.9 kg (mean ± *SD*), and they stood 181.8 ± 6.6 cm (mean ± *SD*) tall. To warrant involvement in this investigation, participants had to be injury-free for a minimum of six months. This study was approved by the University Human Research Ethics Committee (Appendix A), and participants received a Plain Language Information Statement (Appendix B). Prior to this investigation participants were briefed on the pace bowling testing procedures, experimental risks, and the nature of the study, before providing their informed consent. They were instructed to refrain from resistance training, alcohol and caffeine consumption 24 hours prior to each testing session.

3.2.3 Procedures

This investigation required participants to perform two eight-over bowling tests, indoors, separated by four to seven days. The pace bowling test was conducted indoors to control for the weather. As this testing was conducted in the off-season, a three-week familiarisation period (six sessions) was employed to condition participants to bowling. This period also benefited participants because they could learn the degree of swing indoors, and ball-bounce characteristics off the synthetic turf. Participants did not practise the pace bowling test in the familiarisation period. Nevertheless, they practised bowling at different targets and at various speeds, from a full run-up (24 m maximum). The indoor ambient temperature and humidity were not recorded, as the beginning of the run-up was conducted outdoors, but under cover (Figure 3.1).

Figure 3.1. The run-up commenced outdoors (under cover) for most bowlers.

Participants were weighed in shorts and a t-shirt, and their height was measured (without shoes) on a stadiometer, prior to each pace bowling test. Additionally, they provided a subjective rating of their “coping score”; a devised scale to estimate wellness (Figure 3.2). Although this scale has not been published in scientific literature, it was used to check the fatigue levels of participants prior to each test, and was used to identify any possible outliers in performance.

Coping Scale

Best
10 Feel fantastic (energetic, enthusiastic, fresh, no soreness)
9 Feel very good
8 Feel good
7 Feel OK
6 Feel not too bad
5 Neutral (not good or bad)
4 Not so good
3 Feel pretty bad
2 Feel bad
1 Feel very bad
0 Feel horrible (lack energy & enthusiasm, very sore, flat)
Worst

Figure 3.2. The coping scale was used to monitor fatigue prior to the pace bowling test.

Participants were marked with retro-reflective tape (3-cm square) on the lateral surface of their bowling front-leg in standing. This tape was placed in four locations: 5 cm and 20 cm below the greater trochanter in line with the lateral border of the knee-joint centre, and 5 cm and 20 cm above the lateral malleolus in line with the lateral border of the knee joint centre (177). This marking allowed for the two-dimensional measurement of front-leg knee extension angles in the sagittal plane (Figure 3.3) (177), for analysis in Dartfish Connect (Version 7.0, Melbourne, Australia).

Figure 3.3. The locations of the four retro-reflective markers to permit a calculation of the front-leg knee extension angle.

Participants were split into two groups of pairs in each testing session. A general warm-up of five minutes preceded the fast bowling test, and comprised 20-m shuttle runs of progressive intensity, side to side shuffles, sprints, and dynamic stretches. A specific warm-up followed, where participants delivered 10 balls with progressive intensity, starting at 60% effort, working through to 70% effort, 80% effort, 90% effort, and finishing at 95% effort; two deliveries at each intensity. A one minute recovery followed the warm-up, where participants received the following instruction:

> “Bowl as fast, accurate and consistently as possible as you would in a match. We are measuring all of these elements. At different times throughout the test, you will be instructed to bowl some deliveries at maximal speed and some deliveries with your preferred slower ball. Your speed and accuracy with these balls is also measured.”

The bowler's preferred slower ball was emphasised in the instruction, because this delivery is predominately skill-based. Some pace bowlers have many types of slower balls; some spin off the pitch while others do not. Bowling many types of slower balls could negatively affect bowling accuracy, and therefore the test-retest reliability of the pace bowling assessment. Therefore, it was important for bowlers to deliver the same type of slower-ball. The slower-ball was included because pace bowlers sparingly use this type of delivery to deceive a batsman into a mistimed stroke. The maximal-effort delivery was incorporated because pace bowlers are sometimes required to "blast" opposition batsman out with speed, or to deceive the batsman into a mistimed stroke on the odd occasion.

In the pace bowling test, one group bowled while the other performed fielding activities. Participants bowled with a three-week old two-piece cricket ball (Kookaburra Tuf Pitch, Melbourne, Australia). This ball did swing indoors and bowlers were responsible for controlling the swing as they would in a match. After an over was finished, both groups swapped roles until they completed eight overs of bowling. Fielding activities were included to best replicate match demands and recovery periods. The fielding activities comprised a 5-m walk in on each ball, with a 10-m sprint on the second and fourth ball of the over, with an underarm pick-up and throw to a keeper, who stood behind a set of stumps.

The pace bowling test comprised 48 deliveries (8 overs), directed at any one of five circular targets on a vertical sheet. The vertical target sheet was suspended from a horizontal pole at the popping crease (Figure 3.4). The targets encompassed: outside off stump for a right-hand batsman, outside off stump for a left-hand batsman, top of middle stump, bouncer, and yorker. The bouncer target was one meter from the top of middle stump, while the yorker target was 30 cm above the ground (Figure 3.5). The height of the bouncer and yorker targets were chosen from pilot testing with a "live" batsman (live batsman discussed further on). The yorker target was set at correct height, but only if the batsman adopted a hip-width stance with one foot in and out of the batting crease, and took middle-stump guard. The height of the bouncer target was on average with where a typical batsman's head would be located (a majority of batsman are small in stature). Each target had a six centimetre radius, with cross-hairs to facilitate the measurement of bowling accuracy (radial error), and consistency of accuracy (bivariate variable error) in Dartfish Connect.

Figure 3.4. The suspended target sheet and the “live” batsman.

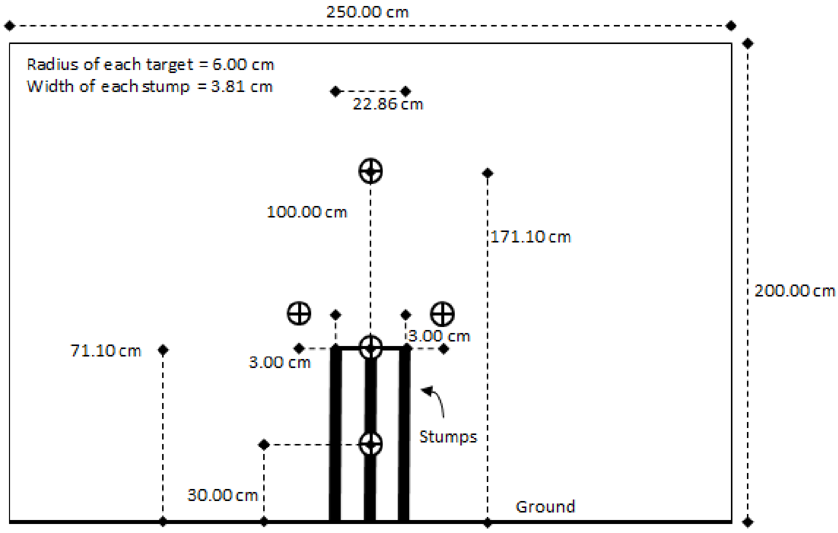

Figure 3.5. The vertical target sheet and its measurements, modified from (30). Note this figure is not drawn perfectly to scale.

Unlike previous pace bowling tests (26, 29, 162), the frequency of deliveries directed at each target varied to better reflect the typical deliveries that bowlers aim to bowl (Table 3.1). This alteration improved the construct validity of the pace bowling test. This bowling test is also the first to include various speed categories (match-intensity, maximal-effort, and slower-ball). Of the 48 deliveries in the test, 40 balls were delivered at match-intensity (speed and accuracy equally important), four at maximal-speed, and four slower-deliveries. The variety of speeds and targets employed was designed to enhance the construct validity of this fast bowling test, but also for the assessment of the speed-accuracy trade-off in Study 2. In a match scenario, bowlers change their pace (i.e., increase and decrease) and their line and length (i.e., bouncer, yorker, good length, off stump, middle stump) on the odd occasion to deceive a batsman. By doing this, bowlers are less predictable and therefore have a greater chance of dismissing a batsman.

The delivery sequence in the first four overs of this test was the same as the last four overs. Participants had 40 s recoveries between deliveries (slightly longer than match conditions), because the high-speed camera had to process the bowling accuracy footage. Within 10 s of delivering each ball, participants rated their perceived effort (percentage from 100). Perceived effort was included as a subjective indicator of intensity, which may indicate fatigue throughout the test. For example, bowling speed and accuracy may diminish as the test progresses, but perceived effort may increase.

Table 3.1. Delivery sequence in the eight-over bowling test.

Delivery #	**Over 1 & 5**	**Over 2 & 6**	**Over 3 & 7**	**Over 4 & 8**
1	Off, RH, MI	Off, LH, MI	Off, LH, MI	Off, RH, MI
2	Off, RH, MI	Off, LH, MI	Off, LH, MI	Off, RH, MI
3	Off, RH, MI	Off, RH, MI	Off, LH, MI	Off, LH, MI
4	Off, RH, MI	Off, RH, MI	Off, LH, MI	Off, LH, MI
5	Off, RH, ME	Bouncer, RH, MI	Off, RH, ME	Bouncer, LH, MI
6	Middle, RH, SB	Yorker, RH, MI	Middle, RH, SB	Yorker, LH, MI

Off, outside off stump; Middle, top of middle stump; MI = match-intensity delivery; ME = maximal-effort delivery; SB, slower-ball delivery; RH, right-hand batsman, LH, left-hand batsman.

A “live” batsman was a distinct inclusion in this test, as others have used no batsman (1, 21, 162), or a superimposed two-dimensional image of a batsman (26). The inclusion of a live batsman was intended to enhance the construct validity of the bowling test. A live batsman provides bowlers with specific cues when bowling a bouncer (i.e., head), and yorker (i.e., feet). In the bowling test, the live batsman faced all deliveries, and was instructed to move away from the ball only after it was released, to allow it to strike the target sheet (Figure 3.6).

Figure 3.6. The batsman evaded the delivery, so that bowling accuracy and consistency of accuracy could be calculated.

3.2.4 Measurement of fast bowling performance variables

As discussed previously, the ability of fast bowlers to generate pace, to bowl accurately and with consistency is imperative to their success in cricket (8, 26). This bowling test assessed peak and mean bowling speed, consistency of bowling speed, bowling accuracy (radial error), and consistency of accuracy (bivariate variable error).

Bowling speed was measured by a radar gun (Stalker Pro, Applied Concepts, Texas, USA) mounted on a tripod positioned 137 cm behind the bowling crease, and ipsilaterally to the participants bowling-arm (30 cm wide of middle stump). The radar gun was fixed at a height of 195 cm, with an inward angle of 25°, to facilitate earliest detection of bowling speed after ball release (Figure 3.7).

Bowling accuracy variables (i.e., radial error, bivariate variable error) were obtained from high-speed camera footage (PCI 2000 S, Redlake Imaging Corporation, CA, USA), collected at 250 frames per second, with a shutter speed of four milliseconds. The high-speed camera was mounted on a tripod 36 cm behind the bowling crease, and ipsilateral to the participant’s bowling-arm (30 cm wide of middle stump). Furthermore, it was fixed at a height of 147 cm, with a slight inward angle of 10° to capture the entire target sheet (Figure 3.7).

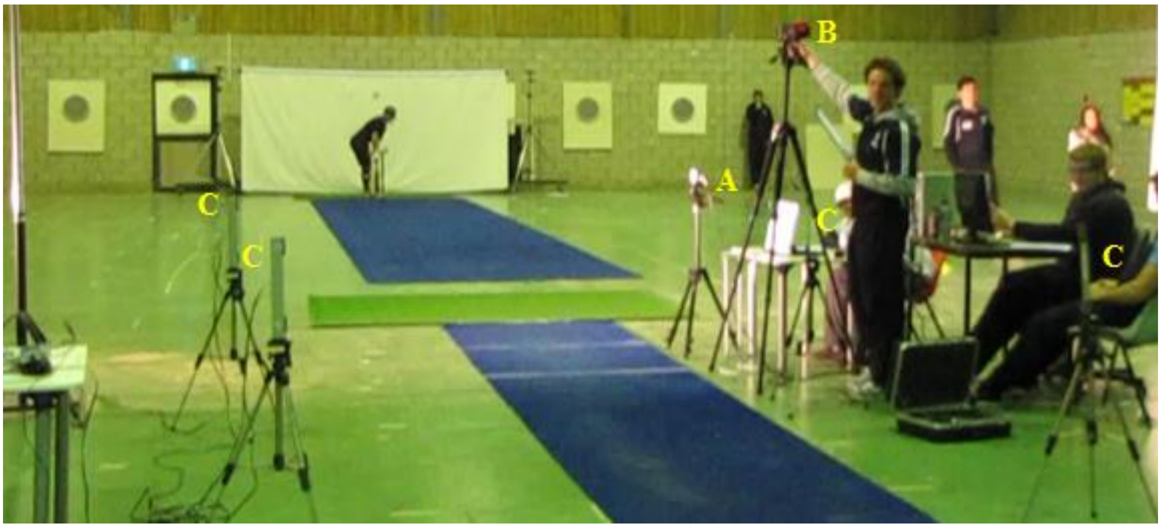

Figure 3.7. Experimental set-up of the pace bowling test. The high-speed camera (A), radar gun (B), and timing gates are shown (C).

The high-speed camera recordings were imported into Dartfish Connect to facilitate the calculation of bowling accuracy (radial error) and consistency of bowling accuracy (bivariate variable error). In Dartfish Connect, a vertical line was drawn from the cross-hair of the bouncer target to the cross-hair of the middle-stump target, and calibrated to 100 cm (Figure 3.8), so that radial error and the horizontal *x* coordinate could be estimated for each delivery (Figure 3.9). The vertical *y* coordinate was calculated using Pythagorean Theorem.

Figure 3.8. The calibration of length was performed in Dartfish Connect.

Figure 3.9. The measurement of radial error (A), and the horizontal *x* coordinate (B) were performed in Dartfish Connect.

Bowling accuracy (radial error) of each ball was calculated as the absolute distance from ball strike (first frame of visible impact) to the target centre (Figures 3.9 & 3.10). Consistency of bowling accuracy (bivariate variable error) is the variability of delivery locations about the centroid (average *x* and *y* coordinates) for a particular target (Table 3.2); calculated by Equation 3.1(176):

$$\text{Equation 3.1. Bivariate variable error} = \sqrt{\frac{\Sigma(x-x_1)^2}{n} + \frac{\Sigma(y-y_1)^2}{n}}$$

*Where Σ is the sum of, x and y are the *x* and *y* coordinates of a specific delivery in relation to the target centre respectively, while x_1 and y_1 are the mean of all *x* and *y* coordinates in relation to the target centre respectively. Furthermore, n is the number of deliveries bowled to a particular target.

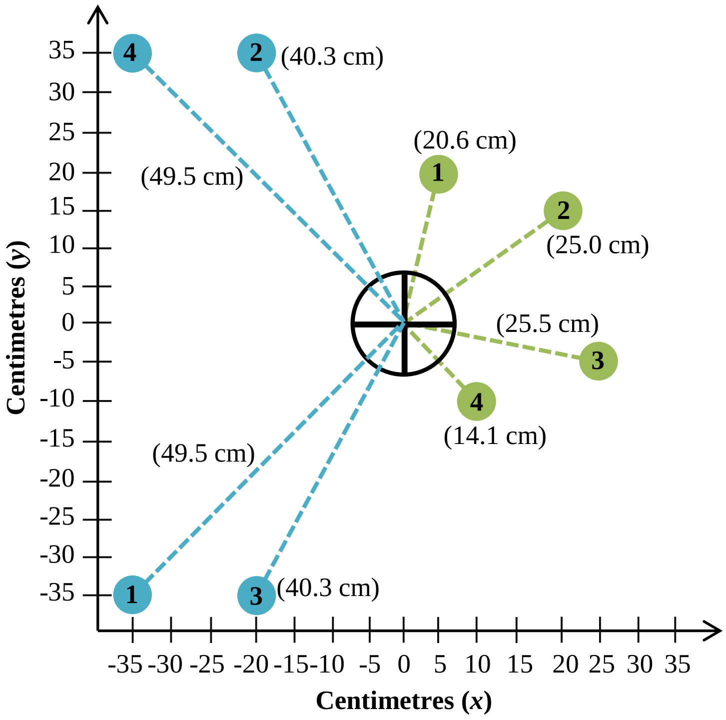

Figure 3.10. Ball strike locations of four deliveries, with two bowlers. Bowler A (blue circles) has the greatest mean radial error (dashed lines), and a larger grouping of deliveries (bivariate variable error) compared to Bowler B (green circles). In this scenario, Bowler B is the better performer, as his/her accuracy and consistency of accuracy are smaller.

Table 3.2. The calculation of bivariate variable error from *x* and *y* coordinates in Figure 3.10.

Delivery #	**Bowler A (blue)**			**Bowler B (green)**		
	Radial Error (cm)	***x* (cm)**	***y* (cm)**	**Radial Error (cm)**	***x* (cm)**	***y* (cm)**
1	49.5	-35.0	-35.0	20.6	5.0	20.0
2	40.3	-20.0	35.0	25.0	20.0	15.0
3	40.3	-20.0	-35.0	25.5	25.0	-5.0
4	49.5	-35.0	35.0	14.1	10.0	-10.0
Mean	**44.9**	**-27.5**	**0.0**	**21.3**	**15.0**	**5.0**
		(x_1)	(y_1)		(x_1)	(y_1)
BVE (cm)			**35.8**			**15.0**

BVE, bivariate variable error.

3.2.5 *Calculation of bowling kinematic measures*

As discussed previously, approach velocity, delivery step length, step-length phase duration, power phase duration, and front-leg knee extension angle at front-foot contact and at ball release were included as a majority of these bowling-kinematic variables significantly correlate to bowling speed ($p < 0.05$) (6, 10, 11, 13).

A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) captured two-dimensional bowling-kinematic footage in the sagittal plane for each delivery. This camera operated at 25 frames per second, with a pre-set shutter speed of two milliseconds to prevent blurring. The camera was fixed at 175 cm above the ground, and was positioned 660 cm away from, and parallel with the popping crease (bowler's end), to the contralateral side of the bowler's bowling-arm (Figure 3.11). A 500-W floodlight was positioned next to the camera, to allow a faster shutter speed and thus a clearer image (Figure 3.11). A white vinyl sheet hung vertically, on the ipsilateral side of the bowler's bowling-arm, which served as a backdrop, to allow easier detection of ball release (Figures 3.12 & 3.13). The footage was imported into Dartfish Connect for the extraction of two-dimensional bowling-kinematic data. The length from the bowling crease to the popping crease was calibrated to 122 cm in Dartfish Connect, to permit the estimation of delivery step length (Figure 3.12).

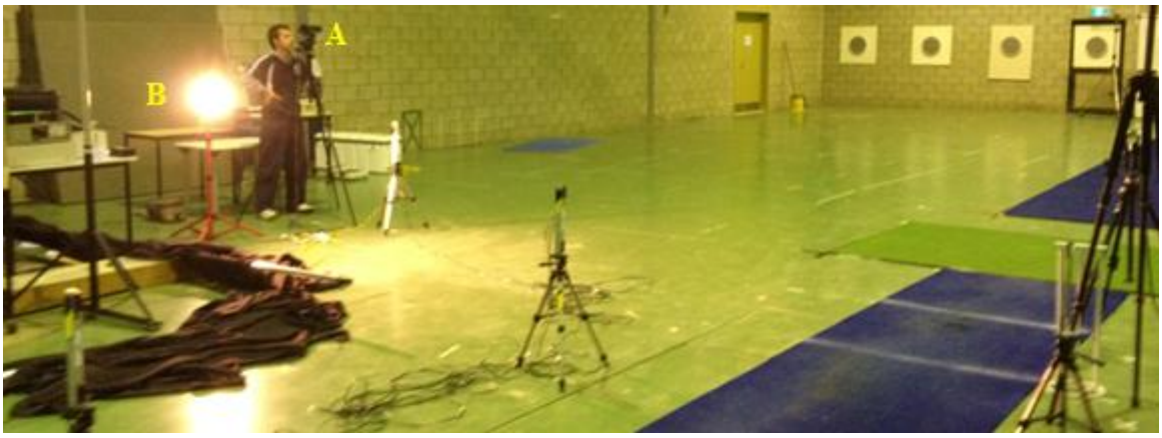

Figure 3.11. Placement of the digital high-definition video camera (A) and flood-light (B), which were positioned parallel with the popping crease (bowler's end).

Figure 3.12. View from the digital high-definition video camera, with the white vinyl backdrop in the background. The distance between the bowling crease and popping crease (122 cm) was calibrated in Dartfish Connect so delivery step length could be estimated.

Approach speed was measured by a dual-beam electronic timing system (Swift Performance Equipment, Lismore, Australia), with a 10-ms timing resolution. Two pairs of timing gates were positioned 2.5 m and 5 m behind the bowling crease to measure approach speed (Figure 3.7). Front-leg knee extension angle was calculated at front-foot contact, and at ball release (Figure 3.13). Delivery step length was estimated from forefoot strike at back-foot contact to heel-strike or forefoot strike at front-foot contact (Figure 3.13). Some bowlers landed on their forefoot or heel with their front-leg foot, but all bowlers landed on their forefoot with their back-leg foot. The step-length phase duration and power phase duration were calculated by using the timer function in Dartfish Connect.

Figure 3.13. The estimation of front-leg knee extension angle at front-foot contact and delivery step length (left), and front-leg knee extension angle at ball release (right).

3.2.6 Statistical analyses

Mean bowling speed, mean consistency of bowling speed, mean bowling accuracy (radial error), and mean perceived effort were calculated from the deliveries bowled at “match-intensity” only (n = 40). Peak bowling speed was analysed as the mean of the four deliveries performed at “maximal effort”. Consistency of bowling accuracy (bivariate variable error) however, was computed for “match-intensity” deliveries at both off-stump targets, and was averaged, to represent one measure of consistency of accuracy. Mean bowling-kinematic variables were also calculated from the deliveries bowled at “match-intensity” only (n = 40). These data were used to assess the test-retest reliability of the eight-over pace bowling test. To examine the test-retest reliability of the first four overs of this pace bowling test, the first 20 deliveries bowled at match-intensity were used to calculate mean bowling performance and bowling-kinematic measures (and perceived effort), with the mean of two maximal-effort deliveries used for peak bowling speed.

The intraclass correlation coefficient (ICC) was included in this study, as it is a relative measure of reliability. That is, it reflects the ability of a variable to distinguish between participants (3). A greater between-subjects variability however, can increase the ICC (178). Unfortunately, there is no agreement on what comprises a “good”, “medium”, or “poor” ICC (178). Nevertheless, Vincent and Weir (179) believe that an ICC that ranges from 0.7–0.8 can be deemed “questionable”, whereas an ICC that is above 0.9 is interpreted as “high”. This investigation will follow these guidelines, with acceptable test-retest reliability set at an ICC greater than 0.8.

The standard error of measurement (SEM) was also incorporated in this study, as it is an absolute measure of reliability, and it quantifies the precision of individual scores for a variable (3). The coefficient of variation (CV) was included as it allows a comparisons between reliability measures, regardless of scaling (4). Although there is no conformity on the interpretation of the CV (180), “acceptable reliability” will be arbitrarily set from a CV that is less than 10% (181). According to Hopkins (4), the smallest worthwhile change can be calculated by multiplying the SEM by 1.5. The smallest worthwhile change can provide inferences on real change from that of “noise”.

To analyse the test-retest reliability of each variable, data from each bowling test was entered into a purpose-made Microsoft Excel spreadsheet (182), where the SEM, exponentially-transformed CV (with 90% confidence intervals), ICC (Model 2,k) (3), and absolute and percent mean difference were extracted. The SEM was calculated by Equation 3.2 (3):

$$\text{Equation 3.2. SEM} = SD_{\mathrm{d}} \div \sqrt{2}$$

*Where SD_d is the *SD* of the difference scores.

The exponential transformation of the coefficient of variation was calculated using Equation 3.3 in Microsoft Excel (182):

$$\text{Equation 3.3. CV} = 100 \times \text{EXP}(\text{SEM} \div 100) - 100$$

*Where *EXP* refers to the exponential function in Microsoft Excel.

A paired samples *t*-Test (2-tailed) was employed to detect any systematic biases (180). A systematic bias between both bowling tests would indicate a possible learning or fatigue effect.

An assumption of the SEM, CV, and paired-samples *t*-test is that they meet the normal distribution (180). The normality of each variable was therefore assessed using a Shapiro-Wilk test in SPSS (Version 19, IBM Corp.). The SEM was not conducted if a variable violated normality. A Wilcoxon signed-rank test (2-tailed) was performed to ascertain any systematic bias for non-parametric data. As the CV was exponentially transformed, it was included irrespective of whether a measure met normality or not. Statistical significance was set at $p < 0.05$ for all statistical analyses.

3.3 Results

Body-mass was deemed to be reliable with a high ICC (0.990) and low CV of 1.5% (Table 3.3). The SEM for body-mass, however, was a little high (1.2 kg). Peak bowling speed and mean bowling speed displayed high ICCs (0.975 and 0.987 respectively) and acceptable CVs (1.3% and 1.0% respectively) in the eight-over test (Table 3.4). Perceived effort had an acceptable CV (3.9%) and SEM (3.2%), but a questionable ICC (0.650).

Consistency of bowling speed, bowling accuracy, and consistency of bowling accuracy failed to meet the pre-set standard for acceptable reliability due to questionable ICCs (range: 0.434–0.739) and poor CVs (range: 12.5–33.4%). The SEM, nevertheless, was relatively small for bowling accuracy (4.7 cm) and consistency of bowling accuracy (5.6 cm). There were no systematic biases in all bowling performance variables in the eight-over pace bowling test.

Peak bowling speed and mean bowling speed displayed high ICCs (0.948 and 0.981 respectively) and acceptable CVs (1.9% and 1.2% respectively) in the first four overs of the eight-over test (Table 3.5). Perceived effort had an acceptable CV (3.8%) and SEM (3.1%), but a questionable ICC (0.659). Consistency of bowling speed, bowling accuracy, and consistency of bowling accuracy failed to meet the pre-set standard for acceptable reliability due to questionable ICCs (range: 0.454–0.562) and poor CVs (range: 16.8–26.6%). The SEM, nevertheless, was relatively small for bowling accuracy (6.4 cm) and consistency of bowling accuracy (6.8 cm). There were no systematic biases in all bowling performance variables in the first four overs of the pace bowling test.

All bowling-kinematic variables, except for approach speed and knee-extension angle at front-foot contact, displayed high ICCs (range: 0.966–0.991) in the eight-over test (Table 3.6). Additionally, all bowling-kinematic variables, except for approach speed, presented acceptable CVs (range: 1.1–3.2%). The SEM for step-length phase duration and power phase duration were zero. There were no systematic biases present in all bowling-kinematic variables in the eight-over pace bowling test.

All bowling-kinematic variables, except for approach speed and knee-extension angle at front-foot contact, displayed high ICCs (range: 0.967–0.991) in the first four overs of the eight-over test (Table 3.7). Additionally, all bowling-kinematic variables, apart from approach speed (CV = 14.6%), presented acceptable CVs (range: 1.2–3.4%). The SEM for step-length phase duration and power phase duration were zero. There were no systematic biases present in all bowling-kinematic variables in the first four overs of the pace bowling test, although knee-extension angle at ball release approached significance ($p = 0.08$).

Table 3.3. The test-retest reliability of body-mass and coping score prior to the pace bowling assessment. Upper and lower confidence intervals were set at 90%, and expressed in parentheses.

	n	**T1 Mean ± *SD***	**T2 Mean ± *SD***	**T2-T1**	**T2-T1 (%)**	***p***	**ICC**	**SEM**	**CV (%)**	**SWC**
Body-mass (kg)	13	78.4 ± 10.4	78.9 ± 10.6	0.6	0.7	0.264	0.990	1.2	1.5 (1.1–2.4)	1.8 kg
Coping score (AU)	13	5.9 ± 1.6	6.0 ± 1.5	0.2	2.6	0.781	0.228	1.4	30.3 (22.1 to 49.4)	2.1 AU

T1, trial one; T2, trial two; SEM, standard error of measurement; CV, coefficient of variation; SWC, smallest worthwhile change; AU, arbitrary units.

Table 3.4. The test-retest reliability of bowling-performance variables in the eight-over pace bowling assessment. Upper and lower confidence intervals were set at 90%, and expressed in parentheses.

	n	**T1 Mean ± *SD***	**T2 Mean ± *SD***	**T2-T1**	**T2-T1 (%)**	***p***	**ICC**	**SEM**	**CV (%)**	**SWC**
Peak4										
BS (m·s^{-1})	13	29.2 ± 2.0	29.2 ± 2.2	0.0	-0.1	0.914	0.975	0.4	1.3 (1.0–2.0)	0.6 m·s^{-1}
Mean										
BS (m·s^{-1})	13	28.2 ± 2.2	28.3 ± 2.2	0.1	0.1	0.882	0.987	0.3	1.0 (0.8–1.6)	0.5 m·s^{-1}
BA (cm)	13	43.3 ± 7.5	41.3 ± 8.1	-2.0	-4.5	0.303	0.685	4.7	12.5 (9.3–19.6)	7.0 cm
PE (% of 100)	13	86.1 ± 5.2	86.7 ± 5.2	0.6	0.7	0.629	0.650	3.2	3.9 (2.9–6.0)	4.8%
Consistency										
BS (m·s^{-1})	13	0.7 ± 0.1	0.7 ± 0.2	0.0	3.2	0.584	0.739	0.1	15.6 (11.5–24.5)	0.2 m·s^{-1}
BA (cm)	13	40.0 ± 7.3	36.0 ± 7.3	-3.9	-9.9	0.100	0.434	5.6	15.3 (11.3–24.0)	8.4 cm

T1, trial one; T2, trial two; SEM, standard error of measurement; CV, coefficient of variation; SWC, smallest worthwhile change; Peak4, peak ball speed obtained from four maximal-effort deliveries; BS, bowling speed; BA, bowling accuracy; PE, perceived effort.

Table 3.5. The test-retest reliability of bowling-performance variables in the first four overs of the pace bowling assessment. Upper and lower confidence intervals were set at 90%, and expressed in parentheses.

	n	**F4T1 Mean ± *SD***	**F4T2 Mean ± *SD***	**F4T2-F4T1**	**F4T2-F4T1 (%)**	***p***	**ICC**	**SEM**	**CV (%)**	**SWC**
Peak2										
BS (m·s^{-1})	13	29.4 ± 2.0	29.2 ± 2.1	-0.2	-0.8	0.296	0.948	0.5	1.9 (1.4–2.9)	0.8 m·s^{-1}
Mean										
BS (m·s^{-1})	13	28.4 ± 2.2	28.3 ± 2.2	-0.1	-0.4	0.348	0.981	0.3	1.2 (0.9–1.8)	0.5 m·s^{-1}
BA (cm)	13	43.2 ± 8.5	40.6 ± 8.9	-2.6	-6.0	0.321	0.491	6.4	16.8 (12.5–26.6)	9.6 cm
PE (% of 100)	13	85.8 ± 5.0	86.2 ± 5.1	0.3	0.4	0.799	0.659	3.1	3.8 (2.8–5.8)	4.7%
Consistency										
BS (m·s^{-1})	13	0.7 ± 0.1	0.7 ± 0.3	0.0	0.0	0.442	0.562	0.2	26.6 (19.5–43.0)	0.3 m·s^{-1}
BA (cm)	13	39.1 ± 7.6	36.5 ± 10.2	-2.7	-6.8	0.343	0.454	6.8	19.3 (14.3–30.7)	10.2 cm

F4T1, first four overs of trial one; F4T2, first four overs of trial two; SEM, standard error of measurement; CV, coefficient of variation; SWC, smallest worthwhile change; Peak2, peak ball speed obtained from two maximal-effort deliveries; BS, bowling speed; BA, bowling accuracy; PE, perceived effort.

Table 3.6. The test-retest reliability of bowling-kinematic variables in the eight-over pace bowling assessment. Upper and lower confidence intervals were set at 90%, and expressed in parentheses.

	n	**T1 Mean ± *SD***	**T2 Mean ± *SD***	**T2-T1**	**T2-T1 (%)**	***p***	**ICC**	**SEM**	**CV (%)**	**SWC**
Mean										
AS (m·s^{-1})*	13	5.2 ± 0.7	5.1 ± 1.1	-0.1	-2.5	0.861	0.615		14.1 (10.5–22.1)	
SL (cm)	13	135.5 ± 21.6	135.3 ± 23.9	-0.2	-0.1	0.926	0.983	3.3	2.7 (2.0–4.1)	4.9 cm
KE FFC (°)	8	157.4 ± 4.1	157.3 ± 3.0	-0.1	-0.1	0.889	0.849	1.7	1.1 (0.7–1.9)	2.6°
KE BR (°)	12	149.9 ± 21.0	148.6 ± 20.4	-1.3	-0.9	0.165	0.991	2.2	1.5 (1.1–2.3)	3.3°
SLP (s)	13	0.21 ± 0.03	0.21 ± 0.03	0.00	0.0	0.181	0.971	0.0	0.0	0.0 s
PP (s)	13	0.13 ± 0.02	0.13 ± 0.02	0.00	0.0	0.830	0.966	0.0	0.0	0.0 s

* Data violated normal distribution. T1, trial one; T2, trial two; SEM, standard error of measurement; CV, coefficient of variation; SWC, smallest worthwhile change; AS, approach speed; SL, step length; KE FFC, knee extension at front-foot contact; KE BR, knee extension at ball release; SLP, step-length phase duration; PP, power phase duration.

Table 3.7. The test-retest reliability of bowling-kinematic variables in the first four overs of the pace bowling assessment. Upper and lower confidence intervals were set at 90%, and expressed in parentheses.

	n	**F4T1 Mean ± *SD***	**F4T2 Mean ± *SD***	**F4T2-F4T1**	**F4T2-F4T1 (%)**	***p***	**ICC**	**SEM**	**CV (%)**	**SWC**
Mean										
AS (m·s^{-1})	13	5.2 ± 0.6	5.1 ± 1.1	-0.1	-2.5	0.606	0.586	0.6	14.6 (10.8–22.9)	0.9 m·s^{-1}
SL (cm)	13	136.1 ± 21.2	135.2 ± 23.9	-0.9	-0.7	0.470	0.982	3.4	2.9 (2.2–4.4)	5.1 cm
KE FFC (°)	8	157.5 ± 4.5	157.3 ± 3.2	-0.2	-0.1	0.830	0.838	1.8	1.2 (0.8–2.1)	2.7°
KE BR (°)	12	150.5 ± 21.2	148.8 ± 20.2	-1.7	-1.1	0.080	0.991	2.2	1.4 (1.1–2.3)	3.3°
SLP (s)	13	0.21 ± 0.03	0.21 ± 0.03	0.00	0.0	0.108	0.967	0.0	0.0	0.0 s
PP (s)	13	0.13 ± 0.02	0.13 ± 0.02	0.00	0.0	0.956	0.970	0.0	0.0	0.0 s

F4T1, first four overs of trial one; F4T2, first four overs of trial two; SEM, standard error of measurement; CV, coefficient of variation; SWC, smallest worthwhile change; AS, approach speed; SL, step length; KE FFC, knee extension at front-foot contact; KE BR, knee extension at ball release; SLP, step-length phase duration; PP, power phase duration.

3.4 Discussion

The ability of pace bowlers to bowl quickly, accurately, and consistently is imperative to their success in cricket (8, 26). A dearth of research exists however, on the assessment of these performance measures (1, 21, 26). A few studies have reported relationships between selected bowling-kinematic variables (e.g., approach speed, front-leg knee extension angle at front-foot contact and at ball release) and bowling speed (10, 12, 21). Most pace bowling tests (21, 29, 162), and bowling-kinematic studies (10, 12, 21) have not reported the test-retest reliability of their measures. To date, only one study has explored the test-retest reliability of their bowling assessment (1); albeit bowling accuracy the only measure of interest. This limitation is problematic, as the “noise” of important bowling performance and kinematic measures are obscure, and therefore inferences regarding the efficacy of training interventions cannot be made for these measures (4). Therefore, this study had two purposes: 1) to determine the test-retest reliability of bowling performance measures and selected bowling-kinematic variables in a novel eight-over test, and 2) to ascertain if the first four overs of this test presents acceptable test-retest reliability.

As expected, the mean bowling speed (28.2 $m{\cdot}s^{-1}$) for this cohort of community-standard pace bowlers was slower than national medium-fast bowlers (34.9 $m{\cdot}s^{-1}$) (25). Regardless, this cohort of pace bowlers could still be classed as medium-fast according to the speed classifications proposed by Abernethy (36). Due to methodological disparities in the analysis of bowling accuracy in other studies (26, 30), no comparisons can be made for this performance measure.

This group of bowlers were slower in their approach speed (5.2 $m{\cdot}s^{-1}$) than national-standard pace bowlers (6.3 $m{\cdot}s^{-1}$) (25) (Table 3.6). The bowlers in this investigation also adopted similar but slightly smaller front-leg knee extension angles at front-foot contact (157.4 ± 4.1°) and at ball release (149.9 ± 21.0°) to junior pace bowlers (157.4 ± 4.1° and 157.4 ± 4.1° respectively) capable of bowling 29.0 $m{\cdot}s^{-1}$ (10). Premier league pace bowlers however (greater standard than the bowlers in this investigation), exhibit greater front-leg knee extension angles at front-foot contact (165.7 ± 4.7°) and can bowl at 34.0 $m{\cdot}s^{-1}$ (19).

The ability to determine test-retest reliability of a measure is challenging, given there are no clear guidelines on how to interpret the ICC and CV (180). Nevertheless, peak bowling speed and mean bowling speed were the most reliable bowling performance measures in the eight-over test (Table 3.4), as well as the first four overs of the test (Table 3.5). A bowler's perceived effort rating was partially reliable; the ICC was questionable (0.650), but the CV was acceptable (3.9%). Low between-subject variability could be the cause of the poor ICC identified for perceived effort.

Although bowling accuracy (radial error) and consistency of bowling accuracy (bivariate variable error) measures were unreliable (by ICC and CV interpretation), bowling accuracy was the most reliable measure of the two, in the eight-over test (Table 3.4), as well as the first four overs of the test (Table 3.5). Even though Phillips, Portus (26) did not explore the test-retest reliability of bowling accuracy and consistency of bowling accuracy, the former appeared to possess concurrent validity. That is, there was a significant difference in bowling accuracy between the junior group and emerging / national groups with the short and full length deliveries ($p < 0.05$). Phillips, Portus (26) reported the bowling accuracy (radial error) for short, good, and full length deliveries to range from ≈34–43 cm for national, ≈36–47 cm for emerging, and ≈40–57 cm for junior pace bowlers. Surprisingly, there were no significant differences in consistency of bowling accuracy between performance groups ($p > 0.05$), which indicates this measure could possess poor concurrent validity, or that all three performance groups were inconsistent with their accuracy.

The rather large within-subject variation (CV) in bowling accuracy and consistency of bowling accuracy in this investigation may be attributed to the bowler's ability to adapt to the change in task instruction; known as adaptive variability (26). In this investigation, there were 3–4 changes in task instruction within each over; either the speed of delivery (match-intensity, maximal-effort, slower-ball), target location (outside off-stump, bouncer, yorker, top of middle-stump), and batsman orientation (right- or left-handed). Phillips, Portus (26) showed that national pace bowlers displayed greater levels of adaptive variability to task instructions than emerging or junior pace bowlers, despite a less frequent change in these instructions (i.e., one change every 10 deliveries).

The poor CVs for consistency of bowling speed, bowling accuracy, and consistency of bowling accuracy reported in this investigation may be attributed to the performance standard of the cohort assessed (i.e., community-standard). These bowlers typically train once or twice per week, and bowl in a match once per fortnight. The volume of bowling performed by these bowlers is probably lower than their professional counterparts, which may account for their variability in bowling accuracy and consistency of bowling accuracy in this investigation. Nevertheless, the SEM for bowling accuracy and consistency of bowling accuracy was relatively low for the eight-over test (range: 4.7–5.6 cm), and marginally greater for the first four overs of this test (range: 6.4–6.8 cm). In a match scenario, a six or seven centimetre difference in bowling accuracy would hardly be noticeable to a batsman, as it is approximately the width of a cricket ball (Figure 3.14).

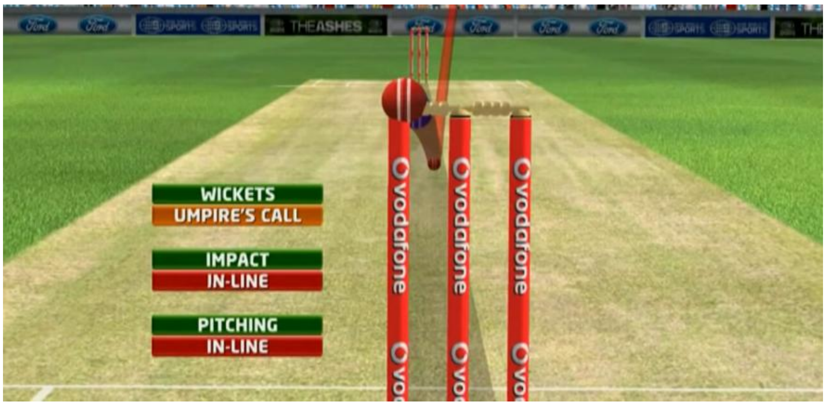

Figure 3.14. The width of a cricket ball is relatively small to the width of the stumps.

The ICCs and CVs for bowling accuracy and consistency of bowling accuracy may have been improved by reducing the frequency of task instructions. For example, Stretch and Goslin (1) required junior cricketers to aim only at one target on the cricket pitch, with only 10 deliveries in their bowling test. A small improvement in bowling accuracy between the first two bowling tests were observed with their junior cricketers (1), but this measure stabilised in three subsequent tests (1). The difference in bowling accuracy, however, between the first two tests could have been attributed to a learning effect, as there was no familiarisation period included. This investigation discovered no systematic biases in all performance measures ($p > 0.05$), which suggests the three-week familiarisation period was sufficient to negate learning effects. With no systematic biases presented in bowling accuracy and consistency of bowling accuracy between tests, it is possible that a reduced number of targets (or frequency of task change), or a consistent speed requirement, would have given bowlers a greater chance of settling into a "rhythm", where they could perform more consistently in the eight-over test.

All bowling-kinematic variables, excluding approach speed, exhibited acceptable test-retest reliability in the eight-over test (Table 3.6) as well as the first four overs of the test (Table 3.7). The large CV with approach speed indicates an inconsistency of bowlers to adopt a reproducible run-up speed. The inconsistency in approach speed could be explained by the bowler’s self-evaluation of performance (i.e., knowledge of results). For example, Brees (175) identified that as bowlers artificially increase their run-up speed, their bowling speed also increases, but at the detriment of bowling accuracy. However, when bowlers adopted a slower run-up, they bowled slower, but more accurately (175). In this investigation, bowlers may have altered their run-up speed to optimise bowling speed and accuracy with match-intensity deliveries.

Dynamic systems theory (183) may also explain the large variability in consistency of bowling speed, bowling accuracy, consistency of bowling accuracy, and approach speed observed in this study. According to dynamics systems theory, the optimal pattern of coordination and control is governed by organismic, task, and environmental constraints (i.e., qualities that limit motion) (183). For example, the frequent change in the delivery instruction (i.e., task constraint) or fatigue throughout the bowling test (i.e., organismic constraint) may have altered the optimal pattern of coordination and control. This may have led bowlers to bowl with less consistency in speed and accuracy.

According to Hopkins (4), a threshold can be set for deciding that “real change” has occurred from a training intervention by multiplying the SEM by 1.5. Previous fast bowling assessments have not reported the SWC of their measurements (21, 29, 162), so it is difficult to ascertain what would be a realistic change following a training intervention. Petersen, Wilson (2) arbitrarily set the SWC for bowling speed to be 1.4 $m{\cdot}s^{-1}$ or 0.7 $m{\cdot}s^{-1}$. Based on the results of this investigation, bowlers would need to exceed 0.6 $m{\cdot}s^{-1}$ and 0.5 $m{\cdot}s^{-1}$ for peak and mean bowling speed respectively, for there to be a realistic change (positive or negative) following a training intervention.

The determination of test-retest reliability of a measure was the same in the eight-overs as well as the first four overs of the test. However, there was a slight tendency for a majority of measures to be less reliable in the first four overs, as opposed to the entire eight overs of the test. This discrepancy may be due to the lower number of deliveries analysed, which could cause greater variability in these measures, and thus error. Nevertheless, the first four overs of the test could be used to assess bowling performance and bowling kinematics. A shorter bowling test would reduce the time required for coaches to assess bowlers, but is less likely to test the endurance capabilities of fast bowlers. Consequently, the consistency of bowling speed and consistency of bowling accuracy are not truly examined with a shorter test, but rather peak and mean bowling speed, and bowling accuracy become the focus of the test.

An indoor pace bowling test, such as presented in this investigation, is more likely to present greater test-retest reliability of bowling performance and bowling-kinematic measures than an outdoor pace bowling test. This may be due to the removal of environmental variables such as wind, rain, run-up slopes, and foot marks, which could all impact on the test-retest reliability of the pace bowling test.

3.5 Conclusions

Peak and mean bowling speed were the most reliable bowling performance measures in the bowling test. Perceived effort was partially reliable; however, bowling accuracy and consistency of bowling accuracy presented with poorer test-retest reliability. All bowling kinematic variables except approach speed exhibited acceptable reliability. Bowlers may have varied their approach speed in attempt to optimise bowling speed and accuracy with match-intensity deliveries. As there were no systematic biases with all variables between bowling tests, the poor CVs and questionable ICCs with consistency of bowling speed, bowling accuracy, consistency of bowling accuracy, and approach speed indicate bowlers had difficulty adapting to task instructions. Dynamic systems theory might explain the effect of task or organismic constraints on the optimal pattern of coordination and control during the fast bowling motion. That is, the 3–4 changes in task instructions per over may have led bowlers to be less consistent in performance and approach speed, which suggests they may have presented difficultly in achieving “rhythm”.

3.6 Practical applications

For the first time in fast bowling research, the smallest worthwhile change for bowling performance and bowling-kinematic measures were reported. Sport scientists can use the smallest worthwhile change data to make inferences regarding true changes in performance or kinematics after any type of intervention (training, skill-based). Furthermore, coaches can use the first four overs of this bowling test to measure performance and kinematics in less time. However, measures such as consistency of bowling speed and consistency of bowling accuracy would not be truly evaluated; as bowlers typically do not fatigue within four overs. The smallest worthwhile change data is slightly higher in the first four overs of the test, compared to the entire eight overs. Sport scientists are recommended to use the correct smallest worthwhile change data for the length of the test employed.

Chapter 4 – Study 2:

The Relationships between Selected Physical Qualities, Bowling Kinematics, and Bowling Performance Measures

4.1 Background

Strength and conditioning of elite and sub-elite pace bowlers has become more prevalent recently, in the quest to produce faster bowlers. The Australian cricket team focus on mastering the Olympic lifts, as a time-efficient means of developing strength and power (184). Muscular power, strength-endurance, flexibility, aerobic power, and anaerobic power are thought to be important for pace bowling performance (14, 33). Some of these physical qualities have been tested, but not significantly correlated to bowling performance measures or bowling kinematics (14, 33). In Study 1, bowling performance measures and selected bowling kinematics were obtained for correlational research with the physical qualities examined in this investigation. Recently, Phillips, Davids (185) revealed that elite pace bowlers believe certain physical qualities to be critical for bowling performance: strong gluteals and abdominals, speed, and endurance. Australian fast bowler Peter Siddle confirmed his belief in the importance of strength training for developing bowling speed (186):

> “I definitely lost a couple of Ks [$k \cdot hr^{-1}$], that's for sure, but you can definitely find it back. Just with weights and getting strength back in my legs. [When] your bum’s not as strong as it could be your legs are falling away and you can’t get through the crease as well. Without doing the weights and the preseasons, you miss out on that. So [now] it's about getting as strong as you can.”

The relationships between bowling kinematics and bowling speed has been studied extensively (6, 10-13, 19, 21, 25, 187). Bowling speed associates with many bowling-kinematic variables, such as approach speed (6, 11, 12, 25), front-leg knee extension angle at front-foot contact (10, 62) and at ball release (10, 13, 19, 22-24), and plant-angle (similar to delivery step-length) (54). However, as discussed in Chapters Two and Three, the consistency of bowling speed, bowling accuracy, and consistency of bowling accuracy are other bowling performance measures that are just as important for fast bowlers. The relationships between bowling kinematics and bowling accuracy has rarely been investigated (21). Furthermore, the associations between bowling kinematics, consistency of bowling speed and consistency of bowling accuracy are not understood.

Research into the relationships between physical qualities, bowling kinematics, and bowling performance is still in its infancy (10, 19, 21). Moreover, the associations with physical qualities and other bowling performance measures such as bowling accuracy (21), consistency of bowling speed, and consistency of bowling accuracy have received little attention. There are other physical qualities (e.g., reactive strength, lower-body strength, flexibility, power-endurance, and repeat-sprint-ability) that have not been included in a physical testing battery, and thereby their relationships with bowling kinematics and bowling performance measures are not understood. Consequently, coaches and sport-scientists do not have sufficient evidence of the physical qualities pertaining to bowling kinematics and bowling performance measures. This in turn, leads to the development of training programs that lack evidence.

The speed-accuracy trade-off suggests that when pace bowlers attempt to increase their bowling speed, it will be at the cost of bowling accuracy (25). Previous research has reported no trade-off between bowling speed and accuracy (25, 26), possibly because these pace bowling assessments required participants to deliver at “match-intensity”, where speed and accuracy are of equal importance (25, 26). Pace bowlers however, sometimes deliver a maximal-effort or slower-ball delivery to deceive a batsman. The speed-accuracy trade-off has not been explored when a combination of delivery types are included (i.e., match-intensity, maximal-effort, slower-ball). The relationships between physical qualities and pace bowling performance measures could change with delivery instruction, but this has not been investigated.

The associations with physical qualities and bowling speed have been explored when bowlers were instructed to bowl with maximal effort (10, 19), or without any instruction (21). These relationships may differ depending on delivery instruction; a maximal-effort delivery may require more of a bowler’s strength and power generating capacity to generate bowling speed, rather than a match intensity or slower-ball delivery. Therefore, there were four purposes of this investigation: 1) to investigate the relationships between selected physical qualities and bowling performance measures, with maximal-effort, match-intensity, and slower-ball deliveries, 2) to determine the associations between chosen physical qualities and bowling kinematics irrespective of delivery instruction, 3) to ascertain the relationships with specific bowling kinematics and bowling performance measures regardless of delivery instruction, and 4) to investigate the speed-accuracy trade-off with a combination of various delivery instructions (i.e., match-intensity, maximal-effort, slower-ball).

4.2 Methods

4.2.1 *Experimental approach to the problem*

This cross-sectional study investigated the relationships between selected physical qualities, bowling kinematics, and bowling performance measures, and the speed-accuracy trade-off. The strength of the correlations reported in this study is assumed to represent the importance of various physical qualities with bowling kinematics and bowling performance measures. Correlations do not indicate cause and effect but suggest importance due to common characteristics. Training interventions are required to validate statistically significant relationships.

The robustness of these correlations can also be determined by the test-retest reliability data presented in Study 1. This study revealed that peak and mean bowling speed were the only bowling performance measures with acceptable test-retest reliability (i.e., ICC > 0.8, CV < 10%), whereas all bowling kinematic variables, except for approach speed, presented acceptable test-retest reliability. Correlations between physical qualities and these reliable bowling performance / kinematic variables should be interpreted as the most robust, and caution should be advised when interpreting correlations with unreliable measures as they are less valid.

Certain physical tests comprised: body mass, standing height, reach height (bowling arm), drop jump, three repetition-maximum (RM) bench press, 3-RM half-squat, 1-RM pull-up, 20 countermovement jumps, 20 bench press throws, prone hold for maximum duration, side hold (left and right side) for maximum duration, 20-m shuttle run (i.e., beep test), 10 × 20-m repeat sprints, straight-leg raise (bowling front-leg), and bowling-arm shoulder horizontal abduction. These physical tests were included as anecdotal evidence suggests muscular power, strength-endurance, flexibility, aerobic power, and anaerobic power to be important for fast bowling performance (33).

Selected bowling kinematics included: approach velocity, delivery step length, step-length phase duration, power phase duration, and front-leg knee extension angle at front-foot contact and at ball release. The novel eight-over bowling test detailed in Study 1 was used to assess selected bowling kinematics, as these measures were slightly more reliable than the first four overs of the pace bowling test. Specific bowling-kinematic measures were included to possibly explain their influence on the relationships between physical qualities and bowling performance measures (Figure 4.1). Furthermore, they were chosen because previous research has reported relationships with a majority of these kinematic variables to bowling speed (6, 25, 62).

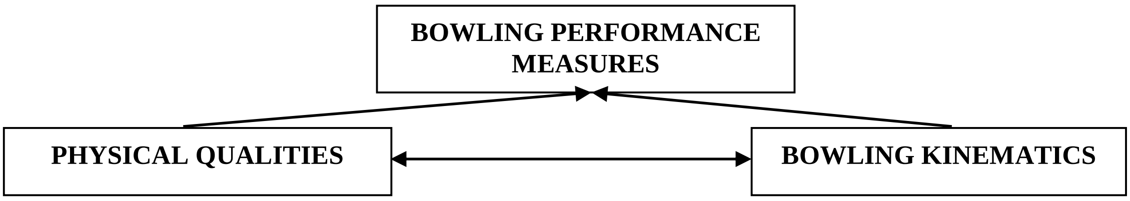

Figure 4.1. The suggested interplay between selected physical qualities, bowling kinematics, and bowling performance measures.

Bowling performance measures comprised: bowling speed, consistency of bowling speed, bowling accuracy (radial error), and consistency of accuracy (bivariate variable error). The rating of perceived exertion was also obtained from each delivery to assess differences in “effort” with each delivery instruction. The novel eight-over bowling test described in Study 1 was used to evaluate bowling performance measures more comprehensively than previously designed tests (1, 21). The eight-over test was chosen over the first four overs of this test because the bowling performance measures were slightly more reliable, and that it is more likely to assess the consistency of bowling speed and consistency of accuracy due to a possible elicitation of fatigue. This investigation required participants to perform an eight-over bowling test, and a series of physical tests, spread over three sessions (Figure 4.2).

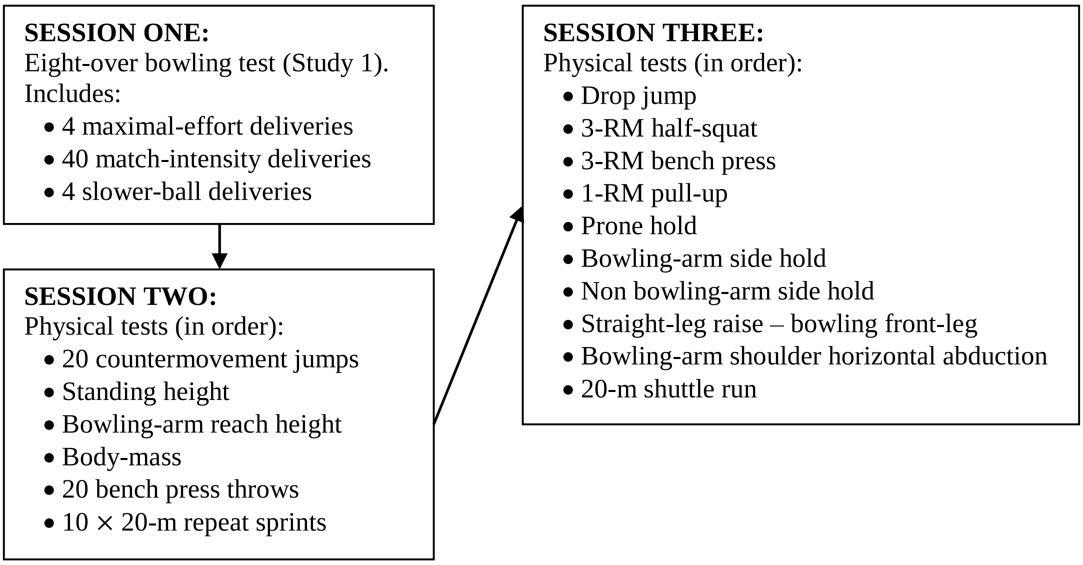

Figure 4.2. Sequence of testing for this investigation.

Each session was separated by four to seven days. Testing of physical qualities, bowling kinematics, and bowling performance measures were conducted during the cricket off-season. Therefore, a three-week familiarisation period (six sessions) was employed to condition participants to pace bowling, where they practised bowling to the different targets, and at various speeds. Participants also learned how to perform each physical test with correct technique.

4.2.2 Participants

Since it is desirable to apply the results of this investigation to elite-standard pace bowlers who engage in physical conditioning, a high-performance sample would ideally be assessed. However, due to the difficulty in recruiting such athletes for comprehensive testing, a community-standard group was recruited. Therefore, thirty-one male pace bowlers of community-standard (i.e., A and B grade local cricket) volunteered for this study. Participants were on average 21.7 ± 4.7 years old (mean ± *SD*), and had 9.1 ± 4.5 seasons (mean ± *SD*) of pace-bowling experience in outdoor cricket. They had a resistance training background of 1.4 ± 1.7 years (mean ± *SD*). Approximately half of the participants had no resistance training experience (n = 15), while others had 2.7 ± 1.4 years (mean ± *SD*) of resistance training (*n* = 16). It would have been ideal for all participants to have resistance training experience, but this varied experience is typical of community-standard pace bowlers. Their body-mass was 82.0 ± 12.9 kg (mean ± *SD*), and they stood 182.4 ± 6.3 cm tall (mean ± *SD*). To qualify for involvement in this investigation, participants had to be injury-free for a minimum of six months. This study was approved by the University Human Research Ethics Committee (Appendix A), and participants received a Plain Language Information Statement (Appendix B). Prior to this investigation, participants were briefed on the pace bowling and physical testing procedures, experimental risks, and the nature of the study, before providing their informed consent. They were instructed to refrain from resistance training, alcohol and caffeine consumption 24 hours prior to each testing session.

4.2.3 Physical testing procedures

Muscular power, strength-endurance, flexibility, aerobic power, and anaerobic power are thought to be important for bowling performance (14, 33). This investigation sought to assess these physical qualities, as well as others (e.g., speed, reactive strength, strength, power-endurance, flexibility) on some of the muscle groups considered important for pace bowling: gluteals, quadriceps, hamstrings, calves, pectorals, latissimus dorsi, obliques, and abdominals.

4.2.3.1 20 Countermovement jump test

The 20 countermovement jump test was included as a measure of lower-body power-endurance. Pace bowlers may require powerful legs to accelerate to their optimal run-up speed, and possibly for their take-off step. In this test, the participant stood on the portable force platform (400 Series Force Plate–Fitness Technology, Adelaide, Australia) with an aluminium dowel positioned on the upper trapezius, and downward pressure was applied with their hands to keep the bar horizontal (Figure 4.3). A linear position transducer (PT5A, Fitness Technology Australia) was attached to the end of the aluminium dowel, to permit the measurement of jump height.

Figure 4.3. The 20 countermovement jump test.

The portable force platform and linear position transducer were calibrated prior to this test. As the participant stood tall on the force platform, the displacement was "zeroed". The force platform was also zeroed with the participant standing off to the side. The participant resumed a standing position on the force platform, and was instructed to "jump for maximal height each repetition", and to wait for a "go" command prior to each jump. The countermovement jump movement comprised a self-selected dip followed by an explosive jump and a landing to absorb the force. The participant was to "reset" into a standing position prior to the next jump. One jump was performed every three seconds. An assistant used a stopwatch to monitor the time and said "go" for each jump. Another helper provided encouragement for every jump, but also checked the technique of each jump. Specifically, it was imperative the bar maintained a horizontal position throughout the jump, and the participant performed each jump with a safe landing, and a reset to standing position. The participant was instructed to inhale during the eccentric (lowering) phase, and exhale on the concentric (raising) phase.

Displacement and peak power measurements were collected during the 20 countermovement jump test. Concentric peak power and displacement of the first three countermovement jumps were obtained to provide a measure of lower-body power. However, the mean concentric peak power and displacement of the 20 countermovement jumps were analysed for the evaluation of lower-body power-endurance. The collection and analysis of displacement and concentric peak power was performed with Ballistic Measurement System Software (Version 2011.2.0, Innervations, Australia). The sampling rate for the force plate and linear position transducer was set to 600 Hz. Although the test-retest reliability of power in a 20 countermovement jump test has not been evaluated, peak power from a 30 countermovement jump test demonstrates high test-retest reliability (ICC = 0.96, CV = 3.2%) (188).

4.2.3.2 20 Bench press throw test in Smith Machine

The 20 bench press throw test was included as a measure of upper-body power-endurance for the pectoralis major and triceps brachii muscles. Pace bowlers may require powerful contractions of the upper-body in the power phase (70). Furthermore, the pectoralis major is strongly activated during the propulsive phase of baseball pitching (189); a motion that is similar to pace bowling. Furthermore, the bench press throws were performed in a Smith Machine, to increase participant safety and reduce balance requirements, as the vertical motion of the bar is fixed (190).

In this test, participants adopted a supine position on a bench, and were positioned in the middle of a Smith Machine (Figure 4.4). They had to maintain contact with the bench (head and back) and with the floor (left and right foot). A linear position transducer was attached to the end of a 20-kg bar, to permit the measurement of throw height.

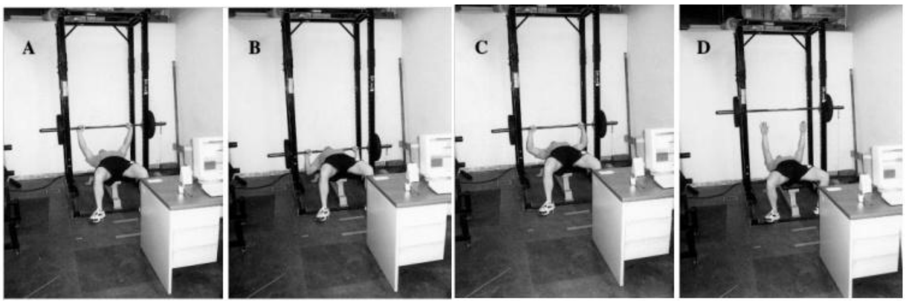

Figure 4.4. The 20 bench press throw test in the Smith Machine (188). There was no weight on the bar during the test.

Prior to this test, participants were instructed to “throw for maximal height each repetition”, and to wait for a “go” command prior to each throw. The linear position transducer was calibrated to enable reliable collection of throw height. As participants un-racked the bar and fully extended their arms, displacement was “zeroed”. The bench press throw movement comprised a self-paced dip followed by an explosive throw and a “catch” to absorb the force. The participant was to “reset” into a fully extended position prior to the next throw. A pronated and slightly-wider than shoulder width grip was used, and the bar was lowered to gently touch the mid-chest region (nipple line). One throw was performed every three seconds. An assistant used a stopwatch to monitor the time and said “go” for each throw. Another helper provided encouragement for every throw, and checked the technique of each throw. Specifically, correct technique meant that the participant had to remain in contact with the bench and floor, perform each throw with a safe catch, and reset to a fully extended position prior to each throw. Participants were also instructed to inhale during the eccentric (lowering) phase, and exhale on the concentric (raising) phase.

Displacement measurements were collected during the 20 bench press throw test. The peak displacement of the first three throws was obtained to provide a measure of upper-body power. However, the mean peak displacement of the 20 throws was analysed for the evaluation of upper-body power-endurance. The collection and analysis of displacement was performed with Ballistic Measurement System Software. Although the test-retest reliability of peak and mean displacement values in a 20 bench press throw test is equivocal, peak power from a 30 bench press throw test possesses high reliability (ICC= 0.92, CV = 6.3%) (188).

4.2.3.3 3-RM Smith Machine half squat

The 3-RM Smith Machine half squat was included as a lower-body strength test (Figure 4.5). Lower-body strength may be important for pace bowlers, as they typically experience large vertical and horizontal ground reaction forces in the power phase (38), and would need to transfer this kinetic energy to the ball, while maintaining a stable position. The 3-RM test was chosen in preference to the 1-RM, as participants were typically inexperienced with resistance training (191). Furthermore, the 3-RM half squat was performed in a Smith Machine, to increase participant safety and reduce balance requirements, as the vertical motion of the bar remains on a fixed path (190).

In this test, participants placed the bar onto their upper trapezius, with a hip-width stance, and squatted to a depth that permitted 90° knee flexion; assessed with a goniometer. One end of the goniometer was directed towards the hip-joint centre, and the other end to the centre of the lateral malleolus. Half-squat depth was measured by a tape measure affixed to the Smith Machine. A metal pin was set to the participant's half-squat depth, to ensure the correct depth was performed each repetition. This gauge was used for an assistant to check half-squat depth, and provide feedback to the participant. Furthermore, the safety catch features were set approximately 15 cm below the participant's half-squat depth.

Figure 4.5. The 3-RM Smith Machine half-squat test.

A warm-up set of five repetitions with a 20 kg bar mass was initially performed to ensure correct squat technique. Participants were instructed to “lower and raise the bar with control each repetition”, and listen for the assistant to say “up” before raising the bar. Participants were also instructed to inhale during the eccentric (lowering) phase, and exhale on the concentric (raising) phase. Encouragement was provided with every repetition. From each set following, four repetitions were conducted with a safe but gradual increase in load (based on observation and participant feedback), until “technical failure” occurred on the fourth repetition. Technical failure was evident if participants could not maintain correct squatting technique (i.e., neutral spine), or could not raise the bar to a fully-extended position (192). At the end of a testing set (four repetitions), participants were asked how many more repetitions they could have performed, and the amount of weight added for next set varied from 5–40 kg so that technical failure could be met or almost met on the next testing set. This mass was added with the participant’s consent. The 3-RM load was typically determined within five testing sets, to minimise the effects of fatigue on subsequent sets (193). A four minute passive rest was employed between testing sets, as this is believed to be sufficient for central nervous system recovery (194). Although the test-retest reliability of a 3-RM Smith Machine half squat is not known, the 3-RM Smith Machine parallel squat exhibits excellent test-retest reliability (ICC = 0.92) (193).

4.2.3.4 3-RM Smith Machine bench press

The 3-RM Smith Machine bench press was included as an upper-body strength test for the pectoralis major and triceps brachii muscles (192). Upper-body bench press strength is strongly related to upper-body bench press throw power (195). Faster bowlers typically produce greater upper-body horizontal adduction power during the power phase of the bowling motion, compared to slower bowlers (70). The pectoralis major is strongly activated during the propulsive phase of baseball pitching (189); a motion similar to pace bowling. The 3-RM test was chosen in preference to the 1-RM, as participants were typically inexperienced with resistance training (191). Furthermore, the 3-RM bench press was performed in a Smith Machine, to increase participant safety and reduce balance requirements, as the vertical motion of the bar remains on a fixed path (190).

In this test, participants adopted a supine position with head and back in contact with the bench, and left and right foot in contact with the ground (192). A pronated but slightly-wider than shoulder-width grip was used, and the bar was lowered to gently touch the mid-chest region (nipple line) (Figure 4.6).

Figure 4.6. The 3-RM Smith Machine bench press test.

A warm-up set of five repetitions with a 20 kg bar mass was initially performed to ensure correct bench press technique. Participants were instructed to "lower and raise the bar with control each repetition", and inhale during the eccentric (lowering) phase, and exhale on the concentric (raising) phase. Encouragement was provided with every repetition. From each set following, four repetitions were conducted with a safe but gradual increase in load (based on observation and participant feedback), until "technical failure" occurred on the fourth repetition. Technical failure was evident if participants could not maintain correct bench press technique (i.e., head, feet, or back raised off bench), or could not raise the bar to a fully-extended position (192). At the end of a testing set (four repetitions), participants were asked how many more repetitions they could have performed, and the amount of weight added for next set varied from 5–20 kg so that technical failure could be met or almost met on the next testing set. This mass was added with the participant's consent. The 3-RM load was typically determined within five testing sets, to minimise the effects of fatigue on subsequent sets (193). A four minute passive rest was employed between testing sets, as this is believed to be sufficient for central nervous system recovery (194). The 3-RM Smith Machine bench press test exhibits excellent test-retest reliability (ICC = 0.97) (193).

4.2.3.5 1-RM pull-up

The 1-RM pull-up was included as an upper-body strength test for the latissimus dorsi muscle (196) (Figure 4.7). The latissimus dorsi muscle would contract when the bowling-arm shoulder extends during the power phase. The latissimus dorsi is strongly activated during the propulsive phase of baseball pitching (189); a motion that is similar to pace bowling. The 1-RM test was chosen in preference to the 3-RM used for the half-squat and bench press tests, as some participants could not perform multiple repetitions with their body-mass during familiarisation period. Furthermore, the 1-RM pull-up was performed in a Smith Machine, where the bar could be adjusted and fixed to a height that participants could just touch in standing.

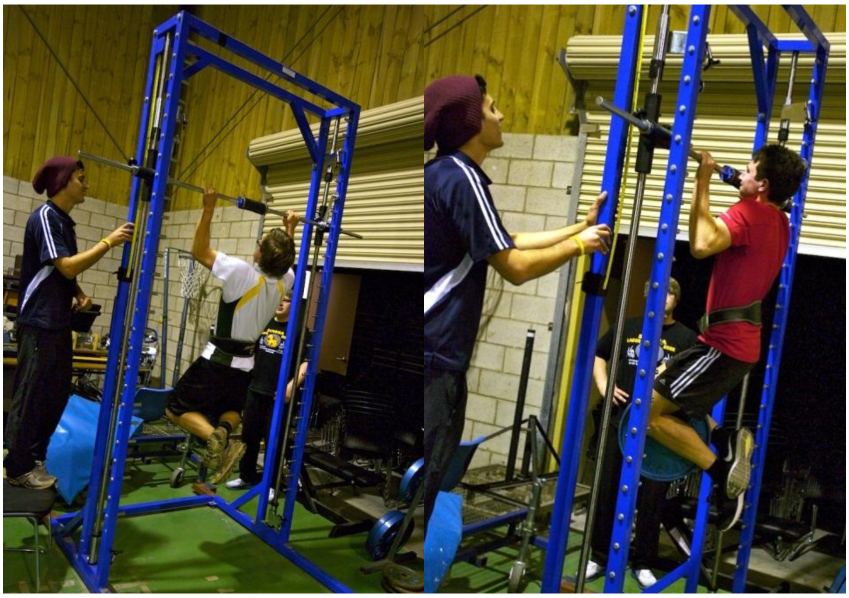

Figure 4.7. The 1-RM Smith Machine pull-up test.

The technique of this test required participants to adopt a pronated but slightly wider than shoulder-width grip on the Smith Machine bar. Without jumping, participants were instructed to pull their body upwards so that their chin cleared the bar. Upon lowering, they had to achieve a “full-hang” position (elbows fully extended). Participants were instructed to inhale during the concentric (raising) phase, and exhale throughout the eccentric (lowering) phase. They were permitted to cross their legs throughout, but to not swing from their hips to generate momentum.

A warm-up set of three repetitions at the participant's body mass was initially performed to ensure correct pull-up technique. Some participants could only achieve one repetition at body-mass load, while others could not complete a repetition with this load. Participants who could not complete the test did not receive a score for this test. Nevertheless, for those with sufficient pull-up strength, two repetitions were conducted from each set afterwards, with a safe but gradual increase in load (based on observation and participant feedback), until "technical failure" occurred on the second repetition. Technical failure was evident on this test if participants could not complete full range of motion (i.e., raise their chin above the bar) (197). Load was increased via a weight-belt and chain that accommodated weight plates. At the end of a testing set (two repetitions), participants were asked how many more repetitions they could have performed, and the amount of weight added for next set varied from 2.5–5 kg so that technical failure could be met or almost met on the next testing set. This mass was added with the participant's consent. The 1-RM load was typically determined within five testing sets, to minimise the effects of fatigue on subsequent sets (193). A four minute passive rest was employed between testing sets, as this is believed to be sufficient for central nervous system recovery (194). Encouragement was provided with every repetition. Performance on this test was characterised by the absolute mass lifted (body-mass plus additional weight). Although the test-retest reliability of the 1-RM pull-up is equivocal, the maximal amount of pull-ups at 80% 1-RM exhibits excellent test-retest reliability (ICC = 0.92–0.96) (197).

4.2.3.6 10 × 20-m repeat-sprint test

The 10 × 20-m repeat-sprint test was included as a measure of repeat-sprint-ability (Figure 4.8). Pace bowlers usually repeatedly run (sub-maximally) in the run-up throughout all game formats (76). A 20-m sprint distance was chosen as this is close to the typical run-up employed by Australian medium-fast bowlers (17.7 ± 4.1 m) (25). Furthermore, final 5-m run-up speed positively associates with bowling speed (25). Speed-acceleration may be important for pace bowlers who employ a short run-up, where they may need to quickly accelerate to optimal speed. Ten sprints were chosen as a means of overload; as pace bowlers are typically conditioned to at least six efforts per over in a game.

Figure 4.8. The 10 × 20-m repeat-sprint test.

Three pairs of dual-beam electronic timing gates (Swift Performance Equipment, Lismore, Australia), were positioned at 0 m, 10 m, and 20 m. The timing gates had a timing resolution of 0.01 s. Synthetic turf was placed on top of an all-purpose floor to minimise slipping, and was fixed down with carpet tape (Figure 4.8). A white starting line was marked on the carpet at 0 m.

Participants completed five 20-m runs at 50%, 60%, 70%, 80%, and 90% of maximum effort, to serve as a warm-up prior to the test. The technique used for the sprint comprised a stationary split stance, with the participant's preferred leg at the starting line, and his opposite arm in front of his body. Following the warm-up, participants were instructed to "sprint as fast as possible for each repetition", with no "rocking" backwards and forwards at the starting line, departing every 20 s. After each sprint, participants jogged back to the starting line, and received a five second countdown prior to their next sprint. One assistant monitored a stopwatch and provided feedback on timing, while another recorded 10-m and 20-m split times for each sprint. Another helper provided continual encouragement throughout the test. A fourth assistant checked starting technique. The first 20-m sprint of this test was taken as a measure of speed-acceleration performance, while the sum of 10 sprints was used to calculate total sprint time. Ideal sprint time was calculated by multiplying the time of the first 20-m sprint by 10. The percent decrement score was obtained by dividing the ideal sprint time by total sprint time (198). Although the test-retest reliability of the 10 × 20-m repeat-sprint test is not understood, the percent decrement score is a valid and reliable measurement of quantifying fatigue in repeat-sprints (198, 199). Furthermore, 10-m and 20-m sprints exhibit high test-retest reliability (ICC = 0.87 and 0.96 respectively, CV = 1.9% and 1.3% respectively) (200).

4.2.3.7 Drop jump test

The drop jump test was included as a measure of lower-body reactive strength (201); the ability to change quickly from an eccentric to concentric muscular contraction (202). Reactive strength may be important for pace bowlers who adopt a "flexor-extender" front leg technique (62) in the power phase. The flexor-extender front leg technique associates with larger ground reaction forces, and a faster time to peak force (62), which may assist in generating greater bowling speed.

The drop jump test involved testing a participant's reactive strength index; jump height (cm) divided by ground-contact time (ms) (203), from a variety of box heights. However, the initial box height was set at 30 cm, and was progressed by 15 cm (maximum box height of 75 cm), every three jumps, until the participant's reactive strength index score diminished with an increase in box height. The participant's peak reactive strength index score (from any box height) was chosen for analysis. The drop jump test exhibits excellent test-retest reliability (ICC = 0.967) (202).

The technique of the drop jump comprised participants standing on the box, with the balls of their feet hanging over the edge. Participants were instructed to "jump for maximal height and minimal ground-contact time" (201). They placed their hands on their hips, so that an arm-swing could not be used. Participants stepped off the box, landed on their forefeet with extended legs, and performed an explosive jump (Figure 4.9). They were instructed to land with fully extended legs from the rebound jump, but to flex at the hips, knees, and ankles to absorb the vertical ground reaction forces (201). A contact mat system (Swift Performance Equipment, Queensland, Australia) and custom-made computer software was used to compute jump height from ground contact time data (Figure 4.9) (204). Jump height was calculated by Equation 4.1 (202):

Equation 4.1. $\text{Jump height (m)} = [\text{gravity } \times (\text{flight time})^2] \div 8$

*Where *gravity* refers to acceleration due to gravity (9.81 $m \cdot s^{-1}$), and *flight time* is expressed in seconds.

Figure 4.9. The drop jump test. The participant in this figure stepped off a 60-cm box.

4.2.3.8 Maximal multi-stage 20-m shuttle run

The maximal multi-stage 20-m shuttle run test is an estimation of aerobic power (205). This test was included because aerobic power is thought to influence repeat-sprint ability performance (206), which is evident during pace bowling (76). Furthermore, the contribution of the aerobic energy system towards repeat-sprint ability performance is thought to increase with greater sprint duration, more sprints per bout, and lower rest periods between efforts (207).

In the maximal multi-stage 20-m shuttle run test, participants ran between two cones placed 20 m apart from each other (Figure 4.10). Synthetic carpet was fixed at each end to reduce slipping with the change of direction required between shuttles. The maximal multi-stage 20-m shuttle run test commenced at a required running speed of $\approx 2.4\ m{\cdot}s^{-1}$, and increased by $\approx 0.1\ m{\cdot}s^{-1}$ every minute. Participants were instructed to complete each 20-m shuttle by the time of the next audible “beep”. This test was terminated when participants did not reach the cone on two consecutive beeps. Participants were verbally encouraged throughout the entire test. The participant’s relative maximal oxygen consumption and utilisation score ($\dot{V}O_{2max}$) were estimated by the total of 20-m shuttles completed (205), and served as the measure of aerobic power in this study. The maximal multi-stage 20-m shuttle run test exhibits excellent test-retest reliability ($r = 0.95$) (208), and possesses excellent concurrent validity (209).

Figure 4.10. The maximal multi-stage 20-m shuttle run test.

4.2.3.9 Prone hold for maximal duration

The prone hold for maximal duration was included as an isometric trunk-endurance test. This test primarily targets the trunk musculature (210), with a contraction of the transversus abdominis muscle evident (210). Although the pace bowling motion is dynamic, the transversus abdominis muscle isometrically stabilises the trunk region during isometric (211) and dynamic movements (212).

In this test, participants were instructed to support their body-mass on their forearms and toes. The elbows were placed underneath the shoulder, with palms flat on a foam mat. Participants were also instructed to "lift their hips off the mat, maintain a neutral spine, and hold for as long as possible" (Figure 4.11). A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage that was imported into Dartfish Connect, where the duration of each participant's test was analysed, as well as their technique. Termination of this test was indicated by an inability to maintain correct technique (i.e., neutral spine). Participants were verbally encouraged throughout the test. The prone hold for maximal duration presents acceptable test-retest reliability (*r* = 0.86) (213).

Figure 4.11. The prone hold test for maximal duration.

4.2.3.10 *Side hold for maximal duration*

The side hold for maximal duration was included as an isometric trunk-endurance test for the external oblique muscle on the supporting-limb side (Figure 4.12) (210). The strength-endurance of the external obliques should be tested, as they are active during the bowling motion (214). The external obliques on left and right sides contract together to flex the trunk (215), with greater trunk flexion in the bowling motion reported to increase bowling speed, but possibly at the detriment of bowling accuracy (69). Furthermore, the external obliques cause ipsilateral trunk rotation and lateral flexion (215); motions that are evident in pace bowling (48). A greater trunk angular displacement throughout the power phase is strongly related to bowling speed ($r = 0.64$, $p < 0.05$) (68); this relationship might be influenced by external oblique strength-endurance.

In this test, participants were required to support their body-mass on a forearm and foot. The supporting-arm elbow was placed underneath the shoulder, with the palm of the hand flat on a foam mat. The non-supporting hand was placed on the pelvis. The non-supporting foot was positioned on the supporting foot. Participants were instructed to "lift their hips off the mat to maintain a straight line over their full body length, and hold for as long as possible". A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage in the sagittal plane, which was imported into Dartfish Connect to measure the duration of each participant's test, and to monitor their technique. Termination of this test was indicated by an inability to maintain correct technique (i.e., neutral spine, raised hips). Participants were verbally encouraged throughout the test. They completed both sides of the body, where the time to termination for each side was retained for analysis. The side hold test for maximal duration exhibits high test-retest reliability ($r = 0.99$) (216).

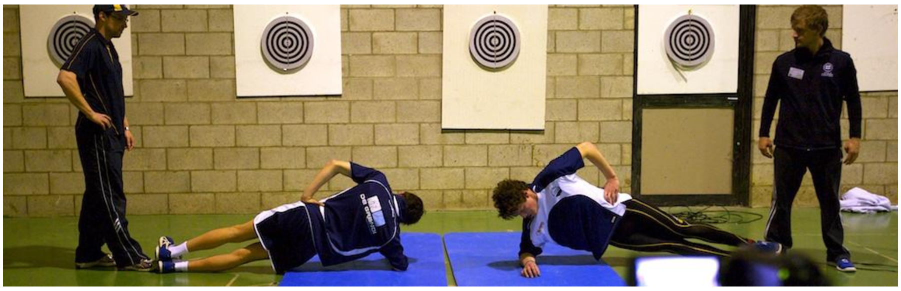

Figure 4.12. The side hold test for maximal duration.

4.2.3.11 Active straight-leg raise (bowling front-leg only)

The active straight-leg raise test was included as a measure of hamstring flexibility (217); a quality that may relate to an extended front leg technique in the power phase. An extended front leg at front-foot contact (10, 62), and at ball release (10, 13, 19, 22-24) relates to faster bowling speeds (10), possibly by maximising tangential endpoint velocity (38, 81).

Participants had their iliocristale, greater trochanter, and lateral knee joint centre marked on their bowling front leg. They adopted a supine position on a massage table with legs fully extended, and feet ≈20 cm apart. Participants were instructed to “bring their front leg towards their face as far as possible, without flexing at the knee, but to maintain a 90° angle at the foot”. The uninvolved leg rested in an extended position on the table, and their back and head remained in contact with the table. An assistant held the uninvolved leg down to assist the participant. Participants completed this test when warm, as they had performed lower-body physical tests beforehand. A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage in the sagittal plane, which was imported into Dartfish Connect to determine the largest range of motion (with correct technique), and to estimate the angle of the pelvis in relation to the iliocristale, based on the location of markers (Figure 4.13). Note, the reflex angle was calculated and retained for analysis, by subtracting the acute or obtuse angle from 180°. Although the test-retest reliability of the active straight-leg raise test is equivocal, the passive straight-leg raise test presents high test-retest reliability (ICC= 0.93, SEM = 2.5°) (218).

Figure 4.13. The active straight-leg raise test on the bowling front-leg. Note the reflex angle in this example would be 70.5°.

4.2.3.12 Bowling-arm shoulder horizontal abduction

The bowling-arm shoulder horizontal abduction test was included as a measure of pectoral flexibility (215). In pace bowling, the ability to delay circumduction of the bowling-arm correlates with bowling speed (13). Such a delay, combined with vigorous trunk flexion, is suggested to create an "inertial lag" on the bowling-arm, where a pre-stretch occurs in the anterior shoulder musculature (i.e., pectoralis major) (71). This pre-stretch is thought to store elastic energy, which would assist with faster bowling-arm circumduction and thus greater bowling speed (71).

Participants had their acromiale marked on both shoulders, and their lateral elbow joint centre marked on the bowling-arm side. Participants adopted a supine position on a massage table, and laterally positioned their body to the edge of the table, ipsilateral to the bowling-arm. An assistant placed gentle pressure on the contralateral shoulder to prevent the participant from rolling off the table. Participants were passively placed in 90° shoulder abduction, with a supinated forearm. From this position, they were instructed to "let their arm hang as low as possible, with their palm facing the ceiling, and remain relaxed". An assistant stood in the sagittal plane and ensured the bowling-arm maintained 90° shoulder abduction throughout the test. A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage in the frontal plane, which was imported into Dartfish Connect to determine the largest range of motion, and to estimate the angle of the shoulder segment (acromiale to acromiale) in relation to the lateral elbow joint centre (Figure 4.14). This reflex angle was retained for analysis. The bowling-arm shoulder horizontal abduction test is novel, and therefore its test-retest reliability is not understood. However, as horizontal adduction is a function of the pectoralis major muscle (215), this test may possess great construct validity.

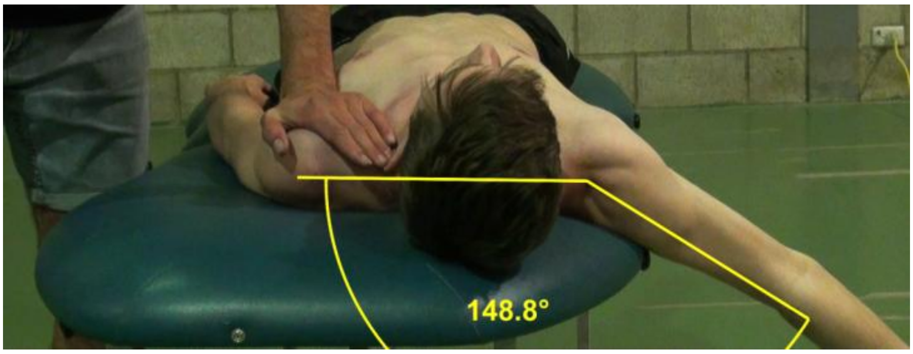

Figure 4.14. Bowling-arm shoulder horizontal abduction test.

4.2.3.13 Body mass, standing height, bowling-arm reach height

Body mass was obtained with the participant standing on a set of digital scales, with minimal clothing (i.e., no shoes, socks, jumpers, pants), and was recorded to the nearest 0.01 kg. The participant's standing height was assessed on a stadiometer, with no shoes or socks, following the free-standing method (219).

Bowling-arm reach height was also assessed, as a greater reach may positively relate to bowling speed. This test provides a slightly different measure to standing height, as it accounts for bowling-arm length. Glazier, Paradisis (12) postulated that a longer bowling-arm will increase bowling speed; given there is no change in bowling-arm angular velocity. In this test, participants stood upright, with their backs flat and heels against a brick wall (not wearing shoes or socks), and raised their bowling-arm as high as possible, while maintaining level shoulders (i.e., no scapular elevation or upward rotation) (Figure 4.15). An assistant placed downward pressure on the participant's shoulders to maintain a horizontal position. Another assistant marked the wall with chalk, and a ruler was used to measure the length from the ground to the wall mark. The bowling-arm reach height test is novel, and its test-retest reliability has not been established. Body mass, standing height, and bowling-arm reach height were assessed because they may associate with bowling performance. If true, then these variables would need to be controlled for when exploring the relationships between selected bowling kinematics and bowling performance measures.

Figure 4.15. The measurement of bowling-arm reach height.

4.2.4 Bowling kinematic and performance testing procedures

The eight-over version of the pace bowling test was used to measure selected bowling kinematics and bowling performance measures, previously detailed in Study 1 (Study 1). This version was chosen over the first four overs of the test because it possessed slightly greater test-retest reliability, and would be a more valid measure of consistency of bowling speed and consistency of bowling accuracy, as it is more likely that fatigue would be elicited from a longer pace bowling test. The indoor ambient temperature and humidity during the bowling test were not recorded, as most bowlers commenced their run-up outside (but under cover), and delivered the ball inside. Consequently, most bowlers were exposed to cooler temperatures outside, and warmer temperatures inside.

4.2.5 Statistical analyses

All statistical analyses were performed using SPSS (Version 19, IBM Corp.). The mean and *SD* of physical qualities, bowling kinematics, and bowling performance measures were calculated to provide insight into the performance of the participants. Many variables violated the normal distribution (deemed by a Shapiro-Wilk test), and thus Spearman’s rank order correlations (two-tailed) were performed instead of multiple regression analysis to assess the relationships between selected physical qualities, bowling kinematics, and bowling performance measures. The links between physical qualities and bowling performance variables for each delivery instruction (i.e., match-intensity, maximal-effort, slower-ball) and for all delivery instructions pooled together were calculated using Spearman’s rank order correlations (two-tailed). The associations between physical qualities and bowling kinematics, as well as bowling kinematics and bowling performance measures were performed for all delivery instructions pooled together. For all correlations, missing data were treated by excluding cases pairwise, and not listwise. The relationships between bowling speed and bowling accuracy were evaluated for the group, and for each bowler using Spearman’s rank order correlations (two-tailed), with all delivery types pooled together. Mean bowling speed and mean bowling accuracy were extracted from each bowler for the calculation of the group speed-accuracy relationship. For the within-bowler analysis, each delivery served as its own trial. Correlations were classified using modified Hopkins (220) thresholds / descriptors as follows: trivial ($r < 0.10$), small ($r = 0.10–0.29$), moderate ($r = 0.30–0.49$), large ($r = 0.50–0.69$), very large ($r = 0.70–0.90$), and nearly perfect ($r > 0.90$). These descriptors were used to identify differences in the strength of correlations with each delivery instruction. Significance was set at $p < 0.05$ for all analyses.

4.3 Results

The descriptive data of physical tests, bowling kinematics, and bowling performance measures are presented in Table 4.1, Table 4.2, and Table 4.3 respectively. Some variables contain missing data, as not all participants completed physical testing due to injury concerns or malfunctioning equipment. The knee extension angles could not be estimated for some bowlers due to excessive foot inversion or eversion.

There were a shortage of significant ($p < 0.05$) correlations between physical qualities and bowling performance measures. Large significant relationships ($p < 0.05$) between 1-RM pull-up strength and bowling speed for each delivery instruction (and overall) were observed (Table 4.4). The strength of these correlations marginally increased with delivery effort. Moderate significant relationships ($p < 0.05$) between 20-m sprint time and bowling speed for each delivery instruction (and overall) were identified, but significance was only detected with maximal-effort and match-intensity deliveries. Regardless, the strength of these correlations slightly increased with greater delivery effort.

Greater straight-leg raise flexibility was moderately related ($p < 0.05$) to the consistency of bowling speed for a match-intensity delivery (Table 4.5). No other physical qualities were significantly correlated ($p < 0.05$) with consistency of bowling speed.

Slower 10-m and 20-m sprint times were moderately and significantly associated with poorer bowling accuracy overall ($p < 0.05$), but not for each delivery instruction (Table 4.6). Greater peak countermovement jump height was significantly related to better bowling accuracy overall ($p < 0.05$), but not for each delivery instruction. The associations between bowling accuracy and concentric peak power from three countermovement jumps were stronger with a maximal-effort delivery, as opposed to a match-intensity delivery. A greater reactive strength index associated with poorer bowling accuracy and consistency of bowling accuracy for maximal-effort deliveries only ($p < 0.05$).

A greater standing height was significantly related to poorer consistency of bowling accuracy for a slower-ball delivery ($p < 0.05$) (Table 4.7). No other physical qualities significantly related ($p > 0.05$) to the consistency of bowling accuracy.

3-RM bench press strength was significantly related with overall approach speed ($p < 0.05$) (Table 4.8). A greater performance on the straight-leg raise test was significantly correlated to overall step-length phase duration ($p < 0.05$). Predicted $\dot{V}O_{2max}$ and reaching height were significantly associated with the power phase duration ($p < 0.05$).

A greater bench press power-endurance was significantly associated with a more extended front-leg at front-foot contact ($p < 0.05$) (Table 4.8). No other physical qualities were significantly associated with step length, and knee extension angle at front foot contact and at ball release ($p > 0.05$).

A faster power phase duration and longer step length were significantly related to bowling speed ($p < 0.05$), while a faster approach speed and greater knee flexion angle at the moment of ball release were significantly associated ($p < 0.05$) with a better consistency of accuracy (Table 4.9). No kinematic qualities were significantly correlated to consistency of bowling speed or bowling accuracy ($p > 0.05$).

Table 4.1. Descriptive data of physical qualities.

Physical quality	***n***	**Mean ± *SD***	**CV%**
Body-mass (kg)	31	81.9 ± 12.9	15.8
Height (cm)	31	182.4 ± 6.3	3.5
Reaching height – bowling-arm side (cm)	29	230.6 ± 11.2	4.9
3 repetition maximum half squat (kg)	30	124.2 ± 35.8	28.8
3 repetition maximum bench press (kg)	26	64.6 ± 11.7	18.1
1 repetition maximum pull-up (kg)	24	87.3 ± 10.9	12.5
Predicted $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	27	49.7 ± 7.2	14.5
10-m sprint time (s)	28	1.95 ± 0.09	4.6
20-m sprint time (s)	30	3.28 ± 0.13	4.0
Decrement score from 10 × 20-m sprints (%)	21	7.7 ± 4.2	54.5
Best reactive strength index (contact time ÷ jump height)	30	140.9 ± 36.5	25.9
Best height of 3 countermovement jumps (cm)	28	40.5 ± 6.1	15.1
Mean height of 20 countermovement jumps (cm)	27	37.6 ± 5.6	14.9
Best CPP of 3 countermovement jumps (W)	28	4000.2 ± 639.0	16.0
Mean CPP of 20 countermovement jumps (W)	27	3960.6 ± 621.1	15.7
Best height of 3 bench press throws (cm)	29	30.8 ± 5.9	19.2
Mean height of 20 bench press throws (cm)	28	23.7 ± 5.2	21.9
Side hold – bowling-arm side (s)	28	65.2 ± 22.0	33.7
Side hold – non-bowling-arm side (s)	30	67.2 ± 28.7	42.7
Prone hold (s)	30	114.9 ± 54.6	47.5
SLR ROM – non-bowling-arm side (°)	29	71.9 ± 12.2	17.0
SHA ROM – bowling-arm side (°)	27	147.4 ± 10.1	6.9

CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.2. Descriptive data of bowling-kinematic measures for all delivery instructions pooled, and for each delivery instruction.

		Overall (n = 48)	***Maximal-effort (n = 4)***	***Match-intensity (n = 40)***	***Slower-ball (n = 4)***
Bowling-kinematic measure	***n***	**Mean ± *SD***	**Mean ± *SD***	**Mean ± *SD***	**Mean ± *SD***
Mean					
Approach speed (m$\cdot$s^{-1})	31	5.5 ± 0.7	5.6 ± 0.7	5.5 ± 0.7	5.4 ± 0.7
Step-length phase duration (s)	31	0.19 ± 0.03	0.19 ± 0.04	0.19 ± 0.3	0.20 ± 0.03
Power phase duration (s)	31	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.13	0.12 ± 0.01
Step length (cm)	31	138.1 ± 19.8	139.2 ± 19.8	137.9 ± 19.9	138.6 ± 19.9
Knee extension angle at front-foot contact (°)	21	158.9 ± 4.3	159.2 ± 4.0	158.9 ± 4.3	158.9 ± 5.3
Knee extension angle at ball release (°)	27	146.2 ± 21.5	146.7 ± 22.3	146.4 ± 21.5	144.2 ± 21.2

Table 4.3. Descriptive data of bowling performance measures for all delivery instructions pooled, and for each delivery instruction.

		Overall (n = 48)	***Maximal-effort (n = 4)***	***Match-intensity (n = 40)***	***Slower-ball (n = 4)***
Bowling performance measure	***n***	**Mean ± *SD***	**Mean ± *SD***	**Mean ± *SD***	**Mean ± *SD***
Mean					
Bowling speed (m$\cdot$s^{-1})	31	28.6 ± 2.1	29.7 ± 1.9	28.8 ± 2.1	24.9 ± 2.4
Bowling accuracy (cm)	31	42.6 ± 5.8	42.5 ± 14.3	42.3 ± 5.9	45.3 ± 21.3
Perceived effort (% of 100)	31	86.2 ± 4.4	95.6 ± 4.0	86.1 ± 4.6	77.8 ± 9.3
Consistency					
Bowling speed (m$\cdot$s^{-1})	31	1.4 ± 0.4	0.6 ± 0.4	2.7 ± 0.8	0.7 ± 0.4
Bowling accuracy (cm)	31	47.2 ± 7.2	42.8 ± 13.7	47.9 ± 7.6	52.8 ± 21.0

Table 4.4. The relationships between physical qualities and bowling speed for all delivery instructions pooled, and for each delivery instruction.

		Bowling speed							
		Overall		***Maximal-effort***		***Match-intensity***		***Slower-ball***	
Physical quality	***n***	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**
Body-mass (kg)	31	0.22	Small	0.11	Small	0.23	Small	0.09	Trivial
Height (cm)	31	0.15	Small	0.08	Trivial	0.17	Small	0.07	Trivial
Reaching height – bowling-arm side (cm)	29	< 0.01	Trivial	-0.08	Trivial	< 0.01	Trivial	-0.01	Trivial
3 repetition maximum half squat (kg)	30	0.14	Small	0.09	Trivial	0.14	Small	0.16	Small
3 repetition maximum bench press (kg)	26	0.29	Small	0.29	Small	0.31	Moderate	0.29	Small
1 repetition maximum pull-up (kg)	24	0.55**	Large	0.56**	Large	0.55**	Large	0.53**	Large
Predicted $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	27	0.09	Trivial	0.12	Small	0.09	Trivial	-0.02	Trivial
10-m sprint time (s)	28	-0.31	Moderate	-0.35	Moderate	-0.29	Small	-0.38*	Moderate
20-m sprint time (s)	30	-0.37*	Moderate	-0.42*	Moderate	-0.36	Moderate	-0.33	Moderate
Decrement score from 10 × 20-m sprints (%)	21	0.08	Trivial	-0.01	Trivial	0.15	Small	0.02	Trivial
Best reactive strength index (contact time ÷ jump height)	30	-0.05	Trivial	0.08	Trivial	-0.07	Trivial	-0.05	Trivial
Best height of 3 countermovement jumps (cm)	28	0.18	Small	0.21	Small	0.18	Small	0.04	Trivial
Mean height of 20 countermovement jumps (cm)	27	0.23	Small	0.29	Small	0.22	Small	0.15	Small
Best CPP of 3 countermovement jumps (W)	28	0.25	Small	0.13	Small	0.26	Small	0.02	Trivial
Mean CPP of 20 countermovement jumps (W)	27	0.34	Moderate	0.21	Small	0.36	Moderate	0.09	Trivial
Best height of 3 bench press throws (cm)	29	0.18	Small	0.28	Small	0.16	Small	0.28	Small
Mean height of 20 bench press throws (cm)	28	0.25	Small	0.34	Moderate	0.22	Small	0.28	Small
Side hold – bowling-arm side (s)	28	-0.09	Trivial	-0.09	Trivial	-0.09	Trivial	-0.17	Small
Side hold – non-bowling-arm side (s)	30	0.07	Trivial	0.03	Trivial	0.06	Trivial	0.03	Trivial
Prone hold (s)	30	0.11	Small	0.18	Small	0.10	Small	0.03	Trivial
SLR ROM – non-bowling-arm side (°)	29	0.32	Moderate	0.17	Small	0.34	Moderate	0.19	Small
SHA ROM – bowling-arm side (°)	27	0.22	Small	0.28	Small	0.20	Small	0.40*	Moderate

*, $p < 0.05$; **, $p < 0.01$; CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.5. The relationships between physical qualities and consistency of bowling speed for all delivery instructions pooled, and for each delivery instruction.

		Consistency of bowling speed							
		Overall		***Maximal-effort***		***Match-intensity***		***Slower-ball***	
Physical quality	***n***	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**
Body-mass (kg)	31	-0.09	Trivial	-0.15	Small	-0.22	Small	0.10	Small
Height (cm)	31	-0.04	Trivial	-0.09	Trivial	-0.07	Trivial	0.05	Trivial
Reaching height – bowling-arm side (cm)	29	-0.14	Small	-0.15	Small	-0.03	Trivial	0.01	Trivial
3 repetition maximum half squat (kg)	30	-0.15	Small	0.30	Moderate	-0.05	Trivial	-0.25	Small
3 repetition maximum bench press (kg)	26	0.02	Trivial	0.21	Small	-0.09	Trivial	-0.32	Moderate
1 repetition maximum pull-up (kg)	24	-0.07	Trivial	0.26	Small	< 0.01	Trivial	-0.09	Trivial
Predicted $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	27	0.18	Small	0.24	Small	-0.06	Trivial	-0.19	Small
10-m sprint time (s)	28	0.05	Trivial	-0.19	Small	-0.01	Trivial	0.01	Trivial
20-m sprint time (s)	30	-0.12	Small	-0.29	Small	-0.01	Trivial	< 0.01	Trivial
Decrement score from 10 × 20-m sprints (%)	21	0.01	Trivial	-0.23	Small	-0.42	Moderate	0.21	Small
Best reactive strength index (contact time ÷ jump height)	30	0.15	Small	0.21	Small	0.29	Small	0.07	Trivial
Best height of 3 countermovement jumps (cm)	28	0.24	Small	0.09	Trivial	0.12	Small	-0.05	Trivial
Mean height of 20 countermovement jumps (cm)	27	0.17	Small	0.17	Small	0.07	Trivial	-0.08	Trivial
Best CPP of 3 countermovement jumps (W)	28	0.09	Trivial	-0.08	Trivial	-0.12	Small	0.12	Small
Mean CPP of 20 countermovement jumps (W)	27	0.05	Trivial	0.05	Trivial	-0.17	Small	0.09	Trivial
Best height of 3 bench press throws (cm)	29	-0.04	Trivial	0.21	Small	0.09	Trivial	-0.14	Small
Mean height of 20 bench press throws (cm)	28	-0.05	Trivial	0.31	Moderate	0.01	Trivial	-0.16	Small
Side hold – bowling-arm side (s)	28	0.07	Trivial	-0.12	Small	0.01	Trivial	-0.11	Small
Side hold – non-bowling-arm side (s)	30	-0.02	Trivial	< 0.01	Trivial	-0.16	Small	-0.12	Small
Prone hold (s)	30	0.23	Small	0.23	Small	0.04	Trivial	-0.08	Trivial
SLR ROM – non-bowling-arm side (°)	29	-0.07	Trivial	-0.03	Trivial	-0.49*	Moderate	-0.13	Small
SHA ROM – bowling-arm side (°)	27	< 0.01	Trivial	0.27	Small	0.33	Moderate	-0.25	Small

*, $p < 0.05$; CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.6. The relationships between physical qualities and bowling accuracy for all delivery instructions pooled, and for each delivery instruction.

		Bowling accuracy							
		Overall		***Maximal-effort***		***Match-intensity***		***Slower-ball***	
Physical quality	***n***	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**
Body-mass (kg)	31	-0.07	Trivial	-0.41*	Moderate	-0.08	Trivial	0.26	Small
Height (cm)	31	-0.12	Small	-0.19	Small	-0.15	Small	0.22	Small
Reaching height – bowling-arm side (cm)	29	-0.28	Small	-0.31	Moderate	-0.21	Small	0.06	Trivial
3 repetition maximum half squat (kg)	30	-0.25	Small	-0.31	Moderate	-0.15	Small	0.12	Small
3 repetition maximum bench press (kg)	26	-0.18	Small	-0.42*	Moderate	-0.08	Trivial	0.09	Trivial
1 repetition maximum pull-up (kg)	24	-0.18	Small	-0.38	Moderate	-0.13	Small	0.21	Small
Predicted $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	27	-0.23	Small	0.01	Trivial	-0.27	Small	0.13	Small
10-m sprint time (s)	28	0.41*	Moderate	-0.19	Small	0.33	Moderate	0.32	Moderate
20-m sprint time (s)	30	0.38*	Moderate	-0.15	Small	0.32	Moderate	0.22	Small
Decrement score from 10 × 20-m sprints (%)	21	-0.19	Small	-0.04	Trivial	-0.09	Trivial	-0.37	Moderate
Best reactive strength index (contact time ÷ jump height)	30	-0.04	Trivial	0.38*	Moderate	< 0.01	Trivial	-0.13	Small
Best height of 3 countermovement jumps (cm)	28	-0.39*	Moderate	-0.20	Small	-0.28	Small	-0.06	Trivial
Mean height of 20 countermovement jumps (cm)	27	-0.33	Moderate	0.07	Trivial	-0.27	Small	-0.12	Small
Best CPP of 3 countermovement jumps (W)	28	-0.41*	Moderate	-0.47*	Moderate	-0.37	Moderate	0.12	Small
Mean CPP of 20 countermovement jumps (W)	27	-0.45*	Moderate	-0.47*	Moderate	-0.39*	Moderate	0.06	Trivial
Best height of 3 bench press throws (cm)	29	-0.13	Small	-0.22	Small	-0.07	Trivial	0.11	Small
Mean height of 20 bench press throws (cm)	28	-0.08	Trivial	-0.31	Moderate	-0.03	Trivial	0.16	Small
Side hold – bowling-arm side (s)	28	-0.23	Small	-0.15	Small	-0.18	Small	0.08	Trivial
Side hold – non-bowling-arm side (s)	30	-0.34	Moderate	-0.11	Small	-0.29	Small	-0.04	Trivial
Prone hold (s)	30	-0.09	Trivial	0.28	Small	-0.02	Trivial	-0.17	Small
SLR ROM – non-bowling-arm side (°)	29	-0.29	Small	-0.12	Small	-0.23	Small	-0.04	Trivial
SHA ROM – bowling-arm side (°)	27	0.11	Small	0.13	Small	0.09	Trivial	-0.22	Small

*, $p < 0.05$; CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.7. The relationships between physical qualities and consistency of bowling accuracy for all delivery instructions pooled, and for each delivery instruction.

		Consistency of bowling accuracy							
		Overall		***Maximal-effort***		***Match-intensity***		***Slower-ball***	
Physical quality	***n***	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**
Body-mass (kg)	31	-0.01	Trivial	-0.21	Small	-0.03	Trivial	0.30	Moderate
Height (cm)	31	< 0.01	Trivial	-0.24	Small	< 0.01	Trivial	0.36*	Moderate
Reaching height – bowling-arm side (cm)	29	-0.11	Small	-0.18	Small	-0.13	Small	0.16	Small
3 repetition maximum half squat (kg)	30	-0.25	Small	-0.16	Small	-0.18	Small	0.12	Small
3 repetition maximum bench press (kg)	26	-0.28	Small	-0.27	Small	-0.11	Small	0.09	Trivial
1 repetition maximum pull-up (kg)	24	-0.07	Trivial	0.02	Trivial	-0.14	Small	0.16	Small
Predicted $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	27	-0.19	Small	-0.08	Trivial	-0.24	Small	0.08	Trivial
10-m sprint time (s)	28	0.09	Trivial	-0.14	Small	0.08	Trivial	0.16	Small
20-m sprint time (s)	30	0.06	Trivial	-0.09	Trivial	0.02	Trivial	< 0.01	Trivial
Decrement score from 10 × 20-m sprints (%)	21	-0.17	Small	-0.18	Small	0.03	Trivial	-0.16	Small
Best reactive strength index (contact time ÷ jump height)	30	0.26	Small	0.43*	Moderate	0.20	Small	-0.22	Small
Best height of 3 countermovement jumps (cm)	28	-0.19	Small	-0.06	Trivial	-0.12	Small	0.05	Trivial
Mean height of 20 countermovement jumps (cm)	27	-0.09	Trivial	0.20	Small	-0.07	Trivial	-0.11	Small
Best CPP of 3 countermovement jumps (W)	28	-0.22	Small	-0.22	Small	-0.19	Small	0.19	Small
Mean CPP of 20 countermovement jumps (W)	27	-0.23	Small	-0.18	Small	-0.24	Small	0.13	Small
Best height of 3 bench press throws (cm)	29	-0.08	Trivial	0.09	Trivial	-0.11	Small	0.09	Trivial
Mean height of 20 bench press throws (cm)	28	-0.09	Trivial	0.02	Trivial	-0.10	Small	0.12	Small
Side hold – bowling-arm side (s)	28	-0.24	Small	-0.07	Trivial	-0.18	Small	0.05	Trivial
Side hold – non-bowling-arm side (s)	30	-0.26	Small	-0.05	Trivial	-0.21	Small	-0.08	Trivial
Prone hold (s)	30	-0.02	Trivial	0.28	Small	< 0.01	Trivial	-0.18	Small
SLR ROM – non-bowling-arm side (°)	29	-0.33	Moderate	-0.27	Small	-0.21	Small	0.01	Trivial
SHA ROM – bowling-arm side (°)	27	-0.05	Trivial	-0.01	Trivial	-0.17	Small	-0.27	Small

*, $p < 0.05$; CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.8. The relationships between physical qualities and bowling-kinematic variables for all delivery instructions pooled (Part 1).

	Approach Speed			**Step-length phase duration**			**Power phase duration**		
Physical quality	r_s	**descriptor**	***n***	r_s	**descriptor**	***n***	r_s	**descriptor**	***n***
Body-mass (kg)	< 0.01	Trivial	31	0.03	Trivial	31	0.21	Small	31
Height (cm)	-0.06	Trivial	31	0.09	Trivial	31	0.27	Small	31
Reaching height – bowling-arm side (cm)	-0.12	Small	29	0.01	Trivial	29	0.52**	Large	29
3 repetition maximum half squat (kg)	0.06	Trivial	30	0.09	Trivial	30	-0.32	Moderate	30
3 repetition maximum bench press (kg)	0.41*	Moderate	26	0.01	Trivial	26	-0.23	Small	26
1 repetition maximum pull-up (kg)	0.24	Small	24	-0.14	Small	24	-0.02	Trivial	24
Predicted $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	0.09	Trivial	27	-0.19	Small	27	-0.42*	Moderate	27
10-m sprint time (s)	0.01	Trivial	28	-0.07	Trivial	28	0.13	Small	28
20-m sprint time (s)	-0.15	Small	30	-0.01	Trivial	30	0.26	Small	30
Decrement score from 10 × 20-m sprints (%)	0.31	Moderate	21	0.31	Moderate	21	0.13	Small	21
Best reactive strength index (contact time ÷ jump height)	0.08	Trivial	30	-0.28	Small	30	-0.07	Trivial	30
Best height of 3 countermovement jumps (cm)	0.06	Trivial	28	-0.13	Small	28	-0.30	Moderate	28
Mean height of 20 countermovement jumps (cm)	0.18	Small	27	-0.20	Small	27	-0.22	Small	27
Best CPP of 3 countermovement jumps (W)	0.17	Small	28	0.03	Trivial	28	0.12	Small	28
Mean CPP of 20 countermovement jumps (W)	0.09	Trivial	27	0.08	Trivial	27	0.18	Small	27
Best height of 3 bench press throws (cm)	0.20	Small	29	-0.13	Small	29	0.11	Small	29
Mean height of 20 bench press throws (cm)	0.16	Small	28	-0.20	Small	28	0.14	Small	28
Side hold – bowling-arm side (s)	0.01	Trivial	28	-0.13	Small	28	-0.18	Small	28
Side hold – non-bowling-arm side (s)	0.29	Small	30	0.05	Trivial	30	-0.09	Trivial	30
Prone hold (s)	0.13	Small	30	0.09	Trivial	30	-0.35	Moderate	30
SLR ROM – non-bowling-arm side (°)	0.15	Small	29	0.46*	Moderate	29	-0.14	Small	29
SHA ROM – bowling-arm side (°)	0.17	Small	27	-0.02	Trivial	27	-0.08	Trivial	27

*, $p < 0.05$; CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.8. The relationships between physical qualities and bowling-kinematic variables for all delivery instructions pooled (Part 2).

	Step length			**Knee extension angle at FFC**			**Knee extension angle at BR**		
Physical quality	r_s	**descriptor**	n	r_s	**descriptor**	n	r_s	**descriptor**	n
Body-mass (kg)	0.13	Small	31	-0.09	Trivial	21	-0.08	Trivial	27
Height (cm)	0.17	Small	31	-0.04	Trivial	21	-0.06	Trivial	27
Reaching height – bowling-arm side (cm)	0.01	Trivial	29	-0.07	Trivial	20	-0.18	Small	26
3 repetition maximum half squat (kg)	0.30	Moderate	30	-0.15	Small	20	-0.01	Trivial	27
3 repetition maximum bench press (kg)	0.10	Small	26	-0.41	Moderate	18	-0.38	Moderate	24
1 repetition maximum pull-up (kg)	0.35	Moderate	24	-0.18	Small	16	-0.06	Trivial	21
Predicted $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	-0.04	Trivial	27	0.14	Small	18	-0.23	Small	24
10-m sprint time (s)	-0.21	Small	28	0.08	Trivial	19	-0.19	Small	24
20-m sprint time (s)	-0.27	Small	30	0.19	Small	21	-0.14	Small	26
Decrement score from 10 × 20-m sprints (%)	0.22	Small	21	-0.24	Small	14	-0.18	Small	19
Best reactive strength index (contact time ÷ jump height)	0.08	Trivial	30	0.02	Trivial	20	-0.11	Small	27
Best height of 3 countermovement jumps (cm)	0.26	Small	28	-0.19	Small	20	-0.12	Small	24
Mean height of 20 countermovement jumps (cm)	0.20	Small	27	-0.17	Small	19	-0.11	Small	23
Best CPP of 3 countermovement jumps (W)	0.29	Small	28	-0.17	Small	20	-0.12	Small	24
Mean CPP of 20 countermovement jumps (W)	0.30	Moderate	27	-0.32	Moderate	19	-0.11	Small	23
Best height of 3 bench press throws (cm)	0.09	Trivial	29	-0.29	Small	20	-0.07	Trivial	25
Mean height of 20 bench press throws (cm)	0.05	Trivial	28	-0.57*	Large	19	-0.07	Trivial	24
Side hold – bowling-arm side (s)	-0.07	Trivial	28	-0.16	Small	18	-0.29	Small	25
Side hold – non-bowling-arm side (s)	0.08	Trivial	30	-0.17	Small	20	-0.18	Small	27
Prone hold (s)	0.17	Small	30	0.07	Trivial	20	0.01	Trivial	27
SLR ROM – non-bowling-arm side (°)	0.24	Small	29	0.43	Moderate	20	0.18	Small	26
SHA ROM – bowling-arm side (°)	0.03	Trivial	27	-0.18	Small	18	0.03	Trivial	24

*, $p < 0.05$; FFC, front-foot contact; BR, ball release; CPP, concentric peak power; SLR, straight-leg raise; ROM, range of motion; SHA, shoulder horizontal abduction.

Table 4.9. The relationships between selected kinematic qualities and bowling performance measures for all delivery instructions pooled.

		Bowling speed		Consistency of bowling speed		Bowling accuracy		Consistency of bowling accuracy	
Kinematic quality	***n***	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**	r_s	**descriptor**
Approach speed	31	0.26	Small	0.01	Trivial	-0.35	Moderate	-0.36*	Moderate
Step-length phase duration	31	0.022	Trivial	-0.17	Small	-0.22	Small	-0.17	Small
Power phase duration	31	-0.45*	Moderate	-0.27	Moderate	0.22	Small	0.30	Moderate
Step-length	31	0.51**	Large	-0.06	Trivial	-0.32	Moderate	0.12	Small
Knee extension angle at FFC	21	0.13	Small	-0.21	Small	0.19	Small	0.23	Small
Knee extension angle at BR	27	0.07	Trivial	-0.12	Small	0.38	Moderate	0.41*	Moderate

*, $p < 0.05$; **, $p < 0.01$. FFC, front-foot contact; BR, ball release.

The individual relationships with bowling speed and bowling accuracy for all deliveries combined are presented in Table 4.10. The group analysis revealed a small negative correlation between bowling speed and bowling accuracy ($p > 0.05$). In the within-bowler analysis, three participants displayed a significant speed-accuracy trade-off ($p < 0.05$). That is, as bowling speed increased, bowling accuracy worsened. However, four participants improved bowling accuracy with an increase in bowling speed ($p < 0.05$). Not all participants bowled the entire 48 deliveries; some deliveries missed the target sheet and were not included for analysis. Participant 15 only delivered 35 balls, as the final two-overs of his bowling test were terminated due to wet weather affecting the run-up.

Table 4.10. The relationship between bowling speed and bowling accuracy within participants. A positive correlation indicates the presence of a speed-accuracy trade-off; that is, as bowling speed increases, bowling accuracy worsens.

Participant #	r_s	**Lower r_s (90% CI)**	**Upper r_s (90% CI)**	**Descriptor**	***p-Value***	**Deliveries**
1	-0.03	-0.27	0.22	Trivial	0.84	47
2	0.17	-0.08	0.40	Small	0.25	46
3	0.23	-0.01	0.45	Small	0.11	48
4	-0.20	-0.42	0.05	Small	0.17	47
5	0.41**	0.19	0.59	Moderate	< 0.01	48
6	-0.24	-0.46	0.01	Small	0.11	46
7	-0.23	-0.45	0.01	Small	0.12	47
8	0.37**	0.14	0.56	Moderate	0.01	48
9	0.18	-0.06	0.40	Small	0.23	48
10	0.17	-0.08	0.40	Small	0.26	47
11	-0.11	-0.34	0.13	Small	0.44	48
12	-0.16	-0.39	0.09	Small	0.29	47
13	-0.08	-0.32	0.17	Trivial	0.62	47
14	0.14	-0.10	0.37	Small	0.35	48
15	0.02	-0.26	0.30	Trivial	0.91	35
16	-0.01	-0.26	0.24	Trivial	0.98	46
17	0.09	-0.16	0.33	Trivial	0.55	47
18	0.08	-0.16	0.31	Trivial	0.59	48
19	-0.44**	-0.62	-0.22	Moderate	< 0.01	46
20	-0.21	-0.43	0.03	Small	0.15	47
21	0.15	-0.10	0.38	Small	0.32	47
22	0.15	-0.09	0.38	Small	0.29	48
23	-0.36*	-0.55	-0.13	Moderate	0.01	47
24	0.29*	0.05	0.50	Small	0.04	47
25	-0.21	-0.43	0.03	Small	0.15	48
26	-0.38**	-0.57	-0.15	Moderate	0.01	48
27	-0.50**	-0.66	-0.29	Large	< 0.01	46
28	0.05	-0.20	0.29	Trivial	0.74	47
29	0.09	-0.16	0.33	Trivial	0.53	47
30	-0.11	-0.34	0.13	Small	0.44	48
31	0.23	-0.01	0.45	Small	0.12	48
Overall r_s	**-0.28**			**Small**		

CI, confidence interval; *, $p < 0.05$; **, $p < 0.01$.

4.4 Discussion

This group of bowlers were of shorter stature (182.4 ± 6.3 cm) and lower body mass (81.9 ± 12.9 kg) compared to professional pace bowlers (height: 185.6 ± 6.8 cm, body mass: 86.9 ± 11.3 kg respectively) (25) (Table 4.1). The bowlers in this investigation were also slower in their approach speed (5.5 $\mathrm{m{\cdot}s^{-1}}$) than national-standard pace bowlers (6.3 $\mathrm{m{\cdot}s^{-1}}$) (25) (Table 4.2). As expected, this cohort of community-standard pace bowlers delivered at slower speeds (28.8 $\mathrm{m{\cdot}s^{-1}}$) than professional pace bowlers (34.9 $\mathrm{m{\cdot}s^{-1}}$) (25) (Table 4.3). No comparisons can be made between this group and a high performance group on the grounds of bowling accuracy, due to the differences in how this performance measure was quantified (26, 30). Faster bowlers therefore seem to be taller, and of larger body mass than slower bowlers. Faster bowlers display faster approach speeds than slower bowlers, which could be indicative of greater lower-body power capabilities.

4.4.1 Relationships between selected physical qualities, bowling kinematics, and bowling speed

The separation of the three delivery instructions (maximal-effort, match-intensity, slower-ball) is a novel approach to determine if physical qualities become more important with increased exertion. In this investigation, large positive correlations were discovered between 1-RM pull-up strength and bowling speed for each delivery instruction (r_s [24] = 0.53–0.56, $p < 0.01$), and for all delivery instructions pooled together (r_s [24] = 0.55, $p = 0.01$). Furthermore, the strength of these correlations marginally increased with delivery effort; hinting that 1-RM pull-up strength could be more important when bowlers strive for more effort and speed. The 1-RM pull-up test was included to evaluate the strength of the latissimus dorsi, biceps brachii, and lower trapezius muscles (196). The latissimus dorsi extends and internally rotates the glenohumeral joint (215), which may assist in front-arm and bowling-arm circumduction. Davis and Blanksby (42) showed that faster bowlers extend their front-arm quicker into their ribs compared to slower bowlers. A faster front-arm circumduction has also been linked with greater ball speeds in national fast bowlers ($r = 0.45$, $p < 0.05$) (60). The latissimus dorsi muscle is strongly activated during the propulsive phase of baseball pitching (189); a motion that exhibits a general proximal-to-distal segmental sequencing pattern (102), similar to pace bowling (71).

In support of the relationship between 1-RM pull-up strength and bowling speed, Wormgoor, Harden (19) discovered a positive relationship between bowling speed and internal rotation strength ($r = 0.43$, $p = 0.02$), and shoulder extension strength ($r = 0.39$, $p = 0.04$). Although speculative, latissimus dorsi strength may enhance the amount of torque produced by the bowling arm, leading to a faster ball speed. The development of bowling-arm torque could be very important, as the angular velocity of the bowling-arm does not significantly correlate to bowling speed ($r = 0.36$, $p > 0.05$) (12).

Moderate negative correlations were observed between 20-m sprint time and bowling speed for each delivery instruction, and significance was only met for a maximal-effort (r_s [30] = -0.42, $p = 0.02$) delivery. Regardless, the strength of correlations slightly increased with delivery effort. These results indicate that 20-m speed becomes more important as bowlers strive for more effort and bowling speed. Surprisingly, there was a small but non-significant correlation between 20-m sprint time and approach speed (r_s [30] = -0.15, $p = 0.43$), and approach speed did not associate with bowling speed (r_s [31] = 0.26, $p = 0.15$), refuting previous studies (6, 12, 25, 43). Concentric peak power production did not influence approach speed as previously hypothesised (r_s [27] = 0.17, $p = 0.38$). These findings suggest that faster bowlers are typically quicker over 20 m, and use more of their speed-acceleration quality when instructed to bowl with maximal-effort. However, community-standard pace bowlers do not use their speed-acceleration ability for their run-up. Instead, they may prefer to adopt a “rhythmical” run-up, rather than a fast run-up (25). The community-standard pace bowlers could also employ a longer run-up where approach speed could be gradually increased, requiring less speed-acceleration ability.

Duffield, Carney (25) showed that national-standard medium-fast bowlers may use more of their speed acceleration ability to bowl quickly, as their approach speed peaked at 89% of their peak 30-m speed, over a relatively short run-up of 17.7 ± 4.1 m (mean ± *SD*). Speed-acceleration therefore, may be more important for bowlers with shorter run-ups, as less time is available to attain optimal approach speed. The purpose of a faster approach speed is to generate kinetic energy, for transfer to the cricket ball during the step-length phase and power phase of the bowling motion (6).

A shorter power phase duration was negatively associated with bowling speed ($p < 0.05$) (Table 8). A recent study by Glazier and Worthington (11) reported no significant association between these variables, albeit a negative correlation ($r = -0.31$, $p = 0.19$). Interestingly, Glazier and Worthington (11) reported the change in horizontal velocity in the power phase to correlate with bowling speed ($r = 0.66$, $p < 0.01$). These authors suggested the magnitude of horizontal velocity reduction during this phase to be more important than the duration of the phase. Their pace bowlers were faster throughout the power phase (80–120 ms), than the bowlers in this investigation (105–150 ms), and consequently, bowled faster (34.9 $m \cdot s^{-1}$ vs. 28.8 $m \cdot s^{-1}$). These findings support the importance of decelerating the body quickly after front-foot contact. A rapid deceleration would allow greater energy transfer to the ball and enhance bowling speed.

A greater reach height, not standing height, correlated to a longer power phase duration (r_s [29] = 0.52, $p < 0.01$), suggesting a longer bowling arm relates to a slower power phase. A slower power phase is related to slower bowling speeds (r_s [31] = -0.45, $p = 0.01$). Theoretically, a longer bowling arm increases the acceleration path of the ball, which should increase bowling speed (12). Glazier, Paradisis (12) calculated that with a 10-cm longer bowling arm, a 3.1 $m \cdot s^{-1}$ increase in ball speed would result, providing bowling-arm angular velocity remained constant at 40.6 $rad \cdot s^{-1}$. In this investigation, bowlers with greater reach height (bowling-arm length) were typically slower throughout the power phase, possibly because their bowling arm rotated slower, or the bowling-arm covered greater angular distance (not measured). Although this cohort of bowlers were of lesser stature and body mass than professional bowlers (25), small and non-significant correlations were presented between bowling speed and standing height (r_s [31] = 0.22, $p = 0.24$), and bowling speed and body mass (r_s [31] = 0.15, $p = 0.41$).

A greater aerobic capacity (predicted $\dot{V}O_{2max}$ from 20-m shuttle-run test) was moderately related to a faster power phase duration (r_s [27] = -0.42, $p = 0.03$). This relationship may be explained by the aerobic energy system's ability in prolonging the onset of fatigue. As pace bowlers fatigue, all of the muscles in the body would be expected to contract slower, extending the duration of the power phase. Furthermore, a bigger aerobic engine would assist with the repeat-sprint ability demands of pace bowlers, which would allow the run-up to be of the same intensity for each delivery. Dupont, McCall (198) discovered that faster oxygen uptake kinetics during recovery from repeat-sprints strongly relates to repeat-sprint performance ($r = 0.85$, $p < 0.01$); a quality evident in pace bowling in each match format (76). In the current investigation, a greater predicted $\dot{V}O_{2max}$ was related to a lower percent decrement on the repeat-sprint ability test (r_s [19] = -0.79, $p < 0.01$), highlighting the importance of aerobic capacity for repeat-sprint ability.

There was no statistically significant link between bench press throw height and power phase duration (r_s [29] = 0.11, $p = 0.58$). Power of the pectoralis major muscle was thought to assist with rapid bowling-arm shoulder flexion in the power phase, as faster bowlers typically produce greater upper-body horizontal adduction power during the power phase of the bowling motion compared to slower bowlers (70). Furthermore, the pectoralis major is strongly activated during the propulsive phase of baseball pitching (189); a motion that relates to the power phase of pace bowling. Perhaps the bowlers in this investigation delivered the ball with a more vertical bowling arm, which would require less shoulder adduction and subsequent pectoralis major activation compared to a "round-arm" type delivery technique.

Greater lower-body strength was considered important for bowling speed, as pace bowlers typically experience large vertical and horizontal ground reaction forces in the power phase (38), and would need to transfer this kinetic energy to the ball, while maintaining a stable position. A quicker transfer of force from the lower-body to the bowling hand could be assumed to relate to a shorter power phase, and thus increase bowling speed. Bowlers in this study typically flexed their front-leg by 13° after front-foot contact up until ball release, where they could be classified as having the "flexor" front-knee technique (62). This knee technique is evident in slower bowlers, where peak forces are lower, and times to peak forces are longer, compared to other front-knee techniques (62). Intuitively, greater lower-body reactive strength might associate with a more extended front-leg at ball release; however, no significant relationships were observed (r_s [30] = -0.07, $p = 0.70$).

Furthermore, a moderate correlation between approach speed and knee extension at ball release was observed (r_s [27] = -0.42, $p = 0.03$), implying that an approach speed that is too fast could result in a collapsed front-leg. The bowlers in this study may have ran-up too fast for their own lower body strength and balance capabilities, and lost the biomechanical advantage of an extended front-leg technique at ball release. An extended front-leg at ball release increases tangential end-point velocity (23, 33), because the trunk can flex further and cause an anterior shift of the centre of gravity, which increases the "pulling effect" and acceleration path of the cricket ball. Therefore some bowlers in this investigation may have bowled slower than what they were truly capable of.

Faster bowlers adopted a longer delivery step length in this investigation (r_s [31] = 0.51, $p < 0.01$). This finding is in agreement with previous research, that a greater plant angle (a variable similar to step length) relates to faster bowling speeds ($r = 0.52$, $p =$

0.02) (54). A longer step length increases horizontal impulse, a mechanism for enhancing bowling speed (*r* = 0.57, *p* = 0.01) (54). A longer step also allows bowlers to flex their trunk further over their centre of gravity, which in turn creates an inertial lag on the anterior chest musculature of the bowling arm, a mechanism for enhancing bowling speed (71). There were no physical qualities that related to step length ($p > 0.05$), suggesting that this variable is probably influenced by other kinematic variables, such as approach speed (6).

A longer step length was moderately related to knee extension angle at ball release (r_s [27] = 0.42, *p* = 0.03). Worthington, King (55) observed that more of a heel strike technique at front-foot contact relates to a straighter front-leg at ball release (Figure 4.16). As previously discussed, an extended front-leg can develop bowling-arm tangential velocity by using the front-leg as an effective lever (38, 81), increasing ball speed.

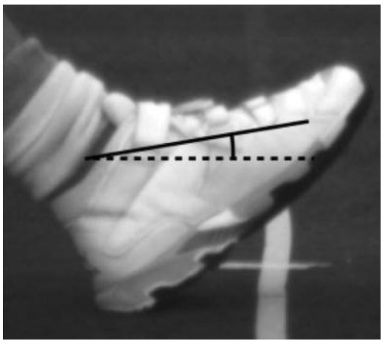

Figure 4.16. The initial foot angle, defined as the angle between the global y-axis (dashed line) and a line joining a projection of the ankle and metatarsophalangeal joint centres onto a vertical global plane (55).

Contrary to a majority of research (10, 13, 19, 22-24), the front-leg knee extension angle at front-foot contact and at ball release did not correlate with bowling speed (r_s [21] = 0.13, *p* = 0.56). This finding may be influenced by the vast differences in physical qualities and bowling kinematics in this cohort of pace bowlers. Nevertheless, the only physical quality to relate to knee extension angle at front-foot contact was the mean height of 20 bench press throws (r_s [19] = -0.57, *p* = 0.01). This relationship implies that bowlers with greater pectoralis major power-endurance landed with a more extended front-leg. Given that this cohort of pace bowlers typically flexed their front-leg from front-foot contact to ball release, they may have been more reliant on upper-body power to generate ball speed.

Reactive strength refers to the ability to change quickly from an eccentric to concentric muscular contraction (202). Reactive strength may be important for fast bowlers who adopt a “flexor-extender” front-leg technique (62) in the power phase (221). This front-leg technique associates with a larger ground reaction forces and a faster time to peak force (62), which may relate to faster bowling speeds. In this investigation however, trivial relationships between reactive strength, bowling speed, and knee extension angle at front-foot contact and at ball release were identified. These findings indicate that reactive strength may not be important for bowling fast in community-standard pace bowlers. Reactive strength displayed a moderate correlation with 20-m sprint time (r_s [29] = -0.45, p = 0.01). Reactive strength could be more important for a bowler who employs a run-up that is closer to their speed-acceleration capacity, and may be a means as to develop their bowling speed.

The isometric tests of trunk-endurance (i.e., prone hold, side hold) displayed trivial to small relationships to bowling speed for each delivery instruction ($p > 0.05$). The weak correlations observed may be explained by the body positions adopted in the prone hold and side hold test, compared to the pace bowling motion. During the prone hold and side hold test, the body is positioned in a lying position, but during pace bowling, bowlers will flex, laterally flex, and rotate their trunk throughout the step-length phase and power phase (48). Also, due to the different types of bowling actions (side-on, front-on, semi-open), the activation of trunk musculature in each bowling action could vary, and separate tests of trunk-endurance are unlikely to account for these differences. For example, side-on bowlers are more likely to rely on lateral trunk flexion and rotation to generate ball speed rather than trunk flexion. A front-on bowler would less likely rotate and laterally flex, but perform greater trunk flexion. Therefore, a more specific test of trunk strength (i.e., 1-RM cable wood-chop) that closely resembles the general bowling motion would probably relate stronger to bowling speed. Also, as the wood-chop motion is performed in standing (not lying), stronger correlations to bowling speed could be expected.

Pectoralis major flexibility (as evaluated in the shoulder horizontal abduction test) was moderately correlated to bowling speed for a slower-delivery only (r_s [27] = 0.40, p = 0.04). In pace bowling, the ability to delay circumduction of the bowling-arm is important in generating ball speed (13). Such a delay, combined with vigorous trunk flexion, is thought to create an inertial lag on the bowling-arm, where a pre-stretch occurs in the anterior shoulder musculature (i.e., pectoralis major) (71). This pre-stretch is thought to store elastic energy, which would assist with faster bowling-arm circumduction, and thus increase bowling speed (71). In this investigation, bowlers may have relied on their shoulder horizontal abduction range of motion to generate ball speed for the slower-delivery, as less kinetic energy may have been developed from their lower-body.

Although 1-RM pull-up strength and speed-acceleration are important for bowling speed, coordination of the bowling action could be more important (71), due to the shortage of relationships between physical qualities and bowling speed. In fact, Frane, Borović (222) reported that the correlation of motor abilities (i.e., strength, power, speed) and javelin throwing performance is dependent on throwing technique. The poorer throwers could not make use their physical qualities because they were limited by throwing technique. This concept may be applied to the present investigation, as the cohort of pace bowlers were of community-standard and may have had technical deficiencies in their bowling action (not measured). Another factor explaining the abundance of non-significant correlations is the poor reliability of approach speed and some bowling performance measures reported in Study 1. Unreliable variables may result in false negative correlations. These factors may explain why only two statistically significant correlations were identified between physical capacities and bowling speed.

4.4.2 Relationships between selected physical qualities, bowling kinematics, and consistency of bowling speed

The ability to consistently bowl quickly by delaying the onset of fatigue throughout multiple bowling spells (series of overs) and successive days of bowling is considered important for a pace bowler. Fatigue during pace bowling is possibly best explained by the biomechanical model of exercise performance (85). This model infers that repeated eccentric contractions alter muscle function, resulting in a loss of stored elastic energy (86). In a pace bowling spell, excessive lower-body decelerations during the stride and power phases may eventually alter muscle function, and consequently less energy may be transferred to the ball. Reactive strength could therefore be considered an important quality for the consistency of bowling speed. Surprisingly, no significant relationship was identified between reactive strength and consistency of bowling speed (r_s [21] = 0.14, p = 0.95). The drop jump test may not have related because the test did not comprise repeated drop jumps (i.e., rebound jumps) to assess reactive strength-endurance.

Greater hamstring flexibility (examined in the straight-leg raise test) was moderately related to the consistency of bowling speed, but only for a match-intensity delivery (r_s [29] = -0.49, $p = 0.01$). A moderate relationship was observed between hamstring flexibility and knee extension angle at front-foot contact (r_s [20] = 0.43, $p = 0.06$). Hamstring flexibility may permit a faster transfer of force by enabling a straighter front leg at front-foot contact, as bowlers with a "constant brace" front-leg technique typically develop larger ground reaction forces and in a shorter time compared to bowlers who adopt "flexor" and "extender" knee techniques (62). The ability to reach peak force quicker by employing a "constant brace" knee technique may relate to a faster and less variable transfer of kinetic and rotational energies to the bowling hand, ultimately assisting bowlers to deliver at consistent speeds.

Percent decrement on the repeat-sprint ability test approached significance with the consistency of bowling speed for a match-intensity delivery (r_s [21] = -0.42, $p = 0.06$). Notably, a smaller correlation was observed between repeat-sprint ability and bowling speed for a match-intensity delivery (r_s [21] = 0.15, $p = 0.53$). Repeat-sprint ability may be more important for maintaining bowling speed for a match-intensity delivery, rather than for generating ball speed. The former correlation may have been statistically significant if bowlers delivered in more strenuous conditions throughout this investigation (i.e., more than eight-over spells, and with less than 40 s recovery between deliveries). A shorter recovery between deliveries may have placed more stress on the aerobic energy system, ultimately challenging the repeat-sprint ability of the pace bowlers.

The isometric tests of trunk-endurance (i.e., prone hold, side hold) displayed trivial to small associations with the consistency of bowling speed for each delivery instruction (Table 4.5). The weak correlations observed may be explained by the differences in body position in these physical tests to the bowling motion. The prone hold and side hold tests were performed in lying, whereas the pace bowling motion involves trunk flexion, lateral trunk flexion, and trunk rotation throughout the step-length phase and power phase (48). A trunk strength-endurance test that closely resembles the general bowling motion (e.g., 15-RM woodchop) may therefore be a stronger predictor of the ability to consistently bowl fast.

There were no bowling kinematic variables that were significantly linked with the consistency of bowling speed ($p > 0.05$). Although this study did not investigate segmental sequencing of the bowling action, it is possible that consistent segmental sequencing coordination would be important for bowlers to bowl at consistent speeds.

4.4.3 Relationships between selected physical qualities, bowling kinematics, and bowling accuracy

Upper body pushing strength (as indicated by the 3-RM bench press test) was moderately correlated with bowling accuracy during a maximal-effort delivery (r_s [26] = - -0.42, p = 0.03). The push-up exercise (similar to the bench press) strongly activates the infraspinatus muscle (223), which may assist in stabilisation of the glenohumeral joint during the moment of ball release (224). Although speculative, a more stable and proprioceptive glenohumeral joint may give bowlers greater control over the moment of ball release, and enhance bowling accuracy.

There was a tendency for the best concentric peak power from three countermovement jumps and mean concentric peak power from 20 countermovement jumps to become more important for bowling accuracy as delivery effort increased (Table 4.6). Furthermore, a greater peak countermovement jump height was associated with better bowling accuracy with all delivery instructions pooled together (r_s [28] = -0.39, p = 0.04), but no statistically significant relationships were observed for each delivery instruction. A maximal-effort delivery could be more fatiguing, and therefore qualities such as lower-body power and power-endurance could become more decisive for bowling accuracy. In this study, bowlers adopted a slightly faster approach speed as delivery effort increased; maximal-effort: 5.6 $\text{m}\cdot\text{s}^{-1}$, match-intensity: 5.5 $\text{m}\cdot\text{s}^{-1}$, and slower-ball: 5.4 $\text{m}\cdot\text{s}^{-1}$ (Table 4.2). With a marginal increase in approach speed, it is likely that lower-body power-endurance would be necessary in delaying the onset of fatigue, and thus assist bowlers in delivering with greater accuracy.

Faster 10 m and 20 m sprint times were associated with better bowling accuracy with all delivery instructions pooled together, but no significant relationships were observed for each delivery instruction (Table 4.6). Furthermore, a faster approach speed was moderately related with improved bowling accuracy (r_s [31] = 0.35, p = 0.05). This finding is in disagreement with Brees (175) who showed that bowling accuracy diminishes with artificial increases in approach speed, and vice-versa. In the current investigation, this relationship may be explained by the moderate link between approach speed and knee extension angle at ball release (r_s [27] = -0.42, p = 0.03), and the moderate association between knee extension angle at ball release with bowling accuracy (r_s [27] = 0.38, p = 0.05). A faster approach speed was more likely to result in bowlers collapsing their front-leg at ball release, which appears to be beneficial for bowling accuracy. Bowlers that collapse their front leg at ball release typically release the ball from a more upright trunk and arm position, as they do not flex their trunk over their base of support. This knee technique allows a bowler to pitch the ball up further on the wicket, which would ensure it is closer to the stumps and targets after the ball has bounced. As a flexed front-leg at the moment of ball release typically relates to slower bowling speeds, the ball would be expected to bounce less and strike lower on the target sheet (closer proximity to most of the targets).

Surprisingly, reactive strength became worse for bowling accuracy as delivery effort increased (Table 4.6). Reactive strength was hypothesised to be important for bowlers who adopt the “flexor-extender” front knee technique (221), and although this was not shown in this investigation (group trend for bowlers to flex knee throughout power phase), an extension of the knee would appear counterproductive for bowling accuracy, given the moderate relationship previously reported (r_s [27] = 0.38, $p = 0.05$). Reactive strength may have been used more for a maximal-effort delivery, where bowlers were approaching the crease slightly faster and may have experienced larger ground reaction forces. In this instance, reactive strength may have served to counteract the magnitude of knee flexion during the power phase and thus compromise bowling accuracy.

Body mass appeared to be more important for bowling accuracy as delivery effort increased (Table 4.6). Bowlers with greater body mass may have been more stable at the bowling crease (not measured), where it is likely the ball was released from a consistent position.

There were many physical qualities that did not significantly relate to bowling accuracy in this study ($p > 0.05$). The non-significant relationships in this investigation indicate the need for more appropriate physical tests to predict bowling accuracy ability, or perhaps indicate that bowling accuracy is largely dependent on other factors such as segmental sequencing coordination and concentration. Ferdinands et al. (4) advised that bowling speed can be enhanced by improving segmental sequencing coordination and the actual power of the muscles actuating each segment. If a bowler achieves an optimal segmental sequencing pattern however, bowling accuracy could also be expected to improve.

4.4.4 Relationships between selected physical qualities, bowling kinematics, and consistency of bowling accuracy

Greater reactive strength levels were related to a poorer consistency of accuracy as delivery effort increased (Table 4.7). Reactive strength may have been required more for a maximal-effort delivery, where bowlers were approaching the crease slightly faster and may have experienced larger ground reaction forces. In this instance, reactive strength may have served to counteract the magnitude of knee flexion during the power phase and thus compromise consistency of bowling accuracy through an inconsistent ball release position.

There was a tendency for standing height to be worse for consistency of accuracy as delivery effort decreased (Table 4.7). A taller bowler may have found difficultly bowling with an optimal segmental sequencing pattern, especially as less effort was placed on the slower-ball delivery. Perceived effort displayed a considerable drop with delivery instruction: maximal-effort: 95.6%, match-intensity: 86.1%, and slower-ball: 77.8% (Table 4.3). With less effort there is typically more variability in force production (167), which may result in an inconsistent release position and a poorer consistency of bowling accuracy.

There were many physical qualities that did not significantly associate with the consistency of bowling accuracy in this study ($p > 0.05$). This observation indicates that either more appropriate physical tests are required for predicting consistency of bowling accuracy performance, or that consistency of bowling accuracy is largely dependent on other factors such as segmental sequencing coordination and concentration.

4.4.5 Relationships between bowling speed and accuracy

This investigation observed no speed-accuracy trade-off for the group (r_s [31] = -0.28, $p = 0.12$), a finding in agreement with other pace bowling studies (25, 26, 30, 175). Similar to other research (25, 26, 30, 175), bowlers in this study were instructed to bowl a majority of deliveries at “match intensity”, where it was hypothesised they would place equal importance on both bowling speed and accuracy. However, no research has investigated the speed-accuracy trade-off with the inclusion of maximal-effort and slower-ball deliveries. Furthermore, the within-bowler relationships between speed and accuracy have never been explored in pace bowling literature.

A within-bowler analysis of the speed-accuracy relationships revealed novel findings (Table 4.10). Three bowlers displayed a speed-accuracy trade-off. That is, as bowling speed increased, their bowling accuracy was compromised. These bowlers could have “muscled” the ball when attempting to bowl with maximal-effort, or were not able to regulate aspects of force production and relative timing between segments (167). Four bowlers bowled more accurately as they strived for extra speed. In contrast, they may have been able to control force production and the relative timing between segments (i.e., a faster segmental sequencing pattern) (167). The other 24 bowlers displayed trivial or small relationships (mix of positive and negative) that indicate bowling speed was not related to bowling accuracy. It is likely that a majority of bowlers were able to coordinate their segments with each delivery instruction, and bowl faster without compromising bowling accuracy.

4.5 Conclusions

Pull-up strength and 20-m speed appear to be important for bowling speed, especially as delivery effort increases. Although there was a small but non-significant correlation between 20-m speed and approach speed, bowlers ran-up slightly faster when instructed to bowl a maximal-effort delivery. The faster bowlers in this study probably preferred to settle into a rhythm during their run-up, and not use their speed-acceleration. Nevertheless, the faster bowlers were typically quicker throughout the power phase, and adopted a longer step length.

A greater hamstring flexibility assisted bowlers who were more consistent with their bowling speed; potentially by a quicker transfer of force from a more extended front leg at front-foot contact. Repeat-sprint ability became more important for bowlers to maintain their delivery speed, as opposed to generating it. This ability could be expected to delay the onset of fatigue, which would allow bowlers to deliver at faster speeds for longer periods.

3-RM bench press strength was indicated to be more important for bowling accuracy as delivery effort increased; potentially as the infraspinatus muscle may be important for stabilising the glenohumeral joint during the bowling motion, facilitating a consistent ball release position. Lower-body power and power-endurance became more important for bowling accuracy as delivery effort increased. Bowlers delivered with greater accuracy with faster approach speeds, and faster 10-m and 20-m sprint times. Power-endurance may serve to allow the intermittent and ballistic bowling motion to occur repeatedly throughout a bowling spell. Greater reactive strength appeared counterproductive for bowling accuracy and consistency of bowling accuracy, perhaps by negating the knee flexion that is related to bowling accuracy. Bowlers with larger body mass may have been more balanced at the bowling crease during a maximal-effort delivery, and were able to bowl with a consistent release position.

Standing height became detrimental to consistency of bowling accuracy as delivery effort decreased. An increased variability in force production typically occurs with a sub-maximal effort, and coupled with taller bowlers, could make it more difficult them to coordinate their bowling technique. These factors could result in the ball being released from an inconsistent position, compromising consistency of bowling accuracy.

The small amount of significant relationships between physical qualities and bowling performance measures could be explained by three possibilities: 1) this cohort of bowlers may have been deficient in their bowling technique, and could not apply the strength and power they may have possessed, and 2) segmental sequencing coordination of the bowling motion could be more important for pace bowling performance (71), and 3) approach speed and some bowling performance measures were unreliable in Study 1, which could create more false negative correlations with these variables and physical qualities.

In support of similar research, there was no speed-accuracy trade-off observed overall for the group. However, the within-bowler analysis revealed that a minority of bowlers exhibited a speed-accuracy trade-off, or bowled more accurately when striving for extra speed. The majority however, displayed trivial to small relationships between bowling speed and accuracy. The bowlers who exhibited a speed-accuracy trade-off may have not been able to coordinate their segments with the change in delivery instruction. These types of bowlers may have “muscled” the ball and disrupted their optimal segmental sequencing pattern. In contrast, the bowlers who required speed to be accurate may have been more suited to a faster segmental sequencing pattern.

4.6 Practical applications

Coaches who are seeking to develop bowling speed may be able to improve it with pull-up strength training and speed-acceleration training. Improving hamstring flexibility may allow a greater delivery step length, which is beneficial for bowling faster. Bowling accuracy may be improved by enhancing bench press strength and countermovement jump concentric peak power. Coaches may need to refrain from training vertical reactive strength, as it appears counterproductive for bowling accuracy and consistency of bowling accuracy, and not beneficial for bowling speed. Although these training recommendations are made based on the statistically significant correlations identified in this study, training interventions are required to validate these relationships.

Coaches should be aware that although physical fitness has its place in developing pace bowlers, bowling technique could be more important. A bowling technique that follows an optimal segmental sequencing pattern would allow bowlers to make use of their strength and power capabilities. Furthermore, pace bowlers display a wide variety of bowling techniques, and some physical qualities could be more important than others for a particular type of bowler. Coaches could consider using a specific means of training, such as weighted-implement bowling (2) to account for technical differences, and to develop functional strength and power for greater transfer to bowling performance.

Most pace bowlers can be instructed to deliver a variety of balls (i.e., match-intensity, maximal-effort, slower-ball) without concerning themselves with the speed-accuracy trade-off. Coaches should individually assess bowlers with their speed and accuracy however, as there are a minority that bowl less accurately as they strive for extra speed, and some who bowl more accurately as they increase their bowling speed. Coaches should be observant of pace bowlers striving to bowl too fast, where the ball is “muscled”, instead of using the optimal segmental sequencing pattern. Pace bowlers may run-up faster to deliver a maximal-effort ball, which may be a noticeable cue to a batsman to expect a faster delivery.

Chapter 5 – Study 3:

The Effects of an Evidence-Based Training Program and Normal Training Program on Pace Bowling Performance, Approach Speed, Speed-Acceleration, and Pull-Up Strength

5.1 Background

Strength and conditioning is an integral component of an elite or sub-elite pace bowler's preparation. Australian fast bowler Peter Siddle was replaced by the quicker James Pattinson in March 2014, as Australian coach Darren Lehmann believed he was bowling ≈2.5 $m{\cdot}s^{-1}$ slower than what was required national standards (i.e., ≈38.9 $m{\cdot}s^{-1}$) (225). At the time of his departure, Siddle said he was "pretty fatigued"; probably because he had bowled the most amount of deliveries (3,427) in Test cricket from 2013 to 2014 (226). He regained his speed through strength and power training, and was reselected into the national team in late 2014 (225). Below is an excerpt of what Siddle said in his comeback to the Australian team (225):

> "Going to England, even though I did play a lot of cricket, I was able to think of a few things to be able to work on - get a bit faster in my run-up, hit the wicket a bit harder, just little things I know I need to improve on to get back to where I was. With those little improvements on the field with what I'm doing off the field, with the weights, doing a real pre-season, something I haven't done for over three years, those little things help. By the time the season starts again I'll be back to where I want to be, a little bit of extra pace, and still bowling with that consistency I have over the last couple of years."

Muscular power, strength-endurance, flexibility, aerobic power, and anaerobic power are thought to be necessary for pace bowling performance (14, 33). However, there is a dearth of research on the relationships between these physical qualities, and others, on pace bowling performance (19-21). Such evidence would assist strength and conditioning coaches develop pace bowling training programs. Nevertheless, given the low correlations between physical tests and bowling performance measures revealed in Study 2, it is likely that segmental sequencing coordination, and the actual power of the muscles actuating each segment are more important for pace bowling performance (71). With this in mind, Petersen, Wilson (2) developed a specific pace bowling training intervention comprising heavy-, light-, and regular-ball bowling, from previous research conducted in baseball pitching (27). This specific form of training is likely to develop the power of the muscles actuating each segment, leading to a better transfer to pace bowling performance.

Furthermore, it may train similar muscles to the pull-up exercise, as 1-RM pull-up strength was strongly linked with bowling speed regardless of delivery effort (Study 2).

A major purpose of heavy-ball bowling is to develop functional strength of the upper-body region. Strength is the foundation of power (192), so it is logical that strength training should precede power training, to build a greater "engine" for power development (94). Prescribing a high intensity (i.e., ≈85% of 1-RM) in a strength training session is critical for developing strength (192). The small improvement (significance not analysed) in bowling speed of 0.75 $m{\cdot}s^{-1}$ (2.4%) in the intervention group (greater than the control group) after 10 weeks by Petersen, Wilson (2) suggests the intensity or volume of the heavy-, light-, and regular-ball bowling training may not have been optimal to enhance bowling speed. Efficacious baseball pitching studies (those that significantly improved throwing velocity, $p < 0.05$) increased and decreased heavy- and light- ball mass by 20% respectively (27, 96), and included 162–234 throws per week, quite larger than the 3.2–16% overload / underload, and 54–108 deliveries bowled per week in the study of Petersen, Wilson (2). This investigation seeks to use a heavier load and greater bowling volume within a session to determine if bowling performance can be improved with a 10-week program.

Study 2 revealed that 20-m speed is significantly correlated with bowling speed, irrespective of delivery effort ($p < 0.05$). While there was a small correlation between 20-m speed and approach speed ($p > 0.05$), bowlers adopted a slightly faster run-up as delivery effort increased. These results suggested that bowlers may use more of their speed-acceleration for a maximal-effort delivery, but prefer to settle into a rhythmic approach to the bowling crease. Many studies have showed approach speed to significantly correlate with bowling speed ($p < 0.05$) (6, 12, 25, 43), so developing a bowler's speed-acceleration or maximum speed could be beneficial; as they could adopt a faster approach speed, but still run up with the same relative speed or effort.

Resisted forms of speed training such as sled sprints (132, 133) and weighted-vests (133) have been used in attempt to develop speed-acceleration, by increasing stride length, through enhanced force application to the ground (227). Resisted sprint training has been reported to be beneficial for speed-acceleration (228, 229), while some studies refute this finding (132, 230). Cronin, Hansen (231) reported that weighted-vest sprinting results in a more upright trunk angle, compared to sled sprinting. Furthermore, Cronin, Hansen (231) postulated that weighted-vest sprinting may increase the braking forces at the beginning of the stance phase. If correct, this mode of sprinting may be beneficial for pace bowling, as horizontal impulse (43) and centre of mass deceleration in the power phase (6) of the bowling motion are strongly related to bowling speed. Weighted-vest sprinting may train the bowler's ability to withstand larger ground reaction forces at the crease; and transfer this energy to the bowling hand to develop bowling speed.

Employing a contrast of resisted and un-resisted sprints may result in a stronger chronic adaptation for speed-acceleration development. Tsimachidis, Patikas (232) indicated that a combination of strength and sprint training was effective in eliciting potentiation within a training session, but only towards the end of their 10 week intervention. The findings from this investigation imply that an increase in strength serves as a foundation for potentiating powerful motions. It is unclear if this concept can be applied to heavy-ball bowling and weighted-vest sprinting, where these modalities serve to develop functional strength of bowling and sprinting respectively.

The "intent" in bowling training and strength / power training may be crucial for developing pace bowling performance. In Study 2, there was no speed-accuracy trade-off present for the cohort, indicating that bowlers could deliver with maximal-effort, providing they use a smooth, coordinated technique; and not "muscle" the delivery. Stewart (90) showed that lifting as explosively as possible during the concentric phase of each strength exercise was sufficient to develop bowling speed by 0.69 $m \cdot s^{-1}$ after 8 weeks, reinforcing the importance of the intent to train explosively.

The issue with previous pace bowling training interventions is that they have not explored the test-retest reliability of their performance measures (2, 90). According to Hopkins (4), the smallest worthwhile change is calculated by multiplying the standard error of measurement by 1.5. The smallest worthwhile change provides information on what are true changes in performance, and what could be attributed to "noise". The smallest worthwhile change was calculated along with the typical error and ICC for many bowling performance and kinematic variables (Study 1). Furthermore, the first four overs of the bowling test exhibited acceptable reliability (albeit not as reliable as the eight-over test), indicating that bowlers can be assessed in a shorter time period.

The purpose of this study is to compare the effects of an evidence-based training program and normal training program on pace bowling performance, approach speed, speed-acceleration, and pull-up strength. This chapter will provide insight into the efficacy of an evidence-based training intervention for pace bowling performance, approach speed, speed-acceleration, and pull-up strength.

5.2 Methods

5.2.1 Experimental approach to the problem

This investigation comprised a pre-test, post-test design, using two training groups to explore the longitudinal effects of an evidence-based training program and normal training program on pace bowling performance, approach speed, speed-acceleration performance, and pull-up strength (Figure 5.1). Participants were allocated to one of two training groups (evidence-based training and normal training) matched for mean bowling speed during pre-test period. The evidence-based training group performed bowling training (heavy-ball and regular-ball), sprint training (weighted-vest sprints and un-resisted sprints), and pull-up training. This training program was labelled "evidence-based" because speed-acceleration and 1-RM pull-up strength were significantly correlated to bowling speed in Study 2 ($p < 0.05$), and that heavy-ball bowling training may have similar effects on bowling speed as heavy-ball pitching does on throwing velocity in baseball (27, 96). The normal training group performed bowling training (regular-ball) and sprint training (un-resisted sprints) as this is typically performed in a training session by professional pace bowlers (233). This training commenced after a two week familiarisation period of bowling, sprint training, and pull-up training. Both groups completed 16, 45–90-minute training sessions spaced over eight weeks. While an eight week training program may be considered short, significant improvements in throwing velocity (4%) following heavy-ball pitching have been realised in a program of similar duration ($p < 0.05$) (96). Training outside the research program was controlled through implementation of a training diary. As most training sessions fell on local cricket club training nights, the only training conducted by most bowlers was through the study itself. Anecdotally, one of the major reasons for participation was because the research study offered a structured "pre-season" indoors, and earlier than when most local cricket clubs commenced training.

The pre-test and post-test period involved one testing session each, spread out over a week. After a general warm-up, participants completed a regular-ball bowling warm-up followed by the four over pace bowling test (Study 1), an un-resisted sprint warm-up followed by a 20-m sprint test, and a 1-RM pull-up test (Study 2). The four over test was chosen over the eight over version because it expedites participant testing, is less fatiguing, and therefore would have less impact on subsequent tests.

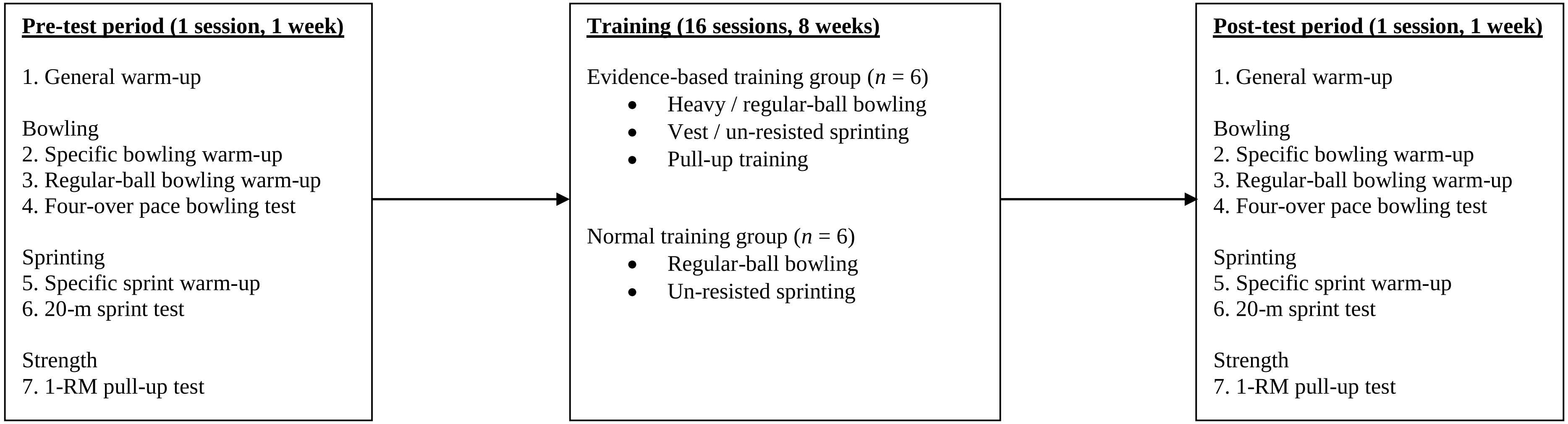

Figure 5.1. Experimental design of this investigation.

5.2.2 Participants

Since it is desirable to apply the results of this investigation to elite-standard pace bowlers who engage in physical conditioning, a high-performance sample would ideally be assessed. However, due to the difficulty in recruiting such athletes for comprehensive testing and training, a community-standard group was recruited. Twenty-one male pace bowlers of community-standard (i.e., A & B grade local cricket) were recruited. Only two participants from Study 1 and 2 were retained for this investigation. Unfortunately, nine participants withdrew from this study: five sustained an injury (outside of study), and four failed to meet acceptable attendance at training; set at 87.5% (absent for three or more sessions). Consequently, six participants remained in the evidence-based training and normal training groups, but there were no statistically significant differences in mean bowling speed at pre-test period. The characteristics of the participants are outlined in Table 5.1. Note, there were no significant differences in age, bowling experience, and resistance training experience between groups ($p > 0.05$).

Table 5.1. Participant characteristics in this investigation. Age, bowling experience, and resistance training experience are expressed as mean ± *SD*.

	n	**Age (years)**	**Bowling experience (seasons)**	**Resistance training experience (years)**
Overall	12	23.7 ± 7.5	7.1 ± 4.7	1.5 ± 2.9
Evidence-based training group	6	26.3 ± 9.3	6.8 ± 6.4	0.3 ± 0.6
Normal training group	6	21.0 ± 4.3	6.7 ± 3.6	2.8 ± 3.8

To qualify for involvement in this investigation, participants had to be injury-free for at least six months and free of illness during the time of the study. This study was approved by the University Human Research Ethics Committee (Appendix A), and participants received a Plain Language Information Statement (Appendix B). Prior to this investigation, participants were briefed on the experimental design, including all forms of testing and training procedures, experimental risks, and the nature of the study, before providing their informed consent. They were instructed to refrain from resistance training, alcohol and caffeine consumption 24 hours prior to each testing and training session.

5.2.3 Experimental procedures

5.2.3.1 Creation of the 250 g and 300 g cricket ball

To date, heavier cricket balls are not available for retail in the cricket market. Therefore, a number of procedures were followed to make the heavy cricket ball. First, a 1-cm diameter hole was drilled from the centre of one side of a two-piece ball (Kookaburra Tuf Pitch, Melbourne, Australia) without piercing through the other side. The contents around this hole were drilled and removed until the ball weighed 120 g (-23.1% reduction). The ball was weighed on a Propert 5 kg slimline glass digital kitchen scale, which was zeroed with a glass on top, so the ball could be mounted and weighed without it rolling off. Second, the ball's mass was increased by infusing pieces of lead, where it was filled with a thin piece of sliced cork and sealed with epoxy resin. Six balls of 250 g mass and 300 g mass were made. These masses represented an increase of 60.3% and 92.3% respectively compared to the regular ball. Third, the balls were waterproofed by an application of Scotch Guard (Pymble, Australia), and were left to dry for three days. Fourth, the balls were spray painted either white (250 g ball) or green (300 g ball) on the drilled location for identification in the study (Figure 5.2). The balls mass were checked every fortnight (on six occasions throughout the investigation), and adjusted to ensure the mass was constant.

Figure 5.2. The 300 g (green mark) and 250 g ball (white mark) on the digital scale.

5.2.3.2 General warm-up

Participants completed the general warm-up routine at the beginning of each testing or training session, following an initial weigh-in (Table 5.2). This warm-up was normally completed in approximately five minutes.

Table 5.2. General warm-up procedures.

#	**Exercise**	**Prescription**
1	Forward jog	5 × 20-m at 50% effort
2	Side to side shuffle	2 × 20-m at 50% effort
3	Grapevine	2 × 20-m at 50% effort
4	Backward jog	2 × 20-m at 50% effort
5	Walking lunges	4 repetitions
6	Skipping for height more than length	1 × 20-m at 75% effort
7	Skipping for length more than height	1 × 20-m at 75% effort
8	Progressive sub-maximal sprints	1 × 20-m at 50%, 60%, 70%, 80%, 90% effort
9	Leg swings (forwards / backwards)	5 repetitions each leg
10	Leg swings (side to side)	5 repetitions each leg
11	Hip circles (flexion, external rotation, abduction)	5 repetitions each leg
12	Calf pushes in push-up position	5 repetitions each leg
13	Arm circles (forwards / backwards)	10 repetitions each arm
14	Lower back rolls (forwards / backwards)	5 repetitions
15	Lower back rolls (side to side)	5 repetitions each side

5.2.3.3 Specific bowling warm-up

Immediately after the general warm-up, participants completed the specific bowling warm-up routine prior to each testing and training session (Table 5.3). In the specific bowling warm-up, one delivery was bowled every 30 s, which was monitored on an iPad (Apple Inc.) with the application *lab timer*. This iPad application was capable of having four timer screens on display at once, and individual bowlers were named on the screen, so they could keep track of their timing (Figure 5.3). Participants received the delivery instruction 10 s prior to each ball, with a three-second countdown to commence the delivery. The first 10 deliveries of the specific bowling warm-up were performed from a short 5-step run-up, which was pre-marked from a previous two-week familiarisation period. Delivery effort gradually progressed from 60–95%, and all balls were bowled with a regular (156 g) cricket ball. Participants practised bowling at all targets required for the four-over pace bowling test. Approximately three minutes of active recovery (walking) followed the specific bowling warm-up.

Table 5.3. Specific bowling warm-up procedures.

Time	Ball #	Ball mass	Effort (%)	Run-up distance	Target
0:00	1	156 g	60%	Short (5-step)	Middle stump
0:30	2				
1:00	3				
1:30	4	156 g	70%	Short (5-step)	Off stump – right hand batsman
2:00	5				
2:30	6				
3:00	7	156 g	80%	Short (5-step)	Off stump – left hand batsman
3:30	8				
4:00	9				
4:30	10	156 g	90%	Full	Yorker
5:00	11				
5:30	12				
6:00	13	156 g	95%	Full	Bouncer
6:30	14				
7:00	15				

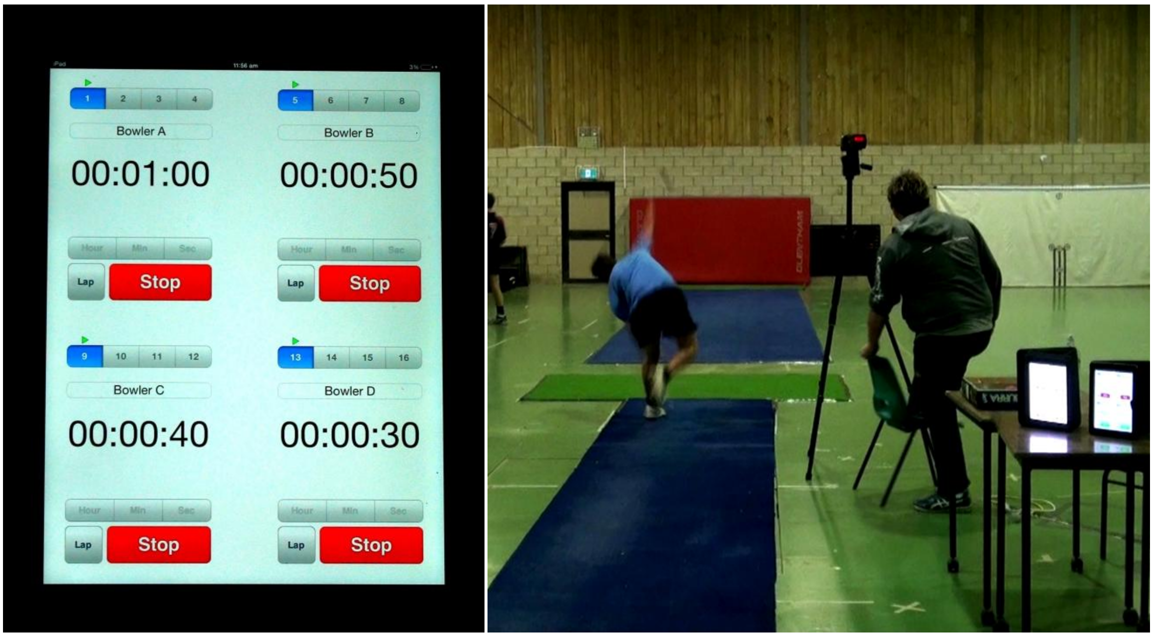

Figure 5.3. The *lab timer* application for iPad was used to monitor timings throughout the specific bowling warm-up, regular- and heavy-ball warm-up conditions, and pace bowling test.

5.2.3.4 Regular-ball bowling warm-up condition

The regular-ball bowling warm-up condition commenced approximately three minutes after the specific bowling warm-up (Table 5.4). One delivery was bowled every 30 s, with the first nine deliveries targeted at off stump to a right hand batsman. The last nine deliveries were directed towards off stump for a left hand batsman. Participants bowled all deliveries from a short five-step run-up, at match-intensity (as they would in a match), and with a regular weight ball. Approximately three minutes of active recovery (walking) followed the regular-ball bowling warm-up condition.

Table 5.4. Regular-ball bowling warm-up condition.

Time	**Ball #**	**Ball mass**	**Instruction**	**Run-up distance**	**Target**
10:00	1	156 g	Match-intensity	Short (5-step)	Off stump – right hand batsman
10:30	2				
11:00	3				
11:30	4				
12:00	5				
12:30	6				
13:00	7				
13:30	8				
14:00	9				
14:30	10	156 g	Match-intensity	Short (5-step)	Off stump – left hand batsman
15:00	11				
15:30	12				
16:00	13				
16:30	14				
17:00	15				
17:30	16				
18:00	17				
18:30	18				

5.2.3.5 Four-over pace bowling test

The four-over pace bowling test was conducted approximately three minutes after the regular-ball bowling warm-up condition. Participants received the following instruction prior to the bowling test:

> "Bowl as fast, accurate and consistently as possible as you would in a match. At different times throughout the test, you will be instructed to bowl some deliveries at maximal speed and some deliveries with your preferred slower ball. Your speed and accuracy with these balls is also measured. Keep your run-up speed as consistent as possible with each ball."

This instruction was slightly modified from the eight-over bowling test described in Study 1, as approach speed was observed to be an unreliable measure; possibly because bowlers were not settled into a "rhythm". Therefore the last sentence of the instruction "keep your run-up speed as consistent as possible with each ball" was included in this study.

Dissimilar to Study 1, there was no batsman used in the four-over bowling test. While this may detract from the ecological validity of the test by removing specific cues for the bowlers to use, the batsman was struck several times during data collection in Study 1. Not only did the batsman sustain bruising, but the accuracy of the delivery could not be evaluated.

The recoveries between deliveries and overs were slightly changed from Study 1. In this study, bowling accuracy was measured with a video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan), instead of a high-speed camera, video footage was continually recorded (25 frames per second, shutter speed of two milliseconds) throughout the test, and the former camera was faster in processing video footage. Each delivery was bowled on a 30-s cycle, and recoveries between overs were fixed to approximately three minutes (Table 5.5). Participants completed a walking recovery between overs, instead of fielding drills, as participants in Study 1 typically performed the drills at an inconsistent intensity, which may have led to more variability in their bowling performance.

The delivery sequence from Study 1 was unchanged (Table 5.5), and participants received an instruction before each maximal-effort delivery and slower-ball delivery informing of the effort change required. The instructions comprised “maximal-effort ball, off stump to a right (or left) hand batsman” and “slower-ball, top of middle stump”. Bowling speed, accuracy, consistency of bowling speed and accuracy, and perceived effort were measured using the same methods and experimental set-up in Study 1.

Table 5.5. Timing and delivery sequence in the four-over pace bowling test.

Time	Over #	Ball #	Target	Delivery effort
21:30	1	1	Off stump – right-hand batsman	Match-intensity
22:00		2	Off stump – right-hand batsman	Match-intensity
22:30		3	Off stump – right-hand batsman	Match-intensity
23:00		4	Off stump – right-hand batsman	Match-intensity
23:30		5	Off stump – right-hand batsman	Maximal-effort
24:00		6	Middle stump	Slower-ball
24:30			Active recovery (walking)	
25:00				
25:30				
26:00				
26:30				
27:00	2	1	Off stump – left-hand batsman	Match-intensity
27:30		2	Off stump – left-hand batsman	Match-intensity
28:00		3	Off stump – right-hand batsman	Match-intensity
28:30		4	Off stump – right-hand batsman	Match-intensity
29:00		5	Bouncer	Match-intensity
29:30		6	Yorker	Match-intensity
30:00			Active recovery (walking)	
30:30				
31:00				
31:30				
32:00				
32:30	3	1	Off stump – left-hand batsman	Match-intensity
33:00		2	Off stump – left-hand batsman	Match-intensity
33:30		3	Off stump – left-hand batsman	Match-intensity
34:00		4	Off stump – left-hand batsman	Match-intensity
34:30		5	Off stump – left-hand batsman	Maximal-effort
35:00		6	Middle stump	Slower-ball
35:30			Active recovery (walking)	
36:00				
36:30				
37:00				
37:30				
38:00	4	1	Off stump – right-hand batsman	Match-intensity
38:30		2	Off stump – right-hand batsman	Match-intensity
39:00		3	Off stump – left-hand batsman	Match-intensity
39:30		4	Off stump – left-hand batsman	Match-intensity
40:00		5	Bouncer	Match-intensity
40:30		6	Yorker	Match-intensity

Approach speed was the only bowling-kinematic variable examined in the four-over bowling test. Approach speed was measured with the same protocols identified in Study 1. This kinematic variable was included because it may change with speed training, and this has not been investigated in previous research.

5.2.3.6 Specific sprint warm-up

The specific sprint warm-up followed a five minute passive recovery from the four-over bowling test. This warm-up comprised five 20-m efforts, progressing from 60% to 95%, on a one minute cycle. Approximately three minutes of active recovery (walking) followed before the 20-m sprint test.

5.2.3.7 20-m sprint test

Participants were required to perform three maximal-effort 20-m sprints, on a three minute cycle. This recovery period was employed as it was thought sufficient for restoration of the phosphocreatine stores. The set-up of the test and instructions given to participants regarding sprint technique were the same as described in Study 2. Speed-acceleration was measured by 20-m time, which has been shown to exhibit high test-retest reliability (ICC = 0.96, CV = 1.3%) (200). The fastest trial from the three sprints was retained for analysis (200). This test was included as 20-m sprint time was significantly related to bowling speed for maximal-effort and match-intensity deliveries ($p < 0.05$) (Study 2).

5.2.3.8 1-RM pull-up test

The 1-RM pull-up was included in this investigation as significant correlations ($r_s = 0.53–0.56$, $p < 0.01$) were discovered between 1-RM pull-up and bowling speed (regardless of delivery effort) in Study 2. The pull-up was performed in the Smith Machine following the same procedures outline in Study 2. The 1-RM pull-up test was conducted after five minutes of passive recovery from the un-resisted sprint warm-up condition and 20-m sprint test. Similar to Study 2, some participants were unable to complete one repetition at body-mass load, and were excluded from this test.

5.2.3.9 Training programs

Both training groups performed bowling training with the same workloads each week (Table 5.6). The evidence-based training group bowled with the heavier balls (300 g or 92.3% increase, and 250 g or 60.3% increase), and regular balls (156 g). Both groups bowled a total of 696 deliveries, less than the 864 prescribed by Petersen, Wilson (2). However, the amount of deliveries bowled each session by both groups in this investigation was typically greater. The normal training group only bowled with a regular-mass ball, as this is typically performed in cricket practice (233).

Each bowling training session commenced with the general warm-up (Table 5.2) and specific bowling warm-up (Table 5.3). The evidence-based training group bowled with the 300 g ball afterwards, as this was used to develop functional strength. Afterwards, this group bowled with the 250 g ball in attempt to develop upper-body power. Each bowling session concluded with regular-ball bowling, to restore the feel of normal bowling and minimise any negative transfer from heavy-ball bowling to regular-ball bowling.

Each delivery was bowled every 30 s. A five-step run-up was used for heavy-ball bowling, whereas a full run-up was employed for regular-ball bowling. The shorter run-up was chosen to reduce metabolic fatigue, but to also allow participants to focus on developing upper-body power without the assistance from the run-up. The full run-up was selected to concentrate on rhythm and coordination. The normal training group matched the evidence-based training group in the prescribed run-ups.

Table 5.6. Bowling training for the evidence-based and normal training groups.

Training weeks	**Deliveries per session**	**Deliveries per week**	**Ball weight (g) H2-H1-R**	**Delivery sequence of weighted balls**
Evidence-based training group				
1	33	66	300-250-156	11-11-11
2	36	72	300-250-156	12-12-12
3	39	78	300-250-156	13-13-13
4	42	84	300-250-156	14-14-14
5	45	90	300-250-156	15-15-15
6	48	96	300-250-156	16-16-16
7	51	102	300-250-156	17-17-17
8	54	108	300-250-156	18-18-18
Normal training group				
1	33	66	156	NA
2	36	72	156	NA
3	39	78	156	NA
4	42	84	156	NA
5	45	90	156	NA
6	48	96	156	NA
7	51	102	156	NA
8	54	108	156	NA

H2, heaviest cricket ball (300 g); H1, heavy cricket ball (250 g); R, regular cricket ball (156g); NA, not applicable.

The target sheet was removed after the specific bowling warm-up, and bowlers delivered to the high jump mat only (Figure 5.4). They were instructed to bowl each delivery at maximal-effort (to elicit maximum explosive contractions), and to not focus on bowling accuracy. This instruction was employed because no group speed-accuracy trade-off was identified in Study 2.

Figure 5.4. Maximal-effort bowling, with a focus on bowling speed.

Each sprint training session commenced after a specific sprint warm-up. The normal training group sprinted at their body-mass only (Table 5.7), as this is typically conducted in cricket practice (233). The evidence-based training group sprinted with weighted-vests (Figure 5.5), because resisted sprint training has been shown to improve speed-acceleration ability (228, 229). Both groups performed maximal-effort 20-m sprints with a two minute recovery between efforts. This recovery was thought to be sufficient for each successive 20-m sprint, given that others have employed a walk-back recovery and have reported improvements in speed-acceleration performance (229).

Table 5.7. Sprint training for the evidence-based and normal training groups.

Training weeks	Sprints per session	Sprints per week	Vest weight (+ % BW)	Sequence of sprints
Evidence-based training group				
1	9	18	20-15-0	3-3-3
2	9	18	20-15-0	3-3-3
3	12	24	20-15-0	4-4-4
4	12	24	20-15-0	4-4-4
5	12	24	20-15-0	4-4-4
6	15	30	20-15-0	5-5-5
7	15	30	20-15-0	5-5-5
8	15	30	20-15-0	5-5-5
Normal training group				
1	9	18	0	NA
2	9	18	0	NA
3	12	24	0	NA
4	12	24	0	NA
5	12	24	0	NA
6	15	30	0	NA
7	15	30	0	NA
8	15	30	0	NA

NA, not applicable.

Figure 5.5. A participant sprinting with the weighted-vest set at +20% of body-mass load.

A 20% and 15% of body-mass load was prescribed because Cronin, Hansen (231) reported these loads to significantly increase the stance phase duration ($p < 0.05$), and reduce the swing phase duration ($p < 0.05$), which may be important for increasing force application to the ground and perhaps speed-acceleration performance. The 15% load was chosen to enhance sprint velocity from the 20% load, which may develop greater power or impulse from a shorter stance phase duration. Participants were weighed prior to training and testing sessions and the weighted-vest (Ironedge, Melbourne, Australia) was adjusted accordingly to be as close as possible to the desired overload. The vest alone weighed 200 g, but had 18 pouches (9 front and back) for additional 1.1 kg weights to be added (Figure 5.6). The sprint training session concluded with un-resisted sprints, to allow participants to experience any elicited potentiation which may have enhanced the training stimulus by improving speed-acceleration.

Figure 5.6. The vest and bars for inclusion into the pouches to meet the desired overload.

The evidence-based training group also performed pull-up training, as performance on the 1-RM pull-up test significantly related ($p < 0.05$) to bowling speed in Study 2. This group performed three sets of maximal repetitions at body-mass load in every session. Some participants could not complete a repetition at body-mass, so they performed five assisted repetitions from a spotter each set. The three minute recovery between sets was chosen as this was thought to be sufficient for restoration of phosphocreatine stores. It was identified in Study 2 that many community standard pace-bowlers do not engage in resistance training, so the normal training group did not perform pull-ups in their program.

5.2.4 *Statistical analyses*

Peak bowling speed was determined by the mean of the two maximal-effort deliveries bowled in the four-over pace bowling test. Mean bowling speed, bowling accuracy, consistency of bowling speed, perceived effort, and approach speed were calculated from 20 match-intensity deliveries. Consistency of bowling accuracy was measured using the same methods detailed in Study 1, with the overall score representative of the mean of match-intensity deliveries aimed at each off-stump target ($n = 16$).

Standard statistical methods were used to calculate means, *SD*s, and 90% confidence intervals. Within group training effects were examined with the effect size statistic (Equation 5.1). Effect sizes were calculated in Microsoft Excel (Version 2010, Microsoft Corporation, Redmond, WA). Effect sizes were interpreted as: trivial (0.00–0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.00–4.00) (220). All other statistical analyses were performed using SPSS (Version 19, IBM Corp.).

Equation 5.1 $effect\ size = \left(mean_{post} - mean_{pre}\right) \div mean(SD_{post} + SD_{pre})$

5.3 Results

A large increase ($d = 1.42$) in mean bowling accuracy of 8.9 ± 3.8 cm (mean ± 90% CI) was observed for the evidence-based training group (Table 5.8). Small improvements in peak bowling speed ($0.9 \pm 0.6\ \mathrm{m{\cdot}s^{-1}}$) and mean bowling speed ($0.9 \pm 0.5\ \mathrm{m{\cdot}s^{-1}}$) were presented by the evidence-based training group. The normal training group displayed trivial changes in peak and mean bowling speed, and mean bowling accuracy. A moderate increase ($d = 0.73$) of 0.08 ± 0.05 s in 20-m sprint time was discovered for the evidence-based training group following training. The normal training group presented a small increase ($d = 0.53$) of 0.10 ± 0.09 s in 20-m sprint time after training. The evidence-based training group showed moderate improvement ($d = 0.68$) of 5.8 ± 6.8 kg in their 1-RM pull-up strength (Table 5.10). The normal training group displayed a trivial improvement ($d = 0.01$) in 1-RM pull-up strength by 0.2 ± 1.7 kg.

Table 5.8. The differences in bowling performance measures following training. Figures are presented as mean ± *SD*, unless otherwise stated.

	Evidence-based training group (*n* = 6)					**Normal training group (*n* = 6)**				
	Pre	**Post**	**Δ from Pre (± 90% CI)**	**ES**	**Interpretation**	**Pre**	**Post**	**Δ from Pre (± 90% CI)**	**ES**	**Interpretation**
Peak2										
BS (m·s^{-1})	29.1 ± 1.8	30.0 ± 2.1	0.9 ± 0.6	0.43	Small	28.8 ± 2.4	28.9 ± 2.5	0.1 ± 0.8	0.02	Trivial
Mean										
BS (m·s^{-1})	28.4 ± 2.2	29.3 ± 2.1	0.9 ± 0.5	0.41	Small	28.1 ± 2.3	28.2 ± 2.6	0.1 ± 0.9	0.07	Trivial
BA (cm)	41.9 ± 5.2	50.8 ± 7.3	8.9 ± 3.8	1.42	Large	46.6 ± 9.1	45.9 ± 5.3	-0.7 ± 4.6	-0.11	Trivial
PE (% of 100)	91.9 ± 6.0	92.8 ± 2.9	0.9 ± 3.5	0.22	Small	90.2 ± 5.0	89.7 ± 5.9	-0.5 ± 3.8	-0.09	Trivial
AS (m·s^{-1})	5.3 ± 0.4	5.4 ± 0.3	0.1 ± 0.3	0.11	Trivial	5.6 ± 0.7	5.6 ± 0.4	0.0 ± 0.3	0.00	Trivial
Consistency										
BS (m·s^{-1})	1.5 ± 2.2	0.5 ± 0.1	-1.0 ± 1.4	-0.86	Moderate	0.7 ± 0.2	0.6 ± 0.2	-0.1 ± 0.2	-0.25	Small
BA (cm)	40.5 ± 6.9	44.6 ± 7.5	-4.1 ± 6.2	0.56	Small	42.4 ± 7.9	42.3 ± 9.1	-0.1 ± 6.3	-0.02	Trivial

CI, confidence interval; Peak2, peak ball speed obtained from two maximal-effort deliveries; BS, bowling speed; BA, bowling accuracy; PE, perceived effort; AS, approach speed; ES, effect size.

Table 5.9. The differences in 20-m sprint time following training. Figures are presented as mean ± *SD*, unless otherwise stated.

	Evidence-based training group (*n* = 5)					**Normal training group (*n* = 4)**				
	Pre	**Post**	**Δ from Pre (± 90% CI)**	**ES**	**Interpretation**	**Pre**	**Post**	**Δ from Pre (± 90% CI)**	**ES**	**Interpretation**
20-m Time (s)	3.43 ± 0.09	3.51 ± 0.13	0.08 ± 0.05	0.73	Moderate	3.26 ± 0.13	3.35 ± 0.23	0.10 ± 0.09	0.53	Small

CI, confidence interval.

Table 5.10. The differences in 1-RM pull-up strength following training. Figures are presented as mean ± *SD*, unless otherwise stated.

	Evidence-based training group (*n* = 2)					**Normal training group (*n* = 5)**				
	Pre	**Post**	**Δ from Pre (± 90% CI)**	**ES**	**Interpretation**	**Pre**	**Post**	**Δ from Pre (± 90% CI)**	**ES**	**Interpretation**
1-RM Pull-up (kg)	80.6 ± 5.6	86.4 ± 11.4	5.8 ± 6.8	0.68	Moderate	92.0 ± 20.5	92.2 ± 18.7	0.2 ± 1.7	0.01	Trivial

CI, confidence interval.

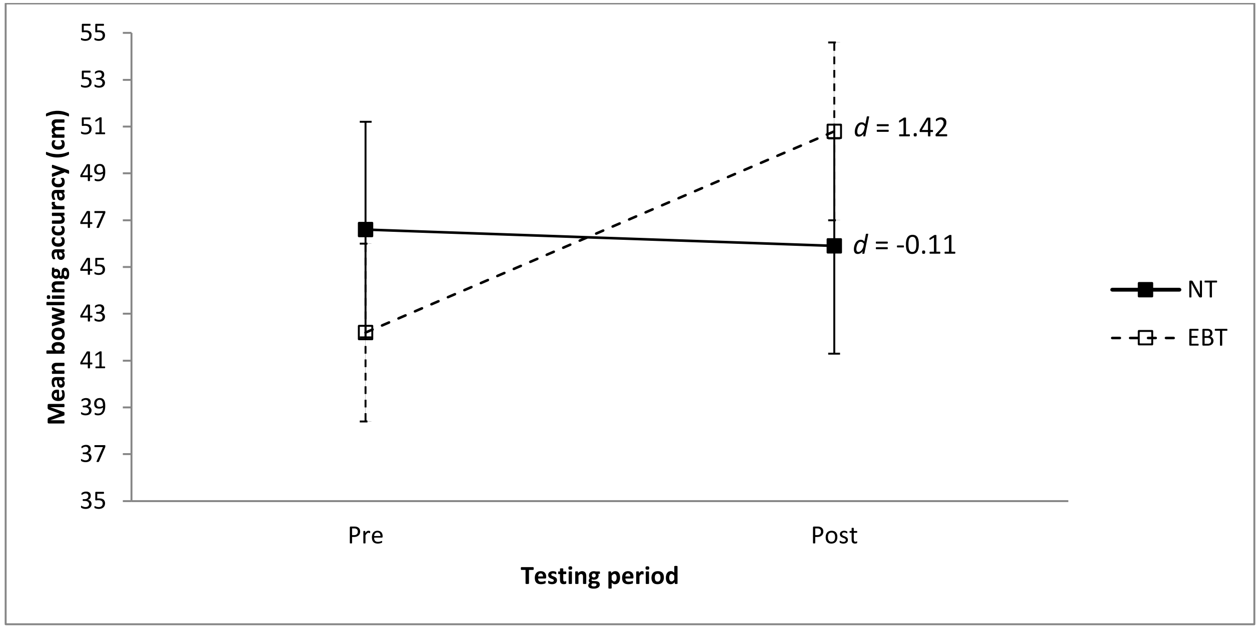

Figure 5.7. The large increase in mean bowling accuracy for the evidence-based training group, compared to the trivial decrease presented in the normal training group. Results presented with ± 90% confidence intervals. EBT, evidence-based training group; NT, normal training group.

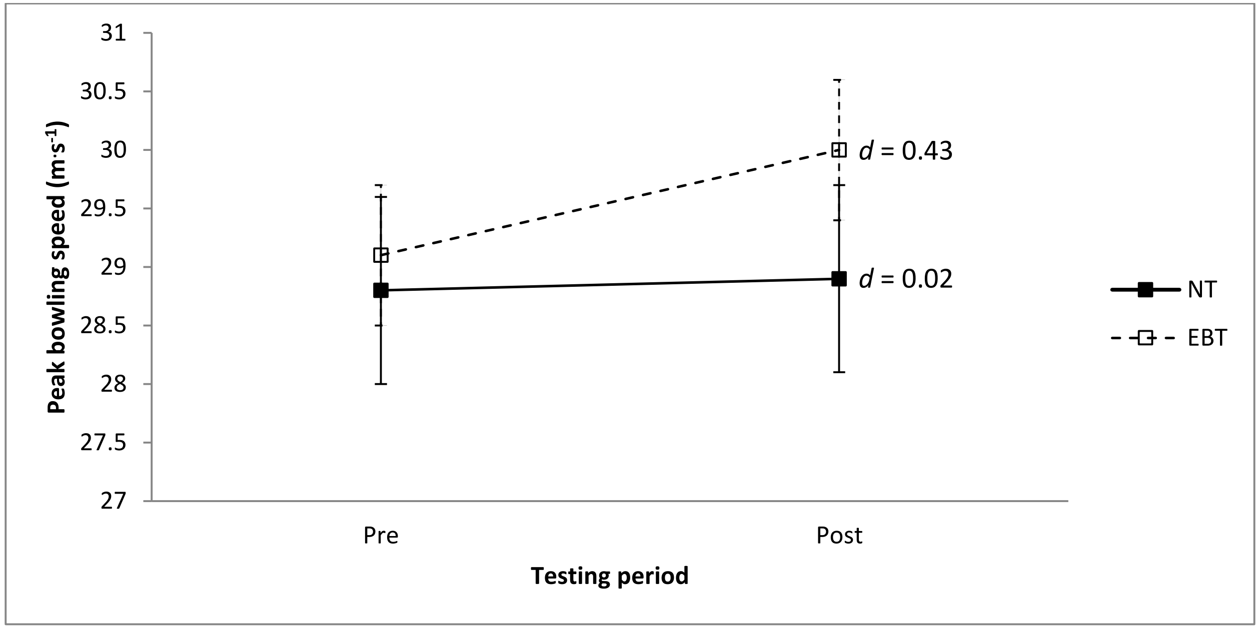

Figure 5.8. The small increase in peak bowling speed for the evidence-based training group, compared to the trivial gain observed in the normal training group. Results presented with ± 90% confidence intervals. EBT, evidence-based training group; NT, normal training group.

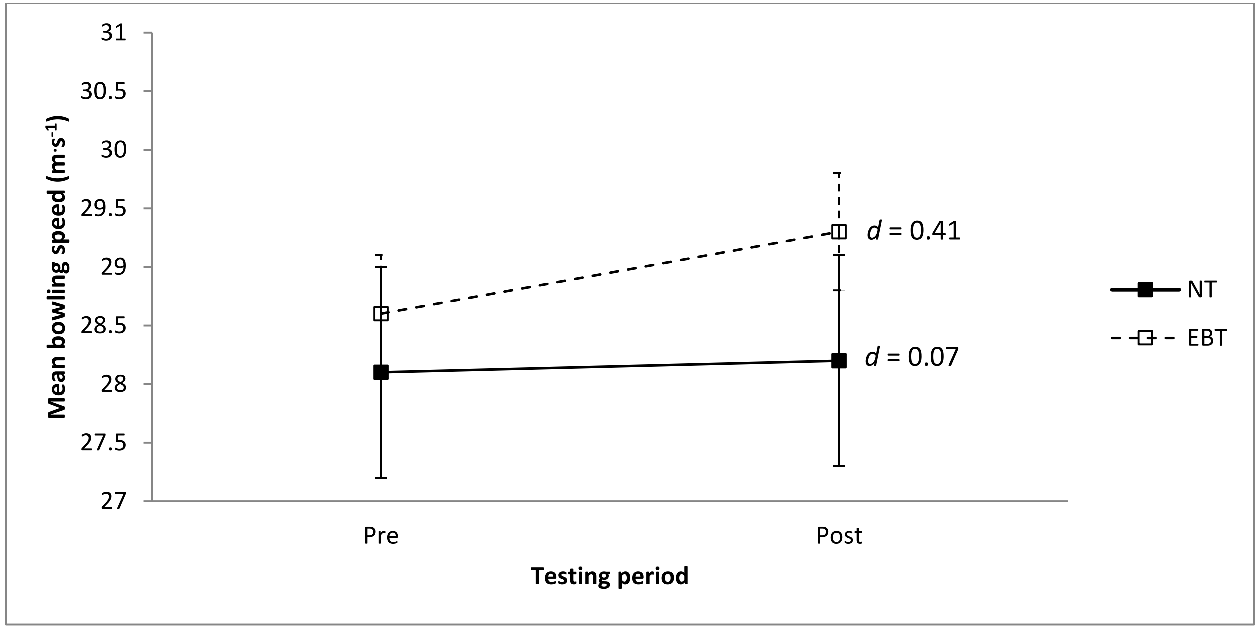

Figure 5.9. The small increase in mean bowling speed for the evidence-based training group, compared to the trivial gain observed in the normal training group. Results presented with ± 90% confidence intervals. EBT, evidence-based training group; NT, normal training group.

5.4 Discussion

5.4.1 Training effects on pace bowling performance

Similar to Petersen, Wilson (2), the evidence-based training group improved their peak bowling speed by 0.9 $m{\cdot}s^{-1}$ (Figure 5.8) and mean bowling speed by 0.9 $m{\cdot}s^{-1}$ (Figure 5.9) (Table 5.8), which is considered meaningful for practitioners as it exceeds the smallest worthwhile change of 0.8 $m{\cdot}s^{-1}$ and 0.5 $m{\cdot}s^{-1}$ respectively (Study 1). The normal training group displayed a trivial increase of 0.1 $m{\cdot}s^{-1}$ in peak and mean bowling speed. Given the meaningful improvement in peak and mean bowling speed for the evidence-based training group, heavy-ball bowling training may have developed upper-body power, by increasing bowling-arm torque and therefore bowling speed. Heavy-ball bowling may have facilitated greater recruitment of fast-twitch motor units, which are known to produce four times greater peak force than their slow-twitch counterparts (234). Due to the high-velocity ballistic nature of the fast bowling motion, it is plausible that heavy-ball bowling recruited a greater percentage of fast-twitch motor units. This form of resisted bowling may be beneficial for enhancing motor unit firing rate, synchronisation, and selective activation of higher order motor units. These neurological adaptations may be important in developing bowling speed. An extended training program could have brought about further developments in peak and mean bowling speed for the evidence-based training group.

The improvement in peak and mean bowling speed for the evidence-based training group came at the cost of a large increase (d = 1.42) in mean bowling accuracy of 8.9 ± 3.8 cm (Table 5.8). Due to the relatively large smallest worthwhile change set for bowling accuracy of 9.6 cm (Study 1), the large effect observed for the evidence-based training group is not considered meaningful to practitioners. In addition, the evidence-based training group were 4.1 ± 6.2 cm worse in their consistency of bowling accuracy score (d = 0.56) (Table 5.8), but this small effect did not exceed the smallest worthwhile change (10.2 cm, Study 1). The normal training group displayed trivial reductions in mean bowling accuracy and consistency of bowling accuracy score (improved performance). In light of these results, it appears that the transfer from heavy- to regular-ball bowling training is negative for bowling accuracy.

Negative transfer occurs when the two performance situations are similar, but movement characteristics differ (159, 160). The negative transfer evident in this investigation could be due to a change in timing of the movement (159, 160). Such an explanation is plausible, as bowling with a ball that is overloaded in mass by 60.3% (250 g ball) and 92.3% (300 g ball) respectively is likely to alter the force characteristics of the bowling pattern. The prescription of ball mass was far greater than the recommended 20% overload reported in previous research (95, 235). DeRenne, Tracy (236) suggested that the weighted implement should be close to the mass of the regular implement, to maintain normal neurological recruitment patterning of the involved limb. An implement that is too heavy or light is thought to modify the motor unit recruitment pattern in the central nervous system (235), and thereby impact technique (236). This is the most plausible explanation, because other factors such as the training environment did not appear to influence bowling accuracy. In training, bowlers were encouraged to deliver each ball with maximal-effort, and the target sheet was removed so they were focussing on eliciting explosive muscular contractions. As the normal training group marginally improved bowling accuracy under the same conditions, the poorer bowling accuracy observed in the evidence-based training group could not be attributed to the training environment.

Bowling with a lighter ball may have been a better choice to develop bowling speed without harming bowling accuracy. Morimoto, Ito (150) showed that a warm-up involving six or 18 maximal-effort throws with a 10% lighter baseball was sufficient to acutely enhance throwing speed without changing throwing accuracy ability. Although this study was not longitudinal, the short term potentiation in throwing speed may have provided a greater training stimulus, and with frequent training sessions it is plausible that throwing speed could be better developed. Others have reported statistically significant gains of 2.5–5.5% ($p < 0.05$) in throwing velocity (greater than a control group) following a 10 week training intervention using 12-20% lighter implements in baseball (96, 119, 121).

Previous research has employed a 2:1 ratio of implement bowling / throwing to regular-ball bowling / throwing (2, 235). This ratio was derived from Vasiliev (95) as it was observed to be the best in maximising throwing velocity and distance thrown in shot-put. However, the transfer of training at this ratio to sports involving accuracy (e.g., pace bowling) has not been examined. Accuracy in shot-put is relatively unimportant, whereas control over a bowlers’ line and length is critical for dismissing batsmen in the game of cricket. As this investigation followed an evidence-based approach, the 2:1 ratio may have resulted in too much heavy-ball bowling, and could have increased the negative transfer to bowling accuracy.

The negative transfer in bowling accuracy observed in this study was likely to be larger than observed by Petersen, Wilson (2), despite the use of different bowling tests and the methods of measuring bowling accuracy. Furthermore, a total of 696 deliveries were bowled by both groups in this study; less than the 864 prescribed by Petersen, Wilson (2). In this instance, it appears a larger increase in ball mass could influence the amount of negative transfer to bowling accuracy in this investigation compared to previous research (2).

Both training groups were more consistent in bowling speed during post-test period, which may be related to the maximal-effort delivery instruction provided in each training session. This notion is supported by Urbin, Stodden (167), who indicated the greatest variability in baseball throwing velocity occurred at 40–60% of perceived maximal-effort, with less variability in throwing velocity as perceived effort reached maximum. Maximal-effort bowling in training appears to have a slight positive transfer to bowling under match-intensity instructions. It could be expected that with less force variability, there is a more consistent transfer of force from the lower-body to the bowling hand, and thereby an improved consistency in bowling speed. Although the improvement observed for both training groups was moderate to small, it may indicate that bowlers were able to resist the onset of fatigue in the bowling assessment. Further exploration of the data highlights that both groups experienced a decline in mean bowling speed throughout the four-over bowling test (irrespective of testing period), but less of a decline was observed in post-testing period.

5.4.2 Training effects on approach speed and speed-acceleration

Both training groups displayed trivial changes in mean approach speed (Table 5.8). A positive change in approach speed was expected following speed-acceleration training. A faster approach speed would have been likely to generate more kinetic energy for transfer to the cricket ball, and in turn allow bowlers to bowl faster providing they remained balanced at the crease (6). Previous studies (6, 12, 25, 43) have reported a strong correlation between run-up velocity and bowling speed.

Surprisingly, both training groups sprinted slower in the 20 m test following training. There was a 0.08 ± 0.05 s increase (d = 0.73) in 20 m sprint time for the evidence-based training group, and a 0.10 ± 0.09 s increase (d = 0.53) increase for the normal training group. Weighted-vest sprinting therefore is unlikely to be the cause of poorer speed-acceleration performance, as the increase in 20-m sprint time was greater with the normal training group (who sprinted un-resisted only). The timing of the speed-acceleration session may have resulted in fatigue. For example, speed-acceleration training was conducted after bowling training, and it is likely that participants were fatigued from performing repeated sub-maximal efforts during the run-up. In the last three weeks of training, both groups bowled 96–108 deliveries per week, but sprinted 600 m per week. The approach speeds during testing indicate that participants were typically running into bowl at 93–94% of their mean 20-m sprint velocity. Although the run-up of the participants ranged between 10–20 m, they performed a third of their deliveries from a full run-up and probably at the same intensity measured during testing.

Previous studies have employed similar sprint distances and volumes to this investigation (227, 229), with shorter recoveries between sprints (227) but have realised improvements in speed-acceleration by 4.6–7.8% (227, 229), through un-resisted and resisted forms of speed training. Furthermore, these studies conducted their speed training sessions when participants were fresh (i.e., not in a state of neural fatigue) (227, 229). According to Baechle and Earle (192), the training session should begin with the most neurally demanding exercises first (i.e., muscular strength / power / speed) and finish with the most metabolically demanding exercises (i.e., muscular endurance). This advice is based on the notion that fast-twitch motor units are known to be less fatigue resistant than slow-twitch motor units (237).

5.4.3 Training effects on pull-up strength

The evidence-based training group improved their pull-up strength by 5.8 ± 6.8 kg ($d = 0.68$), while a trivial gain ($d = 0.01$) of 0.2 ± 1.7 kg was evident in the normal training group (Table 5.10). The disparity in 1-RM pull-up strength between groups is explained by the fact that only the evidence-based training group performed pull-up training, as strong correlations were presented between 1-RM pull-up strength and bowling speed irrespective of delivery effort ($r_s = 0.53$–0.56, $p < 0.01$, Study 2). Nevertheless, only two participants in the evidence-based training group were capable of completing the 1-RM pull-up test. This limitation could have been addressed by testing upper body vertical pulling strength with the latissimus dorsi pulldown exercise. Unfortunately, the latissimus dorsi pulldown machine was not available for data collection. It was interesting to see that one of the participants in the evidence-based training group improved his pull-up strength by 9.9 kg, while the other improved by 1.7 kg. The former improved his peak and mean bowling speed by 3.5% and 3.8% respectively, while the latter improved by 2.3% and 1.7% respectively. At first, these findings suggest that a greater pull-up strength will positively transfer to bowling speed. This conclusion is difficult to make, as pull-up strengthening was included with speed-acceleration training and bowling practise.

Apart from the latissimus dorsi pulldown exercise, the dumbbell pullover exercise would have been a good choice of exercise for training and testing. This single-joint exercise involves participants lying supine on a bench and extending a dumbbell behind their head (with arms almost fully extended), but then raising the mass overhead. The dumbbell pullover exercise targets the latissimus dorsi, teres major, pectoralis major, serratus anterior, triceps brachii, and posterior deltoid (91); muscles that would be used during the pace bowling motion. Chelly, Hermassi (238) reported that the 1-RM pullover test is largely correlated to handball throwing velocity from three steps ($r = 0.55$, $p < 0.05$). Furthermore, Hermassi, Chelly (120) observed a 7.3 kg improvement in 1-RM pullover strength, an 8.1 $m \cdot s^{-1}$ increase in standing throw velocity, and a 6.8 $m \cdot s^{-1}$ enhancement in three-step throwing velocity in elite handball players. Their pullover training was incorporated with bench press and half squat exercise, and comprised three sets of 3–5 reps at a load of 80–95% of 1 RM, similar to the prescription in this investigation for the pull-up exercise. These exercises might be important for developing bowling speed, but need to be examined with a larger sample size. The pull-over was not chosen for this study as the author was not aware of this exercise during the data collection period.

5.5 Conclusions

An eight-week evidence-based training program is capable of improving peak and mean bowling speed, but to the detriment of bowling accuracy. Heavy-ball bowling training could develop speed-strength of muscles of the bowling arm and trunk, and thus improve bowling speed, but because this training modality is specific to the bowling motion, a negative transfer to bowling accuracy is likely to occur. The negative transfer may be attributable to a 60.3% and 92.3% overload in ball mass (250 g and 300 g ball respectively), which was far larger than the recommended 20%. The extra load may have altered segmental sequencing coordination, which would explain the poorer bowling accuracy performance. Furthermore, a 2:1 ratio of heavy-ball bowling to regular-ball bowling may have also influenced the magnitude of negative transfer to bowling accuracy, but should be addressed in future cricket research.

Both groups were slower in the 20-m sprint test following training. Weighted-vest sprinting therefore is unlikely to be the cause of poorer speed-acceleration performance, as the increase in 20-m sprint time was greater with the normal training group (who sprinted un-resisted only). The prescription of sprint training after bowling training may have not permitted participants to sprint when fresh, and thus, elicit positive adaptations to speed-acceleration performance. Fortunately, the slower 20-m sprint times did not negatively influence mean approach speed; a kinematic quality thought to generate larger kinetic energy that can be transferred to the bowling arm to develop bowling speed.

Improvements in 1-RM pull-up strength were presented in the evidence-based training group, supporting that pull-up training enhances pull-up strength. It is difficult to ascertain the influence of pull-up strength on bowling speed, as the evidence-based group completed speed-acceleration training and bowling practise. A better choice of exercise could have been the dumbbell pullover, as both target similar muscles to the pull-up exercise and are easier to perform for weaker individuals. The dumbbell pullover displays a large correlation to handball throwing velocity, and training this exercise appears to positively transfer to throwing velocity in handball.

5.6 Practical applications

Strength and conditioning coaches typically employ a range of exercises that can be classified as general, special, or specific to enhance sporting performance. Heavy-ball bowling is an example of a specific exercise and is thought to show more positive transfer to bowling performance than a general exercise. Although this modality can develop bowling speed to a small extent, it may result in a large negative transfer to bowling accuracy. With an extended heavy-ball bowling training program, and a more balanced ratio of heavy-ball to regular-ball bowling (i.e., 1:1 and not 2:1), this training modality may enhance bowling speed without harming bowling accuracy. Another alternative would be to use more general (e.g., dumbbell pullover, bench press, squat) or special exercises (e.g., medicine ball slam, jump squat) to develop strength and power of the muscles involved in the pace bowling motion, which would negate any negative transfer due to the lower specificity to the pace bowling motion. This training approach would allow a greater strength training stimulus, because the load of the heavy-ball is restricted to ensure bowling technique is not adversely affected.

Regular-ball bowling on its own (normal training) does not alter pace bowling performance in community-standard pace bowlers after eight weeks training, and so can be used to maintain bowling performance in-season but is not recommended for use by itself if the goal in mind is to enhance bowling performance during pre-season.

To develop speed-acceleration, each training session should be performed when athletes are neurally fresh, and not fatigued after a bowling training session. This approach may ensure a greater training stimulus, which could manifest into long-term speed-acceleration improvements. Sprinting with a sled may be more effective than a weighted-vest for improving speed-acceleration. However, weighted-vest sprinting may be more beneficial for maximal speed training. Both speed-acceleration and maximal speed could be important for pace bowlers, but would be dependent on the length of the run-up and approach speed of each bowler.

The pull-up exercise is a good strength exercise that should theoretically enhance bowling speed, by training similar muscles used in bowling-arm circumduction. Individuals who cannot perform the pull-up exercise should perform the dumbbell pullover exercise. The dumbbell pullover exercise trains similar muscles to the pull-up, with the benefit of a near full-extension of the arms, which is more specific to the bowling motion.

Chapter 6 – Study 4:

The Acute Effects of a Heavy-Ball Warm-up on Pace Bowling Performance

6.1 Background

Performing a warm-up can enhance sports performance through a variety of short-term physiological changes, but the recovery period before training or competition has to be carefully planned to optimise performance (239, 240). In cricket, players usually perform a warm-up before training and competition in an attempt to maximise performance. At a community-standard cricket club, the warm-up typically involves a jog around the oval, followed by dynamic stretches, fielding drills, and bowling / batting practise. Pace bowlers typically bowl with a regular mass cricket ball (156 g) at the end of the warm-up, to be “match ready” for their first delivery.

In baseball pitching research, throwing with heavy, light, and regular balls has been prescribed in the warm-up, with the goal to acutely enhancing throwing velocity and accuracy (114, 149, 150). The purpose of the heavier implement is to elicit post-activation potentiation (Chapter 2), through improved motor unit recruitment, motor unit firing rate, and motor unit synchronisation (137). Post-activation potentiation would thereby improve the power output of subsequent muscular contractions (i.e., bowling with a regular mass ball). However, an implement that is too heavy is thought to modify the motor unit recruitment pattern in the central nervous system (235), and thereby influence technique (236). A 20% increase in regular ball mass has therefore been recommended for training purposes (95, 235), but such an overload in ball mass may be insufficient to elicit post-activation potentiation in a warm-up. For example, Rahimi (141) discovered that as intensity of the back squat during the warm-up increased (from 60–85% 1-RM), running speed on the 40 m sprint test significantly improved from 1.9–2.9% ($p < 0.05$) compared to a control group (no back squats in the warm-up). The effects of heavy and regular-ball bowling warm-ups on pace bowling performance has not been investigated. This gap in the pace bowling literature is rather significant, because a heavy-ball warm-up might elicit greater post-activation potentiation compared to a regular-ball warm-up, and the short-term enhancement in bowling performance could be exploited in training and matches.

The heavy-, light-, and regular-ball bowling training approach used by Petersen, Wilson (2) is similar to the principles of contrast training, where a high-load exercise is alternated with a low-load exercise, but are both biomechanically similar (151). Contrast training is designed on the assumption that the high-load exercise potentiates the low-load exercise (151). In this instance, heavy-ball bowling could potentiate regular-ball bowling, but this has never been explored, especially with chronic adaptations. Tsimachidis, Patikas (232) showed that a combination of strength and sprint training was effective in eliciting potentiation within a training session (assumed through improved 10 m and 30 m running velocity), but only towards the end of their 10-week intervention. These findings indicate that increasing strength may provide a foundation for potentiating powerful motions, and thus induce a greater power training stimulus. This concept may be applied to heavy-ball bowling, where the speed-strength of the bowling-arm musculature could be developed (95), and greater potentiation may be realised with frequent heavy-ball bowling training. This concept has never been investigated in pace bowling research.

Therefore, the first purpose of this study was to compare the acute effects of a heavy- and regular-ball bowling warm-up on pace bowling performance. The second purpose of this study was to determine if an evidence-based training program (resistance training and heavy-ball bowling) influences whether a potentiation effect occurs at the end of the eight-week training program. This study will inform coaches of the efficacy of a heavy- and regular-ball bowling warm-up on pace bowling performance, and the impact of an evidence-based training program on any changes of these acute effects.

6.2 Methods

6.2.1 Experimental approach to the problem

This investigation comprised a repeated measures longitudinal design, where participants served as their own controls. Following a two-week familiarisation period of bowling, participants completed one of two bowling warm-ups (heavy-ball or regular-ball) and a four-over pace bowling test, on separate days (counterbalanced) within a week, with 48–72 hours recovery between sessions. The first four overs of the eight-over pace bowling test from Study 1 and 3 were used to test participants in less time. After the initial testing period, an eight-week evidence-based training program was conducted (Study 3), and a post-testing period (same design and duration as pre-testing) was performed (Figure 6.1). This design facilitated the analysis of the acute effects of each bowling warm-up on pace bowling performance, and if an evidence-based training program resulted in greater acute changes in pace bowling performance.

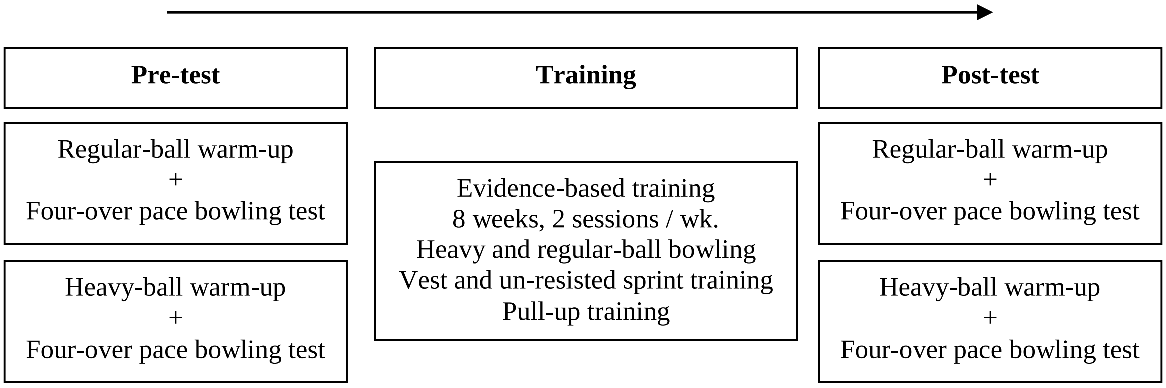

Figure 6.1. The experimental design of this investigation.

6.2.2 Participants

Ideally, a high-performance sample would ideally be assessed in this investigation, because elite-standard pace bowlers typically engage in physical conditioning, and bowl with greater technique and consistency. However, due to the difficulty in recruiting such athletes for comprehensive testing and training, a community-standard group was recruited; six participants from the evidence-based training group in Study 3 (Table 5.1). To qualify for involvement in this investigation, participants had to be injury-free for at least six months and free of illness during testing and training. This study was approved by the University Human Research Ethics Committee (Appendix A), and participants received a Plain Language Information Statement (Appendix B). Prior to this investigation, participants were briefed on the experimental design, including all forms of testing and training procedures, experimental risks, and the nature of the study, before providing their informed consent. They were instructed to refrain from resistance training, alcohol and caffeine consumption 24 hours prior to each testing and training session.

6.2.3 Experimental procedures

Each testing session commenced with a general warm-up (Table 5.2) followed by a specific bowling warm-up (Table 5.3). The regular-ball warm-up (Table 5.4) was used in one testing session followed by the four-over pace bowling test (Table 5.5). The heavy-ball warm-up was used in the other testing session followed by the four-over pace bowling test.

6.2.3.1 Heavy-ball bowling warm-up

The heavy-ball bowling warm-up commenced approximately three minutes after the specific bowling warm-up (Table 6.1). One delivery was bowled every 30 s, with the first nine deliveries targeted at off stump to a right hand batsman, and bowled with a 250 g ball. The last nine deliveries were directed towards off stump for a left hand batsman, and bowled with a 300 g ball. Participants bowled all deliveries from a short five-step run-up and at match-intensity (as they would in a match). The progressive increase in ball weight was chosen to adequately prepare participants to the heaviest ball (300 g), but in a bid to elicit potentiation through increased motor unit recruitment, like a “staircase effect” (241). Approximately three minutes of active recovery (walking) followed prior to the four-over pace bowling test (Table 5.5).

Table 6.1. Heavy-ball bowling warm-up condition. The regular-ball warm-up resembled this except was performed with a regular ball only (156 g).

Time	Ball #	Ball mass	Instruction	Run-up distance	Target
10:00	1	250 g	Match-intensity	Short (5-step)	Off stump – right hand batsman
10:30	2				
11:00	3				
11:30	4				
12:00	5				
12:30	6				
13:00	7				
13:30	8				
14:00	9				
14:30	10	300 g	Match-intensity	Short (5-step)	Off stump – left hand batsman
15:00	11				
15:30	12				
16:00	13				
16:30	14				
17:00	15				
17:30	16				
18:00	17				
18:30	18				

6.2.3.2 Evidence-based training program

Participants completed the evidence-based training program (detailed in Study 3, Tables 5.9–5.11) following a two week familiarisation period of bowling, sprint training, and pull-up training. An attendance requirement of 87.5% (absent for three or more sessions) was enforced for this investigation.

6.2.4 Statistical analyses

Peak bowling speed was determined by the mean of the two maximal-effort deliveries bowled in the four-over pace bowling test. Mean bowling speed, bowling accuracy, consistency of bowling speed, perceived effort, and approach speed were calculated from 20 match-intensity deliveries, using the same methods outlined in Study 1 and 3. Consistency of bowling accuracy was measured using the same methods detailed in Study 1 and 3, with the overall score representative of the mean of match-intensity deliveries aimed at each off-stump target (*n* = 16).

Standard statistical methods were used to calculate means, *SD*s, and 90% confidence intervals. To examine the acute effects of heavy-ball and regular-ball bowling warm-ups on pace bowling performance, effect sizes were calculated separately for each pre and post-test period (Equation 6.1). Effect sizes were used to determine the magnitude of differences, and were calculated in Microsoft Excel (Version 2010, Microsoft Corporation, Redmond, WA). Effect sizes were interpreted as: trivial (0.00–0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.00–4.00) (220). To determine the change in acute warm-up effects with training, the difference in effect size from post- to pre-test period was calculated. The effect sizes used in these calculations were derived from the difference in heavy-ball and regular-ball warm-up conditions for each testing period respectively.

Equation 6.1 $effect\ size\ for\ pre\ or\ post\!-\ test\ period$

$$= (mean_{HB} - mean_{RB}) \div mean(SD_{HB} + SD_{RB})$$

* HB, heavy-ball warm-up; RB, regular-ball warm-up.

6.3 Results

6.3.1 Acute warm-up effects on pace bowling performance

In pre-test period, a small reduction (*d* = -0.23) in peak bowling speed of -0.4 ± 0.4 m·s^{-1} accompanied moderate increases in mean bowling accuracy (8.8 ± 7.4 cm, *d* = 1.19) and consistency of bowling accuracy (6.7 ± 7.7 cm, *d* = 0.92) from the heavy-ball warm-up (Table 6.2). In post-test period, a small enhancement (*d* = 0.21) in mean bowling speed of 0.5 ± 0.5 m·s^{-1} was associated with moderate reductions in mean bowling accuracy (-5.5 ± 6.4 cm, *d* = -0.90) and consistency of bowling accuracy (-4.2 ± 3.9 cm, *d* = -0.87) from the heavy-ball warm-up.

6.3.2 Changes in acute warm-up effects and pace bowling performance with training

When comparing effect sizes from pre- to post-test periods, a small increase in peak bowling speed (Δ *d* = 0.40) and mean bowling speed (Δ *d* = 0.21) accompanied small reductions in mean bowling accuracy (Δ *d* = -0.29), mean perceived effort (Δ *d* = -0.23), and mean approach speed (Δ *d* = -0.27) (Table 6.3). However, the biggest improvements following evidence-based training were realised with the large reduction in consistency of bowling accuracy (Δ *d* = -1.79), and a moderate reduction in consistency of bowling speed (Δ *d* = -0.84).

Table 6.2. The acute effects of two bowling warm-ups on pace bowling performance, before and after an evidence-based training program. Figures are presented as mean ± *SD*, unless otherwise stated.

	Pre-test period (*n* = 6)					**Post-test period (*n* = 6)**				
	RB	**HB**	**Δ from RB (± 90% CI)**	**ES**	**Interpretation**	**RB**	**HB**	**Δ from RB (± 90% CI)**	**ES**	**Interpretation**
Peak2										
BS (m·s^{-1})	29.1 ± 1.8	28.7 ± 2.0	-0.4 ± 0.4	-0.23	Small	30.0 ± 2.1	30.3 ± 2.3	0.3 ± 0.3	0.17	Trivial
Mean										
BS (m·s^{-1})	28.4 ± 2.2	28.4 ± 1.9	0.0 ± 0.2	0.00	Trivial	29.3 ± 2.1	29.8 ± 2.3	0.5 ± 0.5	0.21	Small
BA (cm)	41.9 ± 5.2	50.7 ± 9.5	8.8 ± 7.4	1.19	Moderate	50.8 ± 7.3	45.3 ± 5.0	-5.5 ± 6.4	-0.90	Moderate
PE (% of 100)	91.9 ± 6.0	90.2 ± 6.1	-1.7 ± 1.5	-0.29	Small	92.8 ± 2.9	93.1 ± 4.7	0.3 ± 2.8	0.06	Trivial
AS (m·s^{-1})	5.3 ± 0.4	5.2 ± 0.3	-0.1 ± 0.3	-0.39	Small	5.4 ± 0.3	5.3 ± 0.3	-0.1 ± 0.0	-0.12	Trivial
Consistency										
BS (m·s^{-1})	1.5 ± 2.2	0.5 ± 0.2	-1.0 ± 1.5	-0.84	Moderate	0.5 ± 0.1	0.5 ± 0.2	0.0 ± 0.1	0.00	Trivial
BA (cm)	40.5 ± 6.9	47.2 ± 7.6	6.7 ± 7.7	0.92	Moderate	44.6 ± 7.5	40.3 ± 2.2	-4.2 ± 3.9	-0.87	Moderate

CI, confidence interval; Peak2, peak ball speed obtained from two maximal-effort deliveries; BS, bowling speed; BA, bowling accuracy; PE, perceived effort; AS, approach speed; RB, regular-ball warm-up plus four-over pace bowling test; HB, heavy-ball warm-up plus four-over pace bowling test; ES, effect size.

Table 6.3. The change in acute warm-up effects and pace bowling performance with an evidence-based training program.

	ES Pre (HB-RB)	**ES Post (HB-RB)**	**Δ ES from Pre**	**Interpretation**
Peak2				
BS ($m \cdot s^{-1}$)	-0.23	0.17	0.40	Small
Mean				
BS ($m \cdot s^{-1}$)	0.00	0.21	0.21	Small
BA (cm)	1.19	-0.90	-0.29	Small
PE (% of 100)	-0.29	0.06	-0.23	Small
AS ($m \cdot s^{-1}$)	-0.39	-0.12	-0.27	Small
Consistency				
BS ($m \cdot s^{-1}$)	-0.84	0.00	-0.84	Moderate
BA (cm)	0.92	-0.87	-1.79	Large

Peak2, peak ball speed obtained from two maximal-effort deliveries; BS, bowling speed; BA, bowling accuracy; PE, perceived effort; AS, approach speed; RB, regular-ball warm-up plus four-over pace bowling test; HB, heavy-ball warm-up plus four-over pace bowling test; ES, effect size.

6.4 Discussion

6.4.1 Acute warm-up effects on pace bowling performance

The findings from this investigation suggest that the heavy-ball warm-up resulted in short-term changes to pace bowling performance compared to the regular-ball warm-up. In pre-test period, the heavy-ball warm-up resulted in moderate increases in mean bowling accuracy (d = 1.19) and consistency of bowling accuracy (d = 0.92), indicating a poorer bowling performance. Peak bowling speed was slightly reduced (d = -0.23), with no change in mean bowling speed (d = 0.00), highlighting that the heavy-ball warm-up was ineffective at enhancing pace bowling performance from these fronts (in pre-test period). The only improvements observed in pace bowling performance from the heavy-ball warm-up in pre-test period was the moderate reduction in consistency of bowling speed (d = -0.84).

This is the first investigation that has presented poorer accuracy with a regular-mass implement following a conditioning activity with a heavier implement. Van Huss, Albrecht (149) observed a slightly improved throwing accuracy in just 10 throws (albeit an altered pattern), and Straub (114) reported no changes in throwing accuracy; both studies prescribed a heavier implement as a conditioning stimulus. The difference in accuracy performance in this investigation compared to others can be explained through an understanding of biomechanics and motor control. Although a general proximal-to-distal sequencing has been established in pace bowling (71, 99) and baseball (100-103), the quantification of accuracy performance in both sports is quite different. In baseball, the ball travels through the air without bouncing, but in cricket, the ball typically bounces first on the pitch and the ball is subjected to possible deviation (seam movement) off the pitch. Furthermore, pace bowlers usually deliver the ball with an upright trunk posture, but baseballers use a more “round-arm approach”. This means that the release angle of the baseball and cricket ball differ. Overloading the pace bowling movement pattern (or motor program) with a heavy-ball had a negative effect on bowling accuracy and consistency of bowling accuracy in this investigation; probably through a temporary disturbance of the optimal segmental sequencing pattern, with an inconsistent ball release position. Quite simply, the pace bowlers were not able to bowl with an optimal segmental sequencing pattern with a regular-ball following the heavy-ball warm-up.

The small to trivial changes in peak and mean bowling speed respectively are similar to baseball pitching studies (114, 149). In both studies by Van Huss, Albrecht (149) and Straub (114), there was no recovery period between heavy-ball pitching and regular-ball throwing, suggesting fatigue may have overridden any signs of potentiation. Both studies however, employed a relatively large increase in regular-ball mass (120–200% or 6–10 oz.), which may not have been sufficient to elicit post-activation potentiation and enhance throwing velocity in the short-term. Post-activation potentiation is typically exhibited with intensities of 60–84% 1-RM (242). It could be argued that the lower increase in regular-ball load (60.3–92.3% or 94–144 g) in the present investigation may not have been sufficient to elicit post-activation potentiation. However, throwing a very heavy implement with proper throwing mechanics would be impossible, and would potentially increase the negative transfer to bowling performance and increase injury risk. Therefore, a less biomechanically specific exercise such as the bench press (or resisted push-ups) might have been a more effective method of eliciting potentiation through a greater intensity (load).

The recovery period between the warm-up (conditioning activity) and subsequent muscular contractions should also be considered, as potentiation and fatigue coexists following a conditioning activity (136). According to Sale (136), fatigue subsides faster than potentiation following a conditioning activity, which allows a "window of opportunity" to enhance subsequent muscular contractions via the prevalence of potentiation. A recent meta-analysis by Wilson, Duncan (242) suggests that 7–10 minutes of recovery following the conditioning activity is most preferred to enhance power output via potentiation. In this study, a three minute recovery period followed the heavy-ball and regular-ball warm-ups, which may have been insufficient to allow potentiation to prevail. The short recovery may have meant that fatigue may have masked any potential benefits of the heavy-ball bowling.

An alternative choice of conditioning activity could have been lighter-ball bowling (lighter than regular cricket ball). Morimoto, Ito (150) showed that a warm-up with either six or 18 maximal-effort throws of a 10% lighter baseball was sufficient to acutely enhance throwing speed compared to a warm-up with a regular ball or a heavy ball. Throwing with a lighter ball should theoretically increase the velocity of the throwing arm, which may serve to temporarily reduce any reciprocal inhibition, and allow the regular ball to be thrown with greater velocity. Morimoto, Ito (150) suggested that lighter-ball throwing may have activated the neuromuscular system to a greater extent than regular or heavy-ball throwing. However, electromyography and ultrasonography measures were not employed in their study, which would have shown any differences muscle activation levels and muscle architecture with each warm-up condition.

6.4.2 Changes in acute warm-up effects and pace bowling performance with training

Irrespective of the negative short-term effects that a heavy-ball bowling warm-up had on pace bowling performance during pre-test period, it is evident that adaptation to heavy-ball bowling can occur after only eight-weeks of training (Table 6.3). However, while there is a small improvement observed in peak and mean bowling speed, mean bowling accuracy did not improve enough to negate the moderate difference observed in pre-test period. It is interesting though that the consistency of bowling accuracy was reduced to a large extent ($\Delta\ d$ = -1.79), suggesting a heavy-ball warm-up was preferred to a regular-ball warm-up in post-test period, because the segmental sequencing pattern was more likely to be consistently optimal each delivery. These observations could be explained by the training program.

In training, participants gradually transitioned from heavy-ball bowling with the 300 g ball to the 250 g ball, and then finished their session with the regular 156 g ball. Through this process, they may have gradually learned how to adapt to the short-term change in segmental sequencing pattern, and thus bowl with greater accuracy further into the training program. In pre-test period, the transition from heavy-ball to regular-ball bowling typically resulted in short-pitched bowling, and participants often reported the feeling of bowling much shorter than usual. In post-testing period however, participants adapted to the regular ball much faster. With frequent heavy-ball bowling training, participants may have learned to bowl at a more full length when switching to the regular ball. Morimoto, Ito (150) described this phenomenon as the “memory of dynamical senses”. That is, when switching from a heavier or lighter implement to a regular-mass implement, a temporary disruption occurs to the motor program, because the initial heavy or lighter implement throwing altered the parameters of the motor program (e.g., force, timing) and this remains fresh in memory when immediately switching to a regular ball. In essence, this is not dissimilar to the concept of negative transfer, where the two movement patterns are similar, but movement characteristics (e.g., force, timing) differ (159, 160). These concepts indicate that a gradual transition from heavy- to regular-ball bowling may reduce the degree of negative transfer experienced towards bowling accuracy and consistency of bowling accuracy. Furthermore, with frequent training, it could be expected that the adaptation to each ball mass would be quicker, providing a similar transition occurs from heavy- to regular-ball bowling within each session. That is, instead of taking six deliveries to re-adjust to a regular ball, it might only take three deliveries, because the bowler has learned how the heavier ball changes their optimal segmental sequencing pattern.

6.5 Conclusions

The heavy-ball warm-up appears to temporarily negate bowling performance in the short-term, but with frequent training, adaptation occurs and some positive outcomes from a heavy-ball warm-up exists. A disruption to the optimal segmental sequencing pattern is likely to occur with heavy-ball bowling, but this negative transfer to regular-ball bowling performance can be reduced by prescribing a gradual transition from heavy-ball bowling to regular-ball bowling within a session. Overall, after an eight-week evidence-based training program, there are small improvements seen in peak and mean bowling speed, but small decrements in bowling accuracy.

6.6 Practical applications

Coaches should probably seek alternative methods of eliciting post-activation potentiation, rather than employ heavy-ball bowling. The heavy ball potentially serves to disrupt optimal technique, and thereby bowling speed, accuracy, and consistency of bowling accuracy in the short-term, especially when this modality has not been used before. Perseverance with heavy-ball bowling can reverse some of the negative effects in the long-term, but there is probably a better method to elicit post-activation potentiation in the muscles used for pace bowling by selecting a less biomechanically specific exercise (e.g., bench press throws or resisted push-ups). These types of exercises would serve to reduce the negative transfer by minimising the disruption to the segmental sequencing pattern, and thus allow any elicited potentiation to prevail in the pace bowling motion.

Chapter 7:
Summary, Practical Applications, and Recommendations for Further Research

7.1 Summary

The evaluation of pace bowling performance has varied throughout the literature. Many different types of tests have been formed, with inconsistencies in the amount of overs, the measurement of bowling accuracy, the number of targets delivered to, and the frequency of deliveries at each target. Despite the inherent differences in pace bowling tests across the literature, the test-retest reliability of the bowling performance measures has not been thoroughly investigated. The problem with this limitation is that sport scientists cannot make an informed decision regarding how effective a training program has been on improving a performance measure; as the error of the measure is unknown. The improvement in a performance quality has to exceed the error of the measure for confidence to be placed in a particular training program. But before one can decide on the particular exercises to include in the training program, a correlational analysis between physical capacities, bowling kinematics, and bowling performance measures is warranted. Aside from conducting a correlational analysis, an examination of literature in similar sports can also form a sufficient evidence for the inclusion of particular exercises or training modalities.

With the creation of a new pace bowling test it was important to allow for a familiarisation period to encounter any possible learning effects that could have occurred between both tests. Fortunately, no systematic biases were present, indicating the three week learning period of how to conduct the bowling test was adequate. Irrespective of the familiarisation period though, very few variables were classified with acceptable reliability. In attempt to enhance the construct validity of the new pace bowling test, more targets were included, and frequent changes in delivery instruction meant that the community-standard pace bowlers struggled to settle into a “rhythm”. The lack of coordination or “rhythm” meant greater inconsistency in some bowling performance measures, ultimately resulting in partially reliable or unreliable measures, according to the standards set for the intraclass correlation coefficient and the coefficient of variation. But perhaps the level of error for some of the performance measures was just reflective of the complexity in the pace bowling motion, and how consistency in segmental sequencing coordination is indeed more difficult for community-standard pace bowlers. Even though the pace bowling motion can be defined as a closed and repetitive skill, there are many possible movement outcomes and the degrees of freedom must be limited through stabilisation and appropriate timing of particular muscles to facilitate effective delivery of the cricket ball. A slight change in the timing of this movement is probably enough to produce variations in bowling performance measures. Therefore, while some measures may be in fact not reliable or partially reliable, the error values should be accepted and used to provide insight into the effectiveness of a training program. It just means that a measure with larger error requires greater improvement or reduction for confidence to be placed in the training program.

A dearth of statistically significant correlations between physical capacities and bowling performance measures highlights the importance of selecting physical capacity tests that are more biomechanically similar to the pace bowling motion. A greater performance on the 1-RM pull-up test and 20-m sprint test were both associated with the ability to bowl faster; probably because the muscles targeted in both tests contract in the same fashion during pace bowling. The selection of physical capacity tests should be made in conjunction with electromyography information and a biomechanical analysis, where identification of muscular activity can be made during certain bowling positions.

One key factor in achieving a greater bowling performance appears to be “rhythm” or intermuscular coordination. Anecdotally, the greatest pace bowlers have appeared effortless in their run-up and bowling action (e.g., Wasim Akram, Michael Holding); indicating a smooth sequencing of segments throughout delivery. The ability of each muscle group to contribute force to each segment is also important (i.e., intramuscular coordination). But a distinction needs to be made between intermuscular and intramuscular coordination. Some pace bowlers may possess the strength and muscle build to bowl fast (i.e., intramuscular coordination), but lack intermuscular coordination. Those types of bowlers often appear uncoordinated or rigid in motion. Other pace bowlers may be able to coordinate their segments very effectively (i.e., intermuscular coordination) but lack strength and power of the actuating muscle groups for each segment. These types of bowlers have a smooth technique, but do not deliver the ball at dangerous pace. It could be assumed that both types of bowlers could be seen in a sample of community-standard cricketers. If this is true, then the correlations between physical qualities and bowling performance measures will typically be weaker. From observation of participants in this PhD project, the strongest bowlers were not the quickest.

To deliver a ball with excellent intermuscular coordination is important, but of more importance is the ability to consistently achieve this ball after ball, during a spell of pace bowling. A consistent transfer of force from the front leg to the bowling arm should assist a bowler in achieving rhythm with consecutive deliveries. In pace bowling, a combination of horizontal and vertical forces travel through the front leg to the bowling arm. These forces are probably dependent on kinematic factors such as approach speed, plant angle, initial foot angle, and front knee angle at front foot contact. Therefore, consistency in each of these kinematic variables would assist the bowler in experiencing similar forces and transfer rates from the lower body to the trunk. Providing that the trunk and upper body display smooth segmental sequencing, then the force generated from the lower body should consistently transfer to the bowling hand. This means that a bowler can flex the front leg but still bowl with consistent rhythm providing little variation exists in the front knee angle between deliveries.

The delivery instructions provided to bowlers are very important in the quest to achieve consistent rhythm. For example, a frequent change in delivery type (e.g., bouncer, yorker, top of off stump) and delivery speed (maximal, slower, match-intensity) only serves to increase the amount of force variability and thus inconsistency with intermuscular coordination. Pace bowlers should be instructed to deliver the ball with maximal-effort for two major reasons. First, force variability decreases as effort level increases. This means that a consistent transfer of force from the front-leg to the bowling arm is more likely. Second, muscular power should be developed to a greater extent when delivering the ball with maximal effort. But, there is a consolation. Bowlers should not “muscle” the ball when bowling with maximal effort. This would only serve to disrupt the bowlers’ optimal segmental sequencing pattern and in turn have negative consequences on bowling accuracy and consistency of bowling accuracy.

The inclusion of heavy-ball bowling into the evidence-based training program was designed to improve the functional strength of the bowling arm. The small improvement in peak and mean bowling speed after eight weeks of evidence-based training was outweighed by the large increase in mean bowling accuracy (poorer performance). It is likely that the transition from heavy-ball to regular-ball bowling resulted in negative transfer to bowling accuracy and consistency of bowling accuracy. Further investigation highlighted that in pre-test period, the heavy-ball warm-up moderately reduced both accuracy measures compared to the regular-ball warm-up. Even though pace bowlers appear to adapt to heavy-ball bowling from a warm-up sense, a reliance to this modality is required to bring about short-term improvements in bowling performance. This training modality can potentially do more harm than good to bowling performance in the short and long term. This is because the training method biomechanically mimics the pace bowling motion, and is likely to disrupt the optimal segmental sequencing pattern.

7.2 Practical applications

This thesis provides several practical considerations for coaches and sport scientists in the development of pace bowling performance for community-standard pace bowlers:

1. When assessing bowling performance, peak and mean ball speed are the most reliable measures, and therefore exhibit lower smallest worthwhile change scores. Coaches can easily determine the efficacy of a training program for these two performance measures as they present with excellent test-retest reliability.
2. When evaluating bowling kinematics, step length, step-length phase duration, power phase duration, and knee-extension angle at front-foot contact and at ball release exhibit excellent test-retest reliability, but not approach speed. Coaches can use those reliable measures for assessing changes in bowling kinematics with a training program.
3. Coaches can use the four-over test to measure bowling performance and associated kinematics in shorter time, but should be aware of the slightly bigger smallest worthwhile change scores to the eight-over test. The eight-over test is more valid for assessment of consistency of bowling speed and consistency of bowling accuracy, as community-standard pace bowlers may become fatigued with this length of test.
4. Strength and conditioning coaches can use the 20-m sprint test, 1-RM pull-up test, 3-RM bench press test, reactive strength test, and straight-leg raise test to provide insight into how a pace bowler may perform in the eight-over test. For example, a faster 20-m sprint time and greater pull-up strength might indicate a quicker pace bowler, whereas a greater 3-RM bench press performance and poorer reactive strength ability may indicate a more accurate pace bowler.
5. Coaches should be careful with their instructions to a pace bowler regarding bowling speed and accuracy. A within-bowler assessment of the speed-accuracy relationship would inform coaches of what instructions they should give to a pace bowler at training or before a match. For example, if a bowler delivers with poorer accuracy when attempting to bowl fast, then instructing them to bowl at maximal effort may be counterproductive for performance. In

contrast, bowlers that deliver a ball more accurately when bowling faster should be encouraged by coaches to bowl at maximal effort.

6. Strength and conditioning coaches could prescribe the evidence-based training program to enhance bowling speed, but the possible negative effects on bowling accuracy should be considered. The normal training program resulted in trivial changes in performance, which indicates conventional training is unlikely to improve bowling speed during the pre-season. Coaches may prefer to use the evidence-based training program in pre-season, and the normal training program during the season.
7. To develop speed-acceleration, coaches should perform each training session before the bowling session, or on a separate day. This training approach may ensure a greater training stimulus by avoiding the impact of fatigue on speed-acceleration, which could manifest into long-term speed-acceleration improvements, and perhaps bowling speed.
8. Due to the observation that many community-standard pace bowlers struggle to complete the pull-up exercise, it is advised coaches use the pullover or lat-pulldown exercise to build a general strength base. The pullover trains similar muscles to the pull-up, and is performed with a near full-extension of the arms, which is more specific to the bowling motion than the pull-up exercise.
9. Coaches should seek alternative methods of eliciting potentiation, rather than heavy-ball bowling. The mass of the heavy ball may need to be large to have a considerable effect, which would be detrimental to bowling technique. Another possibility is to increase the recovery period from the warm-ups to allow potentiation to prevail over the fatigue response. Otherwise, lighter-ball bowling could be a good alternative to heavy-ball bowling, as lighter-ball throwing has been shown to acutely enhance throwing velocity without harming accuracy in baseball.
10. If bowlers complete the evidence-based training program they should be aware that they will adapt to heavy-ball bowling after eight weeks. Pace bowlers learn to transition from heavy-ball bowling to regular-ball, but become reliant on bowling with the heavy-ball in the warm-up to achieve greater bowling performance. Therefore, coaches should instruct bowlers to warm-up with heavy and regular balls prior to training or a match, but only with eight weeks exposure to the evidence-based training program.

7.3 Recommendations for further research

7.3.1 Study 1

An extension to the test-retest reliability study could be the inclusion of multiple bowling tests spread over time, to determine if bowlers can adapt to the task demands and to also ascertain if the test-retest reliability can improve, especially with bowling accuracy measures. Furthermore, a longer bowling test may enhance the test-retest reliability due to the greater number of deliveries bowled at each target for various delivery effort requirements. The validity of the bowling test should also be examined by comparing bowlers of various performance standards.

7.3.2 Study 2

More biomechanically similar tests such has the horizontal jump, lateral jump, sprint-bound test, medicine ball slam, and medicine ball trunk throw might be more relevant to pace bowling performance, and reveal stronger correlations. In addition, a detailed three-dimensional kinematic analysis could expose more links with bowling performance measures and physical quality tests. A within-bowler approach may reveal specific information on the importance of certain physical qualities for a specific bowling technique. For example, front-on bowlers generally run-up faster than side-on bowlers, and therefore, lower-body strength and power may be more important for this bowling style / technique. A detailed three-dimensional kinematic analysis may have also revealed the precise within-bowler differences in bowling motion for a particular delivery instruction. Further research could compare the kinematics of bowlers who exhibit the speed-accuracy trade-off and those that do not, to ascertain if there are certain technical or timing characteristics noticeable between the groups.

7.3.3 Study 3

The evidence-based training program comprised bowling training (heavy-balls, regular balls), sprint training (weighted-vest, un-resisted), and pull-up training. This program was compared to a “normal” training program, which involved bowling training (regular balls) and sprint training (un-resisted). Given that both training programs included different training modalities, it was difficult to isolate which components contribute to the changes in bowling performance. Further research should conduct training programs that focus on one component (i.e., heavy-ball bowling) to understand its direct effect on bowling performance. One avenue of further investigation should be the long-term effects of lighter-ball bowling on pace bowling performance, as this approach has been successful in enhancing throwing velocity in baseball pitching studies. A training intervention study should investigate the optimal load and volume of heavy- or light-ball bowling on bowling performance, and assess any changes in bowling kinematics following training. This research could compare bowlers of various playing standards and resistance training backgrounds. A thorough three-dimensional kinematic analysis could assist in determining the optimal load of heavy- and light-balls, which would serve to minimise any negative transfer to regular-ball bowling.

7.3.4 Study 4

Potentiation and fatigue were assumed through acute positive or negative changes in bowling performance respectively from each bowling warm-up. Further research should measure motor unit recruitment through electromyography, and changes in muscle architecture by ultrasonography to non-invasively assess potentiation and fatigue. These experimental methods combined with a detailed three-dimensional kinematic analysis may have revealed any mechanisms underpinning the acute changes in bowling performance. Impending research should investigate the effects of various conditioning contraction protocols on bowling performance, approach speed, and other kinematic variables. For example, bowling after performing heavy sled sprints or sprint-bounding in a warm-up may enhance approach speed and possibly bowling speed. The selected protocols should be able to be applied in training and match scenarios, and factor in relative strength, recovery periods, load, and volume, to optimise the potentiation response, without detracting from any elements of bowling performance.

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Appendix A – Statement of Ethics Approval

Principal Researcher:	Warren Young
Other/Student Researcher/s:	Brendan O’Brien Simon Feros
School/Section:	SHS
Project Number:	A12-086
Project Title:	The determinants and development of fast bowling performance in cricket
For the period:	15/6/2012 **to** 1/3/2014

Laura Quinlan

Ethics Officer

15 June 2012

Appendix B – Plain Language Information Statement

SCHOOL OF HEALTH SCIENCES

PROJECT TITLE:	**Determinants and development of fast bowling performance in cricket**
PRINCIPAL RESEARCHER:	**Associate Professor Warren Young**
OTHER/STUDENT RESEARCHERS:	**Dr. Brendan O'Brien, Mr. Simon Feros**

EXPLANATION OF PROJECT

You are invited to participate in research conducted by Simon Feros in exploring the effects of a general and specific strength and conditioning program on fast bowling performance, under the supervision of Associate Professor Warren Young and Dr. Brendan O'Brien.

Who will take part in the research?

Pace bowlers from Ballarat and surrounding areas who are at least 16 years old and don't play a serious winter sport for 2-3 days per week. You have been invited because you meet this criterion. Your contact details will be obtained by your permission via Facebook communication.

What are you asked to do?

Attend the University of Ballarat – Mt. Helen campus Biomechanics Laboratory and UniSports Gym for the following testing and training described below.

Attend basic training for 2 sessions a week for 2 weeks, starting on the first week of May 2013. Each session lasts 60 minutes. Sessions are conducted at a time that suits you during the week day. Each session involves bowling with standard weight (156g) and heavier weight cricket balls (250g), and learning how to perform resistance training exercises with correct technique (e.g., back squat, bench press, pull-up).

After the basic training block is complete, you will then attend an initial testing period for 3 sessions in one week. Refer to the testing component section below.

Then you will be randomly assigned to one of two groups. One group will perform a general strength and conditioning program, and one group will perform a specific strength and conditioning program. The general strength and conditioning program involves bowling with standard weight cricket balls (156g), sprint training, and resistance training in the gym. The specific strength and conditioning program involves bowling with standard weight cricket balls (156g), sprint training, and bowling with heavier weight cricket balls (250g). Both groups are believed to improve fast bowling performance to the same extent, so you are at no disadvantage by being in one group compared to another.

Physical training component:

- Involves two sessions a week for 12 weeks (divided into two 6-week training blocks). Each session will last between 60-90 minutes.
- Bowling and sprint training conducted indoors at the University of Ballarat Biomechanics Laboratory (Mt. Helen campus).
- Resistance training conducted at UniSports Gym, located at the University of Ballarat (Mt. Helen campus).
- You will need to be physically fresh for each session. In other words, you will not be able to perform training 2 days in a row; you will need at least 1-2 days of recovery in-between.
- You need to bring hardwicket cricket shoes to bowl in, a gym towel, and runners / appropriate attire for the gym, and a water bottle. Due to wet weather in Ballarat over the winter, it is advisable you bring a towel with you to keep yourself and your shoes dry when sprinting and bowling.
- You will need to bring your training diary to each session (this will be provided to you when you commence this research).
- If you are in the general strength and conditioning group, you will receive a free gym access at UniSports gymnasium for the period of training.

Testing component

- Involves performing a 6-over bowling test, 4 of these overs bowled with a standard weight cricket ball (156g), and 2 of these overs with a heavier cricket ball (250g). This test approximately takes 60 minutes.
- Two fitness testing sessions are performed (which will take approximately 60 minutes per session).
- A total of 3 weeks of testing will be conducted throughout the study (1 week before training, 1 week after first 6 weeks of training, 1 week after last 6 weeks of training).
- Please wear shorts at testing, no bowling and sprinting allowed in pants.

Other requirements for participation

- To be free of injury throughout each study
- To be physically and mentally fresh before each session
- To not modify your bowling action throughout this period

What are the risks involved?

The risks involved are no greater than those you would expect when training or playing a game of cricket. You will be asked to exercise at high intensities and this may make you feel momentarily uncomfortable and some mild discomfort may be felt during the bowling and fitness testing, as well as the training program. However, any risks of physical injury are low, as you will be adequately warmed prior to exercise, and will be supervised by a person who is accredited in strength and conditioning and first aid. You will undertake a basic block of training to develop the correct technique for exercises to minimise injury risk, and to become familiar with bowling heavier weight cricket balls (250g). You will also have the option of wearing a weight belt during heavy lifting to minimise any chance of lower back injury.

What do you get out of this project?

The greatest benefit you will receive from this project is participation in either strength and conditioning program. These programs should improve your bowling performance for the season ahead, and will enhance your physical training routine in future pre-seasons. You will gain information about your individual strengths and weaknesses regarding your pace bowling performance (speed, accuracy, consistency), lower limb mechanics (front knee angle, run-up speed), and physical fitness (strength, power, power-endurance, flexibility, speed). You will be provided with an individualised report on the aforementioned measurements, as well as an overall summary of the findings of each study within the project in a report format.

What happens to the information gained from this research?

All information that you provide will be treated with the strictest confidence, subject to legal limitations. All data that is collected in hardcopy will be stored in a locked cabinet, and any data that is collected on computer will be password protected. After five years, all data that has been collected in hardcopy and by computer will be shredded and deleted respectively.

What are your rights as a participant?

Your involvement in this study is voluntary and you are free to withdraw your consent to participate at any time, and to withdraw any unprocessed data previously supplied. However, it will not be possible to withdraw your data from this study once it has been completed and published. Withdrawal from the study will in no way adversely affect you.

How are your results going to be distributed?

The results of the study will be submitted in a de-identified state at conference presentations, published journal articles, and PhD thesis.

Thank you

We appreciate your involvement and commitment in this study, and you will be rewarded!

If you have any questions, or you would like further information regarding the project titled *"Determinants and Developments of Fast Bowling Performance in Cricket",* please contact the Principal Researcher, Warren Young, of the School of Health Sciences – Human Movement and Sport Sciences:

PH: (03) 5327 9685
EMAIL: w.young@ballarat.edu.au

Should you (i.e. the participant) have any concerns about the ethical conduct of this research project, please contact the University of Ballarat Ethics Officer, Research Services, University of Ballarat, PO Box 663, Mt Helen VIC 3353. Telephone: (03) 5327 9765, Email: ub.ethics@ballarat.edu.au

CRICOS Provider Number 00103D

2