Power Hitting in Elite Female Cricketers: Developing Applied Methods to Improve Performance

Sean Graham John Hardy

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Statement of Originality

This is to certify that the content of this thesis is my own work. This thesis has not been submitted for any other degree or purpose. I certify that the intellectual content of this thesis is the product of my own work, and that all assistance received in preparing this thesis and all sources have been acknowledged.

Student: Sean Graham John Hardy

Signature: (REMOVED)

Abstract

Within both the global and the Australian sporting landscapes women's cricket is dominated by the short formats. The rapid growth and professionalisation of women's sport has created demand for evidence-informed high-performance programs. Performance analysis of women's short format cricket has shown that batting performance discriminates between winning and losing teams; specifically winning teams score runs at a faster rate, hit more boundaries, and accumulate less runs from singles. A common method used by teams to achieve these key performance indicators is power hitting. Despite the tactical importance of batting performance and power hitting for match success there is very little research to guide practitioners in how to best support this key area of women's cricket.

Therefore, this thesis aimed to validate field-based measures of bat speed and rotational power, explore the associations between physical capacities and bat speed, and investigate the efficacy of two strength and power interventions in improving bat speed. Ultimately, to enhance the standard of strength and conditioning support for professional women's cricket by establishing a set of evidence informed methods to enhance power hitting performance and impact short format match success.

The first study of this thesis validated a baseball bat-mounted sensor for use in cricketers. Device accuracy was determined by Bland-Altman bias and precision and showed that the device was fit for use in the field with an average bias of 2.7%, precision of 5.1%, and good absolute agreement (ICC = 0.86, (0.77-0.92)).

The second study of thesis assessed the validity and reliability of two medicine ball rotational power assessments, the novel push for maximum velocity by radar (MB_{vel}), and the commonly used push for maximum distance by tape measure (MB_{dis}). Results showed that

MB_{vel} is an excellent choice for field-based assessments of rotational power with accuracy (ICC = 0.97 (0.97-0.98)), bias (-0.09%), precision (1.49%), and reliability (ICC = 0.94 (0.82-0.98)). MB_{dis} is not recommended for the assessment of rotational power (ICC = 0.38 (0.28-0.47)), bias (12.43%), precision (4.55%), and reliability (ICC = 0.72 (0.32-0.90)).

Study three explored the association between strength and power capacities and bat speed in female cricketers and found that bat speed was associated with absolute upper body pulling strength ($r = 0.70$, $p < 0.0001$), dominant rotational power ($r = 0.65$, $p < 0.0001$), non-dominant rotational power ($r = 0.60$, $p < 0.0001$), absolute total body isometric strength ($r = 0.47$, $p = 0.01$). Regression modelling explained 52.7% of variance in bat speed overall (Adjusted R-squared = 0.5267, Standard Error of Estimate = 2.40, $p < 0.0001$).

The fourth study of this thesis assessed the effect of two strength and power training interventions, conventional strength and power (CSP) and supramaximal accentuated eccentric loading (SAEL) on improving bat speed in professional female cricketers. Results showed that bat speed significantly improved during both SAEL (7.9%) and CSP (5.5%) ($F(2,18) = 40.12$, $p < 0.0001$) as well as total body isometric strength (9.13%, 7.83%), upper body pulling strength (5.76%, 4.54%), and rotational power (3.65%, 4.82%). No significant difference between interventions was observed (group x time: $F(1,9) = 0.53$, $p = 0.484$).

This thesis has established bat speed as a modifiable capacity underpinned by specific physical qualities and has validated field-based tools that enable the accurate measurement of both bat speed and rotational power. It represents the foundation of bat speed research for professional women's cricket and establishes a new benchmark for the evidence-informed strength and conditioning support for high-performance programs.

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Student: Sean Graham John Hardy

Signature: (REMOVED)

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Lead Supervisor: Associate Professor Kate Edwards

Signature: (REMOVED)

Artificial Intelligence Statement

I, Sean Graham John Hardy, certify that no content produced by generative AI tools has been used in the preparation of this thesis.

Student: Sean Graham John Hardy

Signature: (REMOVED)

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Table of Contents

List of Figures

List of Tables

Chapter One

Introduction and thesis overview

Cricket

The sport of cricket is essentially underpinned by the contest between batters and bowlers. Using a variety of cricket shots and tactics batters aim to score as many runs as possible by striking the ball in the air or along the ground and evading fielders. The bowling team seek to directly counteract this aim with bowlers using a variety of delivery types (balls bowled) and tactics to limit run scoring and remove batters from the game by taking wickets.

In the global sporting landscape cricket holds a significant position as one of the most popular sports in the world. Across the globe, it is estimated that cricket has more than one billion fans and is played by over three hundred million people. 110 different countries are members of the International Cricket Council (ICC) and all participate in international level matches and tournaments. Cricket also holds a commanding commercial position in world sport, with its global popularity underpinning lucrative broadcast deals such as the most recent Indian Premier League (IPL) rights agreement for 2023-2027, valued at 9.4 billion Australian dollars. Further reflecting the global reach of cricket, the sport is set to feature for both men’s and women’s teams at the 2028 Los Angeles Summer Olympic Games.

Professional women’s cricket is played across four different formats, all of which are defined by different match durations and bowling limits. In cricket, bowling limits for all formats are counted in overs which each consist of 6 legal deliveries excluding the hundred format which uses 10 deliveries per over. The longest format played is known as test cricket, which has no limits on the number of overs bowled and is played over four or five days. The short formats are restricted to a single day fixture and are known as one-day (50-over) cricket, Twenty-20 (T20) cricket, and Hundred-ball (HB) cricket, which have bowling limits of 50 (300 deliveries), 20 (120 deliveries), and 10 (100 deliveries) overs respectively.

The Australian Sporting Landscape

Within the Australian sporting landscape women’s cricket is dominated by the 50-over and T20 formats. Professional cricketers have the opportunity to earn contracts in two top level domestic competitions, the Women’s National Cricket League (WNCL) which is contested by state teams using the 50-over format, and the Women’s Big Bash League (WBBL) which is contested by franchise teams using the T20 format. Currently there is no professional domestic long format competition and so for professional domestic cricketers the short formats make up 100% of fixtures and days played. Women also have the opportunity to earn contracts at the national level for the Australian women’s team (AWT) in place of a state team contract. The AWT competes across all three formats, however the distribution of these fixtures follows the same short format trend. In the last nine years the AWT have played 7 test matches, 71 50-over matches, and 95 T20 matches, which equates to short formats accounting for 96% of fixtures and 83% of days played by the AWT since 2017.

The weighting towards the short formats is a product of the rapid growth and development of Australian women’s cricket since the signing of the landmark memorandum of understanding to professionalise the sport in 2017. ("Cricket pay deal huge for women as Australia's female cricketers get massive windfall," 2017; "Jodie Fields hails cricketers' record pay deal as 'huge step' for women's game," 2017) Over the last nine-year period there has been a significant change in the ability of professional female cricketers to earn an income through cricket with the average domestic (WNCL and WBBL combined) and AWT wages increasing from $39,900 and $79,000 in 2017 to $151,000 and $418,000 in 2025 respectively ("Australian women’s cricketers get new pay deal in five-year MOU," 2023; "Women players benefit most in Cricket Australia’s new $634m pay deal," 2023). In this period the WNCL competition has also doubled in length from 6 to 12 regular season matches, and both state and national team contract lists have grown from 14 to 16, and 15 to 18 players respectively. For professional female cricketers in Australia the landscape is clear, the domestic structure is built around two top level short format competitions in the WNCL and WBBL, and these two competitions drive all for domestic players. At the national level, the short formats account for 96% of fixtures played since the sport was professionalised in 2017. In order to capitalise on the professional opportunities available at both a state and national level female cricketers should focus on maximising their short format skillsets.

Global Trends in Women's Cricket

The emergence of short format cricket and the rapid professionalisation of the sport are consistent trends being seen across the world for women's cricket. In parallel with the change in Australia since 2017, the national women's teams for England, India, New Zealand, and South Africa have played an average of 3 tests, 72 50-overs, and 88 T20s which equates to on average short formats accounting for 98% of fixtures and 91% of days played. All four countries have full-time national team contract lists, and in the last five years all four have also established short format professional domestic competitions. Currently no country has a professional long format competition. Similar to cricketers in Australia, the landscape for professional female cricketers around the world is clear. Domestic structures have been built to champion short format competitions and national level fixtures are heavily weighted the same way with 50-over and T20 cricket accounting for 98% of matches played in the last nine-year period. In order for female cricketers to make the most of their professional careers, there should be a strong focus on short format skillsets.

Research in Women's Sport

It is widely accepted that an evidence-informed approach to optimise performance and health outcomes for athletes is the gold standard for elite sport environments (Emmonds et al., 2019; English et al., 2012; Griffin, 2020; Stewart et al., 2024). Academic research plays a critical role in equipping practitioners with evidence of the tactical, technical, physical, and psychological attributes of both the sport and the cohort of athletes competing, as well as identifying effective ways to leverage these to enhance performance and health outcomes. The depth and breadth of these evidence bases is critical to ensure that the findings and their subsequent applications are robust and reliable across all areas for a given sport. However, for professional women's sport environments, and indeed for women's sport and exercise settings more broadly, taking an evidence-informed approach is only sometimes possible due to the underrepresentation of women within sport and exercise science research (Costello et al., 2014; Cowley et al., 2021; Janse de Jonge & Minahan, 2025).

This disparity was first formally recognised in the literature by Costello et al. (2014) in their review of male and female participants in original research articles across three major sport science and sport medicine (SSSM) journals (Medicine and Science in Sports and Exercise, British Journal of Sports Medicine, American Journal of Sports Medicine). Over a three-year period from 2011 to 2013, 1382 publications involving more than 6 million participants were analysed. Women were shown to be significantly underrepresented, accounting for 39% of total participants across all publications and 35-37% of participants in male and female combined studies. For single sex research designs 4-13% of the included publications focused on women. In 2021 the sex data gap was re-investigated by Cowley et al. (2021) in their review of male and female participants in SSSM research across six major journals (The

European Journal of Sports Science, Medicine & Science in Sport & Exercise, The Journal of Sport Science & Medicine, The Journal of Physiology, The American Journal of Sports Medicine, and The British Journal of Sports Medicine) for the period 2014 to 2020. 5261 publications involving more than 12.5 million participants were assessed. The results showed that women remain significantly underrepresented. Women accounted for 34% of the total participants, and single sex studies on women made up just 6% of all included publications. In comparison to the 2011-2013 dataset, there were no significant changes in female participant inclusion or female specific study design in the next seven-year period through to 2020.

The net effect of this consistent underrepresentation is that women's performance environments are precluded from adopting a genuine evidence-informed approach. With just 6% of studies focused specifically on female cohorts, and women making up only 34% of research participants, there is not nearly enough evidence to 1. reliably describe the breadth and depth of different women's sport and exercise settings and 2. deliver enhanced performance and health outcomes for these cohorts through evidence-based programming. Previously, practitioners have sought to bridge this gap by using evidence from either professional male athletes, or recreational female athletes, however neither of these approaches are recommended due to the significant differences both in cohort and performance level (Emmonds et al., 2019).

The differences between male and female cohorts in SSSM research areas are well established (Cowley et al., 2021) and include response to exercise (Ansdell et al., 2020), injury risks (Lin et al., 2018), biomechanics (Carson & Ford, 2011; McErlain-Naylor et al., 2021), exercise capacity (Hunter, 2016; Roberts et al., 2020), temperature regulation (Wickham et al., 2021), energy metabolism (Adriana & Sara Della, 2018), as well as others. A similar pattern is observed for recreational versus elite cohorts of athletes, with differences in response to exercise (Caputo & Denadai, 2004), injury profile (Hägglund et al., 2016), biomechanics (McErlain-Naylor et al., 2021), anthropometry (Gabbett & Georgieff, 2007), and exercise capacity (Sandbakk & Holmberg, 2017). Alongside the research evidence, there are also important differences in performance environment between elite female and both recreational female and male cohorts including resourcing, facilities, access to expert staff, and remuneration (Emmonds et al., 2019). These differences are critical to consider when interpreting and applying research from outside professional women's cohorts, as they are intrinsically linked to the original research outcomes generated, and may lead to sub-optimal results. Concussion in male versus female athletes is an example of this, where research has shown that women have different anatomical, biomechanical, and hormonal risk factors, higher rates of concussion incidence, and different recovery trajectories post head injury compared to men (Caccese et al., 2024; Rizzone & Ackerman, 2021; Valera et al., 2021). Applying male-based concussion evidence to female performance settings could potentially lead to ineffective concussion prevention programming that does not address the relevant anatomical, biomechanical, and hormonal risk factors, as well as non-representative recovery timelines that inhibit optimal return to play progressions. This can also be seen for thermoregulation, where previously women have been shown to produce less total sweat and experience greater increases in body temperature for set work and heat loads (Corbett et al., 2023; Gagnon & Kenny, 2012), and require longer heat acclimation protocols to achieve the physiological adaptations in comparison to men (Mee et al., 2015; Notley et al., 2021). Once again, applying male-based thermoregulation research to female settings is sub-optimal and potentially leads to the over-prescription of fluid recovery based on male sweat loss norms and rates, the underestimation of heat stress and increases in body temperature, and the limited adaptation in heat acclimation protocols. In order to deliver genuine best-practice support for professional women's sport settings the global SSSM research community needs to produce more elite female sport research.

Sport Science and Sport Medicine Research in Professional Women's Cricket

Women's cricket environments have experienced this same paucity of SSSM research. Prior to 2017 the elite female cricket evidence base comprised of just six peer-reviewed publications which focused solely on the injury (Stuelcken, Ferdinands, Ginn, et al., 2010; Stuelcken, Ferdinands, & Sinclair, 2010; Stuelcken et al., 2008a, 2008b; Stuelcken & Sinclair, 2009) and anthropometry (Stuelcken et al., 2007) of female fast bowlers. No research had explored the other three major skill domains of batting, fielding, or spin bowling in any capacity. No publications had analysed the tactical, technical, or physical demands of match play, and outside of the emerging evidence for fast bowling no wide scale injury surveillance studies had been conducted. At this point in time the number of gaps present across the tactical, technical, physical, and psychological performance literature were so vast that an evidence-informed approach to supporting women's cricket environments was not possible. Over the last nine-year period however, there has been significant change in the research landscape as the sport has ridden the wave of professionalisation. The rapid growth in women's cricket has led to demand from professional environments for evidence to better support and maximise both team and individual performance and has subsequently generated momentum to drive academic research.

Since 2017 elite women's cricket SSSM evidence base has grown significantly with 44 additional peer-reviewed publications now included. The literature for professional women's cricket now includes studies investigating a range of areas including bone health (Alway et al., 2023; Beech et al., 2019; Saw et al., 2024; Saw et al., 2022), concussion (Goh et al., 2021; Hill et al., 2019; James et al., 2021; Lallenec et al., 2021; Saw et al., 2020), injury risk factors (Murphy et al., 2020; Stuelcken, Ferdinands, & Sinclair, 2010; Stuelcken et al., 2008a, 2008b), injury surveillance (Brooks et al., 2020; Eunson et al., 2023; Jacobs et al., 2025; Jacobs et al., 2022; Olivier et al., 2023; Orchard et al., 2023; Panagodage Perera et al., 2019; Pritchard et al., 2022; Stuelcken, Ferdinands, Ginn, et al., 2010; Stuelcken, Ferdinands, & Sinclair, 2010; Stuelcken et al., 2008b; Warren et al., 2019; Williams et al., 2024), anthropometry (Stuelcken et al., 2007), batting biomechanics (McErlain-Naylor et al., 2021), fast bowling biomechanics (Felton et al., 2019; Feros et al., 2024; Jacobs et al., 2024; King & Yeadon, 2012), physical demands of match-play (Garcia-Byrne et al., 2020; Nicholls et al., 2023; Pote et al., 2024), physical determinants of fast bowling delivery speed (Bailey et al., 2023; Feros et al., 2024; Letter et al., 2022a), physical characteristics (Brazier et al., 2024; Letter et al., 2022b), sleep recovery (Lalor et al., 2021), throwing load management (Hoyne et al., 2022), visual performance (Barrett et al., 2017), performance analysis of T20 and 50-over matches (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024), performance analysis of match batting performance (Gupta, 2022), skill acquisition (Lascu et al., 2021), mental health (Cross et al., 2024; Ely et al., 2023), mental performance (van Rens et al., 2021), team leadership (Andrews et al., 2022), as well as two reviews of literature (Jacobs et al., 2025; Munro & Christie, 2018). This change in size of evidence base is highly encouraging and represents one of the many positive and significant impacts of professionalising women's cricket. Practically, the change has also meant that two areas within professional women's cricket can now genuinely be supported by an evidence-informed approach. The literature regarding injury is comprehensively described by 25 different publications detailing all aspects across surveillance, occurrence, rehabilitation, management, and risk factors for both training and match environments. Fast bowling is also relatively well explored with 17 studies describing specific injury risk factors, bone health, anthropometry, biomechanics, physical characteristics, determinants of ball speed, and tactical match performance. The breadth and depth of research in these two areas effectively equips practitioners to have both a clear understanding of the injury and fast bowling environments as well as enabling evidence-based programming to optimise health and performance outcomes.

However, beyond these two areas a number of significant gaps within the literature remain and cause great limitation to evidence-based support. Investigations into the demands of match play are limited. Currently two publications describe the tactical and technical demands of T20 match performance (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024), whilst three studies define the physical demands of the T20 (Garcia-Byrne et al., 2020) and Hundred formats (Nicholls et al., 2023; Pote et al., 2024). The major skill domains of batting, spin bowling, and fielding are also not well explored despite all three playing a key role in matches. The performance literature for batting is comprised of five studies across the areas of power hitting biomechanics (McErlain-Naylor et al., 2021), physical match demands (Nicholls et al., 2023; Pote et al., 2024), and tactical match performance (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024). Spin bowling is described by one publication in tactical match performance (Haworth & Mills, 2024), and fielding is described by a single publication exploring throwing loads in training (Murphy et al., 2020). These gaps in particular are important to recognise because they are a required part of the foundation that enables best practice performance support. Practitioners need to have a deep and thorough understanding of both the demands of the sport in competition, and the major skill domains required by athletes to train and compete.

Determinants of Success in Short Format Cricket

Despite the limited size of the current evidence base, the initial research projects investigating the tactical and technical demands of women's cricket have produced important findings regarding the determinants of success for short format cricket. In their analysis of English women's domestic T20 cricket Haworth and Mills (2024) found that the key variables contributing to match success relate to batting performance. By definition winning teams score more runs than losing teams in cricket, and consequently total number of runs was found to have a significant moderate effect on match outcome. In and of itself this finding has limited application, however it is the way that winning teams accumulate their larger total of runs that holds the key performance insights. Winning teams scored their runs with a significantly faster run rate, more boundaries, and with a lower percentage of runs from singles than their losing opposition (Haworth & Mills, 2024). These three factors of batting performance were shown to be the three highest ranked indicators for winning versus losing teams. The analysis also identified that 63.6% of fours and 94.9% of sixes scored for the competition were from shots hitting the ball in front of square (Haworth & Mills, 2024). In front of square can be interpreted simply as anywhere within the 180 degrees range around the boundary in front of the batter. This finding has important implications within the context of power hitting including that (i) in order to strike the ball in front of square batters commonly choose to play cut, drive, pull, or slog shots, (ii) to produce a boundary outcome these shots need to be played powerfully with large shot distance, and (iii) batters are required to generate this power and are not able to rely on incoming delivery speed as the shot is directed in a different direction to which the ball was delivered. Bhardwaj and Dwyer (2022) demonstrated similar findings in their analysis of the Australian WBBL T20 cricket competition. Again, batting performance was shown to be the most important skill domain regarding performance variables in matches that discriminate between winning and losing teams (Bhardwaj & Dwyer, 2022). This finding was shown to be true for both analysis of individual matches and for whole-of-season win-loss ratios. Winning teams were shown to score runs at a faster rate, with a higher frequency (balls per boundary) and total number of boundaries than losing teams (Bhardwaj & Dwyer, 2022). It is interesting to note that despite entirely different environmental and playing conditions between the English and Australian studies including ground size, pitch, boundary dimensions, and weather, the determinants of match success for T20 women's cricket are aligned. Previous research has shown that pitch composition, field quality, and boundary dimensions all influence bowling and batting outcomes in training, and in men's 50-over and test format cricket matches (Crowther et al., 2020; Singh et al., 2023). It is likely that these same environmental constraints have some level of impact on women's T20 cricket, and that additional performance analysis research from environments outside of Australia and England will demonstrate these same effects. Whilst more research still needs to be completed to ensure that this finding is robust across T20 and 50-over formats, and the domestic and international levels, the initial outcomes are compelling. For professional women's cricket environments seeking to maximise individual and team match performance there needs to be a clear focus on the skill domain of batting, and specifically on training and supporting batting methods that produces high run rates and boundaries.

Power Hitting Research in Professional Cricket

A popular method employed by teams to deliver high run rates and boundary scoring when batting is power hitting (Douglas & Tam, 2010; Irvine & Kennedy, 2017; McErlain-Naylor et al., 2021). Power hitting is a batting method where players maximise their scoring rates by hitting the ball powerfully along the ground or through the air to score boundaries (McErlain-Naylor et al., 2021). The method has demonstrated efficacy in delivering high run rates and impacting match success in both men's and women's cricket (Bhardwaj & Dwyer, 2022; Douglas & Tam, 2010; Haworth & Mills, 2024; Irvine & Kennedy, 2017; McErlain-Naylor et al., 2021; Moore et al., 2012; Petersen et al., 2008), however despite its importance and widespread use by teams there is very little research to guide performance support in this area.

Across all professional male and female cricket SSSM literature only four previous studies have investigated power hitting. Peploe, McErlain-Naylor, Harland and King (2018, 2019) adopted a biomechanics approach for their two investigations into hitting for maximal distance in professional male cricketers and produced a number of key findings. First, that the impact location of ball on bat when power hitting plays a significant role in the subsequently generated ball launch speed (Peploe et al., 2018). Central impacts on or near the "sweet spot" region of the bat led to reductions of less than 6% from the optimal value for ball launch speed compared to reductions of more than 30% near the edges of the bat, and therefore batting skill and specifically the ability to generate central impacts when power hitting is critical (Peploe et al., 2018). Second, that bat speed at impact also plays a significant role in ball launch speed (Peploe et al., 2019). For shots with central impact locations 83% of the variance in ball launch speed was explained by bat speed alone, demonstrating the significance of bat speed as a key factor in power hitting performance (Peploe et al., 2019). Third, that ultimately a batter's shot carry distance is underpinned by the combination of ball launch angle and ball launch speed, and that ball launch speed is underpinned by bat speed (Peploe et al., 2018, 2019). McErlain-Naylor et al. (2021) built on this biomechanics foundation in their study comparing power hitting kinematics between skilled male and female batters. The authors found that female batters exhibit a different kinematic profile and movement solution when power hitting compared to male batters (McErlain-Naylor et al., 2021). Specifically, during downswing female batters were shown to flex not extend their lead elbow and produce less pelvis-trunk separation in the transverse plane compared to male batters (McErlain-Naylor et al., 2021). This difference in power hitting technique is important to consider in the context of what physical capacities might underpin this technical skill, and how these capacities might change across male and female batters. The final study contributing to the power hitting literature was conducted by Taliep et al. (2010) who explored the association between upper body strength and maximum hitting distance in male batters. A significant positive correlation was found between hitting distance and 1-repetition-maximum bench press (Taliep et al., 2010), highlighting that upper body strength plays a role in generating bat speed for male batters.

These publications have all made a valuable contribution to the foundation of an evidence base for power hitting in cricket, however, it is clear that more research needs to be done. An evidence-informed approach to supporting power hitting performance in women's cricket to ultimately drive match success requires research in a number of areas. These include a thorough exploration of bat speed as a modifiable capacity, identifying bat speed's underpinning physical determinants, and using these within an intervention framework to establish training methods to enhance bat speed.

Research in Bat, Club, and Racket Sports Outside of Cricket

By comparison, the research in other bat, club, and racket sports is more advanced than cricket. Baseball (Ae et al., 2024; Orishimo et al., 2024; Spaniol et al., 2010; Szymanski et al., 2011; Szymanski et al., 2009; Szymanski et al., 2010; Taniyama et al., 2021), softball (Lowe et al., 2010; Rice & Duoos, 2016; Till et al., 2011), golf (Coughlan et al., 2020; Ehlert, 2021; Hellstrom, 2009; Read et al., 2013; Robinson, Murray, Coughlan, et al., 2024; Robinson, Murray, Ehlert, et al., 2024; Uthoff et al., 2021) and tennis (Hayes et al., 2021; Landlinger et al., 2010; Seeley et al., 2011) have all previously identified bat, clubhead, and racket speed respectively as determinants of sport performance, and all four sports have pursued research to better understand and enhance these qualities. In particular, baseball and golf have conducted thorough explorations of bat and clubhead speed and represent the research benchmark for ball-striking sports in this area.

Baseball and golf both have well-rounded research frameworks for bat and clubhead speed that include links to sport performance, biomechanical analyses of technical skill, associations to physical capacities, and subsequent applied interventions to identify strength and conditioning methods to enhance bat and clubhead speed. Bat and clubhead speed have been shown to be significant factors that impact baseball and golf performance because of their relationship with hitting distance (Ae et al., 2024; Chu et al., 2010; Hume et al., 2005; Orishimo et al., 2024). For both baseball and golf hitting distance is a determinant of game (Sawicki et al., 2003) and round (Hellström et al., 2014) success respectively. Hitting the ball further in baseball raises home-run probability per swing and drives more runs per innings (Sawicki et al., 2003). Driving the ball further off the tee or by long approach in golf reduces strokes gained and improves round scores (Hellström et al., 2014). The biomechanical analyses of hitting in both sports has demonstrated that bat and clubhead speed are determinants of ball launch velocity, and that ball launch velocity in combination with ball launch angle underpin hitting distance (Ae et al., 2024; Chu et al., 2010; Hume et al., 2005; Orishimo et al., 2024; Zheng et al., 2008). Associations between bat and clubhead speed, and physical capacities have been well explored across a number of studies and significant associations have been found for rotational power (Hayes et al., 2021; Read et al., 2013; Szymanski et al., 2009), lower body power (Read et al., 2013; Robinson, Murray, Coughlan, et al., 2024; Szymanski et al., 2009; Szymanski et al., 2010), lower body strength (Szymanski et al., 2010), total body force production (Robinson, Murray, Coughlan, et al., 2024; Robinson, Murray, Ehlert, et al., 2024), and upper body pushing strength (Robinson, Murray, Coughlan, et al., 2024; Szymanski et al., 2009; Szymanski et al., 2010). Finally, intervention-based research projects have explored and established causal relationships between bat and clubhead speed and several physical capacities including rotational power (Choi et al., 2017; Szymanski et al., 2009; Szymanski et al., 2007), lower body power (Oranchuk et al., 2020; Shaw et al., 2022; Spaniol et al., 2010; Uthoff et al., 2021), and lower body strength (Oranchuk et al., 2020; Shaw et al., 2022; Szymanski et al., 2011; Szymanski et al., 2009; Szymanski et al., 2007; Szymanski et al., 2006). These findings have been widely adopted within high-performance environments and have led to the generation of a broad range of strength and conditioning training interventions that have delivered improvements of up to 6.4% and 15.9% in bat and clubhead speed respectively, as well as subsequently impacting baseball and golf performance (Álvarez et al., 2012; Choi et al., 2017; Oranchuk et al., 2020; Spaniol et al., 2010; Szymanski et al., 2007; Uthoff et al., 2021). These research frameworks represent a true gold-standard approach to strength and conditioning support for professional sport that is informed by evidence and designed to impact performance.

Thesis Aims

This research project aims to enhance the standard of strength and conditioning support for professional women's cricket programs by establishing a set of evidence informed methods to enhance power hitting performance and impact short format match success. The research frameworks for bat and clubhead speed in baseball and golf have served as a blueprint for the study structure of this project.

The foundational work of previous studies has established that power hitting is a known batting method that delivers performance indicators that are critical for short format match success (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024), and that bat speed is a determinant of ball launch velocity and subsequently shot carry distance for power hitting (Peploe et al., 2018, 2019). The current project will build on these works by exploring the associations between bat speed and a broad range of physical capacities. An intervention approach will then follow to establish bat speed as a modifiable capacity, assess the causal links between specific physical capacities and bat speed, and establish evidence informed methods.

In order to deliver this association to intervention framework two essential supporting studies are required. Currently there is no validated field-based method to measure bat speed in cricket, with research previously limited to laboratory-based motion capture solutions (McErlain-Naylor et al., 2021; Peploe et al., 2018, 2019). This is a significant limitation for projects within professional settings where laboratory access is not congruent with high-performance program schedules and represents a barrier to participation limiting research sample size. Therefore, the first essential supporting study will seek to assess the accuracy of a previously validated (Lyu & Smith, 2018; Morishita & Jinji, 2022; Stewart et al., 2021) baseball and softball bat-mounted sensor to provide valid field-based measures of bat speed in cricketers. Currently there is also no published rotational power assessment with criterion reference validity and reliability. Rotational power is the only quality among the associations previously identified in both baseball and golf without a robust and reliable testing method. Across the rotational power research there is high variation in the protocols used, none of which are described in detail. Given the clear importance of rotational power within the context of power hitting and women’s cricket, the second essential supporting study will seek to establish a valid and reliable field-based assessment of rotational power. With these two supporting works complete the research project will then move to the association to intervention framework investigation.

Study 1: Accuracy of a bat-mounted sensor for the measurement of bat speed among elite female cricket players

Study 2: Criterion validity and reliability of a new medicine ball rotational power test

Study 3: The physical determinants of bat speed in elite female cricketers

Study 4: Strength and conditioning methods to enhance power hitting performance

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Chapter Two

Accuracy of a bat-mounted sensor for the measurement of bat speed among elite female cricket players

Author Note

This thesis chapter has been amended after examination and contains minor differences to the published version of this work.

Abstract

Currently there are no validated field-based measures of bat speed in cricket. This study sought to validate a baseball bat-mounted sensor for use in cricketers. Nine professional female cricketers (19.9±2.8 years, 166.6±4.8cm, 68.7±8.6kg) performed forty swings across four shot types (Cut, Drive, Pull, Slog-Sweep). Bat speed from a bat-mounted sensor was compared to optical motion capture (MoCap). Bat speed differed between shot types and ranged from 52.8 - 87.9 km/h. Device accuracy was determined by Bland-Altman bias and precision. The Drive shot had the smallest bias (-1.0 km/h; 1.4%), followed by the Slog-Sweep (2.0 km/h; 2.7%), Pull (2.0 km/h; 2.8%) then Cut shot, (2.5 km/h; 3.9%). The Cut shot had the greatest precision (2.7 km/h; 4.1%), followed by Pull (3.4 km/h; 4.7%), Slog-Sweep (4.0 km/h; 5.3%) and Drive (4.4 km/h; 6.3%). Kendall's tau analysis showed that proportional errors increased with higher bat speeds for all shots except Pull, ($p < 0.05$). The evidence supports use of the sensor for bat speed among female cricket players for all shots between speeds of 52.8 - 87.9 km/h. Caution is warranted for additional shot types, and speeds outside the explored range.

Introduction

In cricket, batters score runs by using a number of different strategies to play shots and hit the ball to various areas of the field. Shot distance is an important outcome for run scoring, with both of the two highest scores available from a single shot requiring the ball to be propelled the maximum distance over the field boundary either along the ground for 4 runs or in air for 6 runs (either score known as 'boundaries'). Although many different shots are possible, four commonly played when aiming to hit boundaries are known as the Cut, Drive, Pull, and Slog-Sweep (see supplementary online content) (Foysal et al., 2019; Jamil et al., 2022; Stuelcken et al., 2005). The approach to maximise scoring boundaries is known within cricket as power hitting (Jamil et al., 2022), a strategy often employed in the shortest format of the sport T20 cricket where previous performance analysis has shown that winning teams score runs at a higher rate and accumulate more boundaries whilst batting (Douglas & Tam, 2010; Moore et al., 2012; Petersen et al., 2008).

While our understanding of determinants of power hitting is still emerging, two foundational tenets have been established in the cricket literature: (i) ball exit velocity is critical for shot distance, and (ii) ball exit velocity is primarily underpinned by bat swing speed (C. Peploe et al., 2018, 2019). This same principle has previously been established in baseball (Nathan, 2003) where bat swing speed has been shown to be a critical factor in determining the velocity of the struck baseball. The enhancement of bat swing speed in particular is identified as a critical area of training focus for players and coaches in maximising shot distances in cricket (McErlain-Naylor et al., 2021; Chris Peploe et al., 2018; C. Peploe et al., 2019).

Research into validated methods for measuring bat swing speed in cricket has been limited to lab-based motion capture solutions with no validated on-field measure currently available.

This has contributed to a slower rate of progress in terms of clinical practice and research relating to bat swing speed in cricket compared with its baseball and softball counterparts. Research investigating commercially available bat swing sensors such as the work in baseball by Morishita and Jinji (2022) and Lyu and Smith (2018), and in softball by Stewart et al. (2021) provide a foundation to aid the creation of new and enhanced training practices, as well as guide practitioners on the current limitations of the available technologies. Validated, field-based measures of bat speed in baseball and softball have led to the development of multiple research areas including specific bat swing speed match warm-ups (De Renne et al., 1992; Montoya et al., 2009; Southard & Groomer, 2003; Szymanski et al., 2011), strength and conditioning programs designed to enhance bat swing speed (Ab Razak et al., 2022; Kobak et al., 2018; Mace & Allen, 2020; Miyaguchi & Demura, 2012; Szymanski et al., 2009; Szymanski et al., 2010), a comprehensive understanding of the relationship between anthropometric measurements and bat swing speed (Lowe et al., 2010; Till et al., 2011), as well as performance benchmarking of bat swing speeds (Spaniol, 2009). The validation of a device capable of measuring bat swing speed in cricket presents an opportunity to evolve the clinical practice and research of the sport in several areas, similar to those observed in baseball and softball.

The aim of this study therefore, was to determine the accuracy of a bat-mounted sensor originally designed for baseball to measure bat swing speed during four different cricket shots (drive, cut, pull, slog-sweep) over a range of swing intensities. The sensor is yet to be validated in cricket but has demonstrated efficacy in baseball where powerful ball striking is equally important to score home runs. We acknowledge that the drive, cut, pull, and slog-sweep shots are to varying degrees different to a baseball swing, however there are also clear similarities in swing paths, batter stances, and overall batting technique that warrant the exploration of the sensor in cricket. We hypothesised that shot types with similar bat swing paths to a baseball swing – specifically, the Cut and the Pull – would produce more accurate bat speed results than shot types with dissimilar bat angles to a baseball swing – that is, the Drive and the Slog-Sweep.

Methods

Participants

This study utilized a convenience sample of professional female cricketers due to their availability as part of the Cricket NSW senior women's program. Nine professional state and national level female cricketers (age: 19.9 ± 2.8 years; height: 166.6 ± 4.8 cm; mass: 68.7 ± 8.6 kg) from Cricket NSW volunteered for the study. Based on the available sample size, it was determined that we could detect r^2 values of ≥0.63 with 80% power and a 0.05 alpha level for associations between the bat-mounted sensor and optical motion capture (GPower 3.1.9.7). Participants were free from injury or musculoskeletal complaints at the time of the study. Prior to taking part, participants were made aware of the experimental procedures (including the benefits and risks of the investigation) and written consent was obtained. This study complied with the ethical guidelines for human research by the Australian National Health and Medical Research Council and was approved by the University Human Research Ethics Committee (Project Number 2019/712).

Procedures

Participants attended a single testing session at an indoor biomechanics laboratory. They were assessed for their height (Seca 222 stadiometer, Seca, Hamburg, Germany) and mass

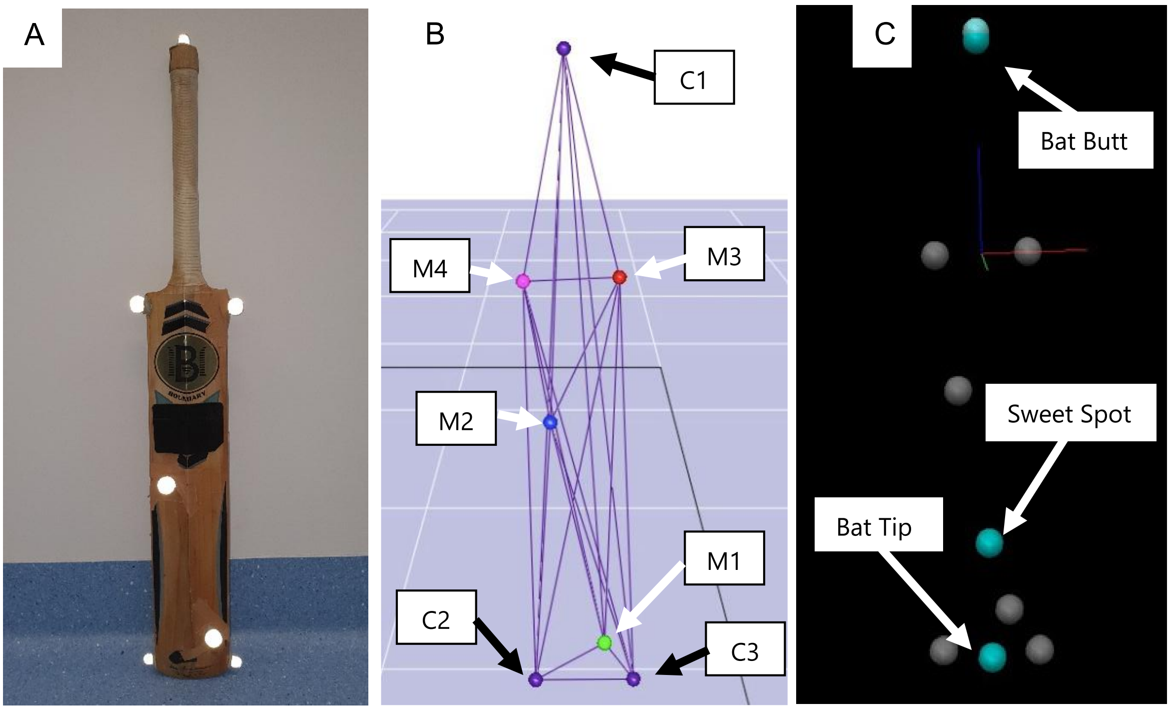
(WS150R, Wildcat, Mettler Toledo, Greifensee, Switzerland) before completing a specific warm-up comprising 10 minutes of batting skills.

Participants each performed a total of forty bat swings against a cricket ball placed on a stationary tee with a modifiable height. Ten shots were executed for each of the following batting shot types: Cut, Drive, Pull, and Slog-Sweep. For the Cut shot, a batting tee was placed at approximately hip-height at a self-selected distance on the off-side of the body (i.e., the right-hand-side for right-handed batters; left-hand-side for left-handed batters). For the Drive shot (characterised by a vertical bat swing), the ball was placed on a small tee located approximately 10 cm off the ground directly in front of the batter. For the Pull shot, the ball was placed at approximately shoulder-height at a self-selected distance away on the on-side of the body (i.e., the left-hand-side for right-handed batters; the right-hand-side for left-handed batters). Finally, for the Slog-Sweep, the ball was placed at a height approximately corresponding to the mid-point between the knee and hip on the on-side of the body. For each shot type, batters were instructed to swing "as hard as possible" at maximal intensity for five shots and an additional five shots were played at a self-selected intensity equivalent to approximately 80% of maximal perceived exertion. The order of shots was randomised in blocks of five, with each shot separated by approximately 10 seconds to minimise the fatigue effect and to mimic training and game scenarios.

The bat-mounted sensor (Blast Baseball, Blast Motion Inc., San Marcos, CA, USA) is a wireless, portable baseball bat swing analyser comprising a bat-mounted dual 3 axis accelerometer, gyroscope, and magnetometer device with a sampling rate of 500Hz and smartphone app 'Blast Baseball' developed by the manufacturer. The sensor is also equipped with a proprietary dynamic calibration algorithm that runs continuously whilst in use to filter measurements and adjust for sensor drift. The sensor was mounted onto the participant's preferred bat at the butt-end of the handle using a rubberised sensor casing designed by the manufacturer. At ball contact, the sensor records gyroscope, accelerometer, and magnetometer data that are immediately transferred to the phone application via Bluetooth. Maximal linear speed at the 'sweet spot' of the bat, which the manufacturer defines as 15 cm (6 inches) from the tip of the bat along the centre of the bat's long axis, is then calculated. Bat length, measured from the butt-end of the handle to the tip of the bat using a standard tape measure, and bat mass using a scale (WS30R, Wildcat, Mettler Toledo, Greifensee, Switzerland) with maximum capacity 30kg and readability 0.005kg were input to the app to enable the calculation.

Bat speed at this same estimated sweet spot was also determined via three-dimensional optical motion capture (MoCap) (Cortex 3.3, Motion Analysis Corporation, USA) using a 14-camera system collecting at 240 Hz. Bat marker data was unfiltered to avoid unwanted changes to bat speed data (Orishimo et al., 2024; Tabuchi et al., 2007). The bat was modelled in Visual 3D (v.6.0, C-Motion, Germantown, MD, USA) using 7 markers, which were placed at the locations outlined in Figure 1A. M1-M4 were used to track the bat for each shot, whilst C1-C3 were for calibration purposes and removed before beginning the swing trials. C1 was placed on top of the bat-mounted sensor and a corrected bat butt location was calculated as a virtual marker offset from C1 to account for the thickness of the sensor and its casing (Figure 1C). The bat tip was modelled as the point along the bat's long axis at the bat length distance away from the bat butt. The bat's sweet spot was located using the definition from the manufacturer.: 15 cm from the tip of the bat along the bat's long axis in the centre of the bat (Figure 1C). Bat speed was calculated using the sweet-spot positional data averaged across the first five frames after bat-ball contact. A cricket ball was wrapped in retroreflective tape and tracked using MoCap. The time of bat-ball contact was defined by the last frame before the ball's displacement changed from its initial resting position on a stationary tee.

Figure 1. Optical motion capture markers (A), 3D marker reconstruction (B) and virtual markers (C) used to calculate bat speed. Marker locations are described in the table.



Marker	Location
M1	Back of bat, on the right side of the spine, approximately 0.15m from bat tip
M2	Back of bat, on the left side of the spine, approximately 0.30m from the base of handle
M3	On the edge of the right side of bat, at the end closest to base of handle
M4	On the edge of the left side of the bat at the end closest to the base of handle
C1	Calibration marker (removed during swing trials) on the butt of the bat
C2	Calibration marker (removed during swing trials) on the edge of left side of bat tip
C3	Calibration marker (removed during swing trials) on the edge of the right side of bat tip

Statistical Analysis

Statistical analysis was conducted using R (RCoreTeam, 2023) Each shot was treated as an individual observation since the aim of this study was to evaluate the validity of the sensor outputs. 17 (4.7%) trials were missed by MoCap (e.g., marker occlusion), of which, 9 (2.5%) were also missed by the sensor (e.g., error given by the smart phone app).

Differences in mean bat speed between the different shot types Drive, Cut, Pull, and Slog-Sweep were assessed using a one way repeated-measures ANOVA using participant-level data. Mean, standard deviation, coefficient of variation (CV) and standard error of mean (SEM) were calculated for all sensor and MoCap bat speeds. Device accuracy was determined via Bland-Altman analysis of bias and precision (Bland & Altman, 1999; Giavarina, 2015) in line with previous sports research assessing accuracy (MacDougall et al., 2024; Santos et al., 2024; Zacca et al., 2023). MoCap was used as the gold-standard criterion reference "true" measurement. Bias was calculated by assessing the mean difference between the two methods, and precision by calculating the standard deviation of the difference between methods, upper and lower limit of agreement (LoA) were calculated for both. Kendall's tau (Goedhart & Rishniw, 2021) was used to assess the variation of sensor measurement error with bat speed magnitude. Intraclass correlation (2, 1) was used to assess the absolute agreement between sensor and MoCap measurement systems, and was interpreted as excellent > 0.9, good 0.75 - 0.9, moderate 0.5 - 0.75 and poor < 0.5, (Koo & Li, 2016). Linear regression using R squared and Pearson's correlation (*r*) was used, and Pearson's r was interpreted as large 0.50 to 0.70, very large 0.70 to 0.90, and nearly perfect > 0.90 (Hopkins, 2000). Significance was set a priori at $\alpha = 0.05$.

Results

Maximum bat speed as measured by the MoCap system was highest for the Pull shot (Max 87.9 km/h; Min 59.6 km/h; Range 28.4 km/h), followed by Drive (Max 86.5 km/h; Min 55.1 km/h; Range 31.4 km/h), Slog (Max 84.9 km/h; Min 63.9 km/h; Range 21.0 km/h) and Cut (Max 74.6 km/h; Min 52.8 km/h; Range 21.8 km/h), (Table 1). These differences were statistically significant, ($F(3, 682) = 80.0$, $p = 0.00$), consequently, bias and precision results are presented in absolute terms and as percentage errors.

Bland-Altman analysis of sensor accuracy revealed that the Drive shot had the smallest bias (-1.0 km/h; 1.4%) and was the only shot type to be underestimated by the sensor. All other shot types were overestimated by the sensor, with the Cut shot having the largest bias (2.5 km/h; 3.9%), followed by Pull (2.0 km/h; 2.8%) and then Slog-Sweep (2.0 km/h; 2.7%). The Cut shot had the greatest precision (2.7 km/h; 4.1%), followed by Pull (3.4 km/h; 4.7%), Slog-Sweep (4.0 km/h; 5.3%) and Drive (4.4 km/h; 6.3%). Assessment of Kendall's tau correlation coefficient showed that sensor measurement error increased with increasing bat speed for Cut (0.22, $p< 0.001$), Drive (0.23, $p< 0.001$), and Slog-Sweep (0.21, $p=0.01$), but not for Pull (Table 1). Intraclass correlation showed the Pull shot to have the highest level of absolute agreement (0.89) followed by the Cut (0.87), Drive (0.84) then Slog-Sweep (0.82) (Table 1). Correlations were significant for all shot types but were stronger for Pull and Cut ($R^2 = 0.80$ and 0.79 respectively) than for Slog-Sweep and Drive ($R^2 = 0.72$ and 0.71 respectively). ($p < 0.001$) (Table 1).

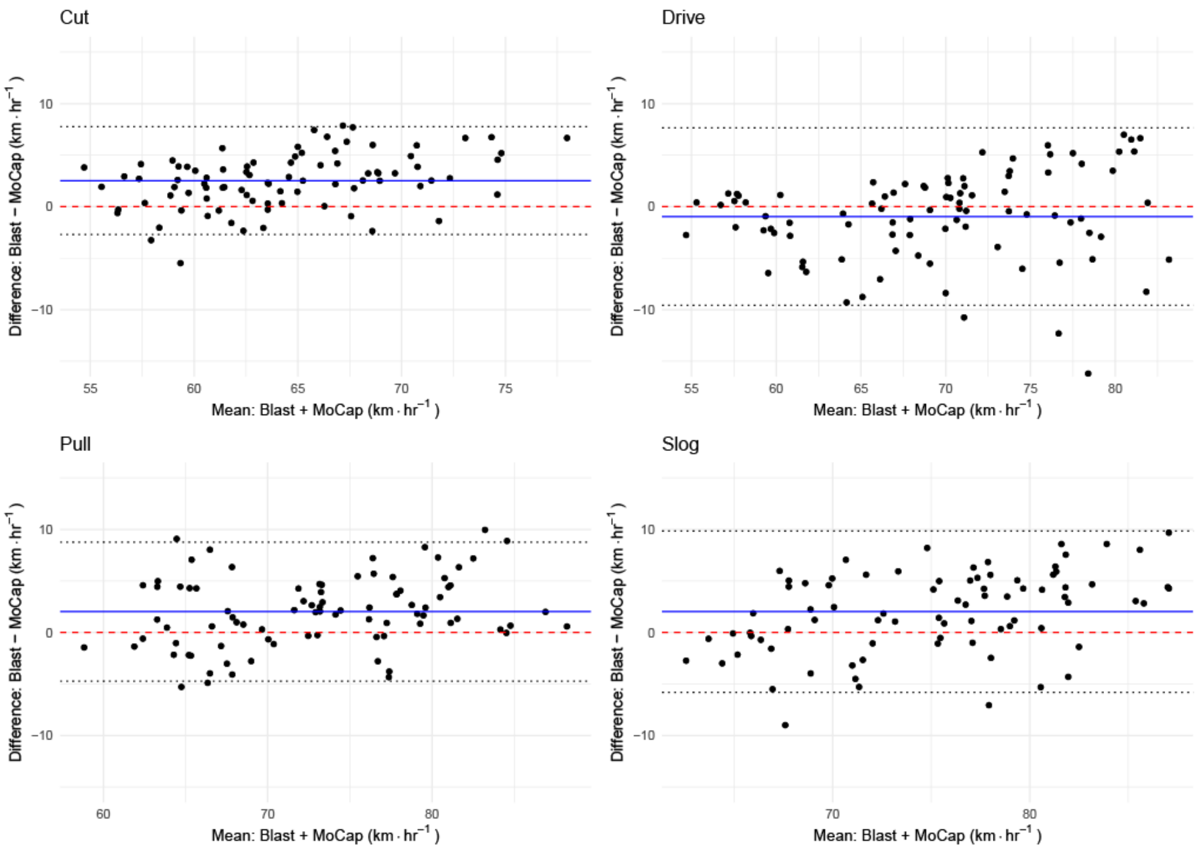
Table 1. Mean (SD) bat speed from the MIMU sensor and optical motion capture. Sensor Accuracy represented by Bland-Altman bias as mean difference and precision as standard deviation of difference between measures respectively. Assessment of heteroscedasticity represented by Kendall's tau correlation coefficient (τ). Absolute agreement of measurements represented by intraclass correlation coefficient (ICC). Linear regression (R^2 and Pearson's r) show the strength of the relationship between measures for each shot type. Number of shots included in each analysis (n) is also listed.

Shot Type	**Bat Speed**		**Bland-Altman**		**Kendall's Tau**	**ICC (2, 1) Absolute Agreement**		**Linear Regression**
	Sensor	**MoCap**	**Bias**	**Precision**				
	Mean (SD) (km/h)	*Mean (SD) (km/h)*	*Mean Diff km/h (%)*	*SD of Diff km/h (%)*	τ	*Mean (CI)*	*Classification*	R^2 *(r)*
Cut	65.6 (5.8)	63.1 (4.8)	2.5 (3.9%)	2.7 (4.1%)	0.22**	0.87	Good-Excellent	0.79 (0.89) **
n = 86	CV = 0.6, SEM = 1.9	CV = 0.5, SEM = 1.6	LoA: -2.7 to 7.8		p < 0.001	(0.81 to 0.92)		p < 0.001
Drive	69.0 (8.2)	69.6 (7.1)	-1.0 (1.4%)	4.4 (6.3%)	0.23**	0.84	Good	0.71 (0.84) **
n = 90	CV = 0.9, SEM = 2.7	CV = 0.8, SEM = 2.4	LoA: -9.6 to 7.6		p < 0.001	(0.77 to 0.89)		p < 0.001

Pull	74.0 (7.8)	72.1 (7.0)	2.0 (2.8%)	3.4 (4.7%)	0.02	0.89	Good-Excellent	0.80 (0.89) **
n = 86	CV = 0.9, SEM = 2.6	CV = 0.8, SEM = 2.3	LoA: -4.7 to 8.8		p = 0.81	(0.83 to 0.92)		p < 0.001
Slog-Sweep	76.0 (7.6)	74.0 (6.0)	2.0 (2.7%)	4.0 (5.3%)	0.21*	0.82	Moderate-Good	0.72 (0.85) **
n = 81	CV = 0.8, SEM = 2.5	CV = 0.7, SEM = 2.0	LoA: -5.8 to 9.9		p = 0.01	(0.74 to 0.88)		p < 0.001

*p < 0.05, **p < 0.01

Figure 2. Bland-Altman plots of bat speed estimates between the sensor and optical motion capture for the Cut, Drive, Pull, and Slog-Sweep. The blue line indicates the bias while the dashed line represents the upper and lower limits of agreement (LoA). Precision was calculated as the standard deviation of the difference between methods.



Discussion and Implications

This is the first study to describe the accuracy of a bat-mounted sensor originally designed for baseball for the measurement of bat speed across four different shot types in cricket. Differences in overall accuracy resulted from different degrees of bias (1.4 – 3.9%) and precision (4.1 – 6.3%) for each shot type. While no previous study has explored the use of a bat-mounted sensor to measure bat speed in cricket, the results of the current study are partially comparable to publications in baseball. Morishita and Jinji (2022) described the accuracy of four commercially available sensors relative to motion capture during a baseball batting task as having precision levels of 8-10%. This previous study's methodology did not allow for between study comparisons of bias as this was reported as a ratio scale after antilog. The sensor precision determined in the current study strongly outperforms the level found by Morishita and Jinji (2022), and may be explained by methodological differences in the baseball study including a smaller number of participants, (n = 7), fewer swings taken with the sensor (5-10 swings per participant per sensor; n = 35 – 70 swings total), significantly higher bat speeds, (average = 108.3 km/h) as well as the bat type (baseball bat) and bat swing path. Lyu and Smith (2018) produced similar findings in their comparison of three commercially available sensors to high-speed video capture during a baseball hitting task finding an average sensor bias of 8%. Due to the statistical analysis choice to use the concordance correlation coefficient by the authors we were not able to directly compare precision. Again, the level of bias (2.7% average) found in the current study significantly outperforms the 8% average determined by Lyu and Smith (2018) and may result from similar methodological differences to those identified for Morishita and Jinji (2022) above including a smaller number of participants, (n = 8), significantly higher bat speeds, (average = 102.6 km/h), bat type (baseball bat), and bat swing path. Although the evidence base for bat swing sensor accuracy in cricket is still emerging, the bias and precision results found in this study suggest that sensor application to assess bat speed in cricket settings is viable.

According to the Intraclass Correlation, the sensor showed "Good to Excellent" absolute agreement for the Pull and Cut, "Good" absolute agreement for the drive, and "Moderate to Good" absolute agreement for the Slog-Sweep (Koo & Li, 2016) compared with the Gold-Standard criterion reference of Motion Capture. These findings support our hypothesis that the sensor is most valid for cricket shot types that more closely resemble that of baseball batting, i.e. the pull and cut shots which have a predominantly horizontal bat swing plane (Sawicki et al., 2003; Williams et al., 2019). Interestingly, sensor absolute agreement was greater for the drive shot compared with the slog-sweep, despite the drive shot having a predominantly vertical bat path, while the mixed horizontal and vertical bat path of the slog-sweep was associated with poorer sensor absolute agreement. Further research is required to better understand the role of bat swing plane on sensor-derived measurements of bat speed in cricket.

Previous research on baseball bat swing sensors has reported that accuracy decreases at higher swing speeds due, amongst other reasons, to saturation of the accelerometer sensors used in that study (Lyu & Smith, 2018; Morishita & Jinji, 2022). This is reflected in the results for Kendall's Tau shown in Table 1 where Cut, Drive, and Slog-Sweep measurement error increased with increasing bat speed. This effect was not present for Pull. This lack of consistent pattern of accuracy varying with velocity for all shot types is most likely because the swinging a heavy cricket bat by female players produced substantially slower swing speeds than for baseball. Rather than velocity, the plane of motion appeared to have more effect, with precision being higher for the cut and pull shots which followed a horizontal plane more similar to that of a baseball swing.

The IMUs within bat swing sensors integrate data from accelerometers (linear acceleration), gyroscopes (angular velocity) and magnetometers (angular displacement) using a data fusion algorithm to account for inaccuracies within each individual sensor (Caruso et al., 2021). These fusion algorithms require specific tuning for different activities to best account for the different contributions of angular velocity and linear acceleration to the overall movement (Nazarahari & Rouhani, 2021). The sensor used in this study was optimised for the kinematics of hitting in baseball. It is therefore possible that the more vertical swing patterns of the drive and slog-sweep shots had quite a different interaction between gravity and the linear acceleration of the bat, resulting in a sensor tune that was less suitable for a device designed primarily for baseball. Similarly, movement of the instantaneous centre of rotation during a swing may change the relative contribution between linear motion of the hand and angular motion of the bat, altering the relative magnitudes of each sensor and thus potentially changing the ideal tuning parameters for a sensor fusion algorithm.

Given the lack of field-based methods currently available to measure bat speed in cricket, we suggest that the evidence presented here is sufficient to recommend use of the sensor to quantify bat speed among elite female cricket players, particularly for the Cut, Drive and Pull shots. While caution is advised for the use of the sensor to quantify bat speed for the slog-sweep shot given its lower overall absolute agreement. In considering the practical interpretation of the results from table 1, the sensor has a maximum CV of 0.9% across shots, and therefore a meaningful change threshold of ±1.8% for detecting bat speed change. For bat speeds within the study range of 52.8km/h to 87.9km/h this means that changes larger than 0.95km/h to 1.58km/h would be considered meaningful. It is important to note that the results of this study show that the intra-comparison of sensor versus sensor bat speeds is highly reliable with 0.9% CV, however comparing bat speeds from sensor to motion capture has lower capability across shots with limits of agreement ranging from -9.6 to 9.9km/h.

Previous research describing the maximal bat speeds of elite female cricket players when performing the Drive shot against a bowling machine were also within the bat speed ranges achieved here, supporting the wider application of the sensor within this player group, (81.4 km/h; McErlain-Naylor et al. (2021) Notably however, while previous research has shown that sub-maximal bat speeds for elite male cricket players fall within this range, (76.3 km/h; Stuelcken et al. (2005) maximal bat speeds for elite male players are significantly higher than those explored here, (97.2 km/h; Chris Peploe et al. (2018, 2019) 102.2 km/h; McErlain-Naylor et al. (2021) Given that the measurement error increased with increasing bat speed for Cut, Drive, and Slog-Sweep, it is unclear what accuracy the device has beyond the speeds explored in the current study. Additional research is therefore needed to determine the accuracy of the sensor for use in other amateur and professional settings outside of elite female cricket, where population speed ranges differ to those explored in this study.The current study had several limitations. Firstly, the findings of this study are limited to a laboratory setting when hitting a stationary ball off a tee; therefore, the ability of the sensor to detect bat speed in practice and game settings should be explored. Secondly, the study was limited to cricket players achieving bat speeds between 52.8 - 87.9 km/h. Given that measurement error increased with increasing bat speed, the performance of the sensor above and below this range is unclear. Thirdly, the sweet spot of the bat was estimated at 15 cm from the bat tip in accordance with the manufacturer definition. However, the sweet spot of a cricket bat varies slightly between implements and are usually slightly further from the tip than this, about 17.5 cm (Chris Peploe et al., 2018, 2019), which means that bat speed values presented here may have been slightly overestimated. This consistent estimate was necessary however, to ensure that the comparisons between measurements were not affected by different definitions for calculating bat speed. Finally, in deciding to maximise data accuracy by using a five-frame average of the MoCap data post contact to calculate bat swing speed there may be some small reduction in maximal speed recorded for the study. This could explain some of the difference in swing speed seen between the sensor and MoCap.

A number of future directions for research remain. Firstly, continued improvements to the bat-mounted sensor, specifically through the development of a cricket-specific algorithm or calibration are required. This is particularly important to improve the sensor accuracy for the slog-sweep shot, as well as reduce the increase in measurement error with increasing bat speed. This would increase the utility of the device to players capable of achiever higher bat speeds beyond those explored here. Secondly, future research should explore bat speed across each of the major shot types among a larger group of players to establish normative reference data. The current study showed significant differences in bat speed between shots however, describing normative ranges was beyond the scope of the study and should be explored with a larger, more representative sample. This information would be helpful for practitioners to describe individual player capabilities against normative standards, as well as help with shot selection in situations where optimizing bat speed is critical.

Conclusions

This is the first study to describe the accuracy of a bat-mounted sensor for the measurement of bat speed in cricket. The sensor demonstrated across shot averages of 2.7% for bias (Cut

3.9%, Drive 1.4%, Pull 2.8%, Slog-Sweep 2.7%) and 5.1% for precision (Cut 4.1%, Drive 6.3%, Pull 4.7%, Slog-Sweep 5.3%). Absolute agreement between MoCap and the sensor was shown to be "Good to Excellent" for Pull and Cut, "Good" for Drive, and "Moderate to Good" for Slog-Sweep. The evidence supports the use of the sensor to measure bat speed among elite female cricket players for these shots between speeds of 52.8 - 87.9 km/h, but caution is warranted for its application for the slog-sweep shot and for speeds outside of the explored range.

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Chapter Three

Criterion validity and reliability of a new medicine ball rotational power test

Author Note

This thesis chapter has been amended after examination and contains minor differences to the published version of this work.

Abstract

This study assessed the validity and reliability of two medicine ball rotational power assessments, the novel push for maximum velocity by radar (MB_{vel}), and the commonly used push for maximum distance by tape measure (MB_{dis}), against the criterion reference three-dimensional motion capture (MoCap) to identify the best-practice field-based assessment. Fifteen professional female cricketers volunteered for two testing sessions each comprising of a specific warm-up and 24 (12 MB_{vel},12 MB_{dis}) maximal throws of a 2-kilogram medicine ball. Radar velocity and tape measure distance were compared to MoCap velocity and projectile motion calculated distance overall, and by dominant and non-dominant sides. Statistical analysis included Intraclass correlations (ICC) for accuracy (1, 1) and reliability (3,1), Bland-Altman plots for bias precision and limits of agreement, Linear regression (R-squared) for variance, and Pearson's (*r*) for correlation. Significance was set $\alpha = 0.05$. MB_{vel} demonstrated excellent accuracy (ICC = 0.97 (0.97-0.98)), and nearly perfect agreement for bias (-0.09%) and precision (1.49%). Side-to-side analysis showed the same profile for MB_{vel} dominant (ICC = 0.96 (0.95-0.97), bias -0.15%, precision = 1.55%) and non-dominant sides (ICC = 0.97 (0.96-0.98), bias -0.05%, precision = 1.53%). MB_{vel} demonstrated excellent reliability overall (ICC = 0.94 (0.82-0.98)), for dominant (ICC = 0.88 (0.69-0.97)), and non-dominant sides (ICC = 0.93 (0.80-0.98). MB_{dis} showed poor accuracy (ICC = 0.38 (0.28-0.47)), large bias (12.43%), lower precision (4.55%) and moderate reliability (ICC = 0.72 (0.32-0.90)). The MB_{vel} assessment validly and reliably measures rotational power performance, enabling practitioners to profile, benchmark, and assess the quality in the field.

Introduction

Rotational power is associated with performance in a number of sports including baseball, cricket, European handball, golf, tennis, and water-polo (Freeston et al., 2016; Ikeda et al., 2009; Taniyama et al., 2021; Zois et al., 2016). The physical quality plays an important role in underpinning multiple athletic tasks across sports including throwing (Freeston et al., 2016; Ikeda et al., 2009), and performing bat, club, or racket shots (Roetert et al., 2009; Szymanski et al., 2007; Taniyama et al., 2021; Zois et al., 2016). Strength and conditioning programs within these sports commonly utilise various methods to develop and enhance rotational power to drive athletic performance (Dahl & van den Tillaar, 2021; Earp & Kraemer, 2010; Oranchuk et al., 2020; Raeder et al., 2015; Read et al., 2013; Szymanski et al., 2007) including heavy lower and upper body strength training, plyometric exercises, and medicine balls throws (Finlay et al., 2022; Seitz & Haff, 2016; Szymanski et al., 2007).

Medicine ball throws are the most widely studied method of developing rotational power in athletes across a variety of age-groups and performance settings (Andre et al., 2012; Dahl & van den Tillaar, 2021; Earp & Kraemer, 2010; Szymanski et al., 2007). There is strong evidence for both the efficacy of medicine ball throws for power training (Andre et al., 2012; Dahl & van den Tillaar, 2021; Earp & Kraemer, 2010; Szymanski et al., 2007), and the ecological validity of completing high velocity multi-planar movements that are reflective of actions performed in a sport setting (Earp & Kraemer, 2010). For example, the medicine ball rotational throw exercise allows a cricket athlete to take a side-on athletic stance akin to their batting stance in match, hold a 1- or 2-kilogram medicine ball similar to their individual bat mass, complete a reactive counter-rotation and explosively throw the ball using a comparable movement pattern with similar timing to the on-field execution of powerfully hitting a ball. Such is the versatility of medicine ball throws that strength and conditioning coaches across various sports utilise some version of a rotational medicine ball throw to target a variety of sporting actions including batting and overhead throwing in baseball (Szymanski et al., 2007; Taniyama et al., 2021), pace bowling in cricket (Taliep & Maker, 2021), and ground stroke play in tennis (Roetert et al., 2009). Given the popularity, efficacy, and effectiveness of medicine ball training for sport specific movements the ability to accurately assess medicine ball training would be highly advantageous for practitioners across environments.

The valid and reliable assessment of rotational power is critical to strength and conditioning practice among rotational athletes. Periodic assessment of this physical capacity allows practitioners to describe and benchmark individual and team performance, as well as evaluate the effectiveness of rotational power training programs. For practitioners seeking to use field-based assessments, the proxy measures of medicine ball throws for maximum distance by visual inspection (Ikeda et al., 2009; McMillian et al., 2006; Read et al., 2013; Salonia et al., 2004; Stockbrugger & Haennel, 2001a; Till et al., 2011) and throws for maximum velocity by radar device (Freeston et al., 2016; Szymanski et al., 2007; Taniyama et al., 2021) are the dominant choices, followed by cable pulley rotations for power by linear position transducer (Zois et al., 2016) and external dynamometer (Andre et al., 2012). While Laboratory based testing has the ability to quantify rotational power, research to date has centred on the motion capture and subsequent kinematic outcomes of athletes completing sporting movements rather than specifically designed rotational power assessments (McErlain-Naylor et al., 2021; Peploe et al., 2018; Szymanski et al., 2007).

Despite the seemingly broad array of available testing options, the current set of rotational power assessments are deficient in their ability to support elite sport performance. The field-based assessments use throw methods without criterion reference validity and reliability, spurious performance data, or protocols requiring seated or kneeling positions wholly unreflective of many sporting actions that practitioners are seeking to support. Laboratory-based testing yields highly accurate information, but requires specialist equipment and a significant time cost, both of which are not feasible for practitioners in elite environments.

Given that rotational power is an important quality in many sports that practitioners regularly seek to enhance in order to drive athletic performance, there is a clear need to establish an accurate and reliable way to measure this capacity, to better support strength and conditioning programs through evidence-based practice. Therefore, the purpose of this study was to assess the validity and reliability of both a novel rotational power test the medicine ball push for maximum velocity (MB_{vel}), and the commonly used assessment the medicine ball push for distance (MB_{dis}), and identify the best practice field-based measure to assess rotational power by proxy.

Methods

Experimental Approach to the Problem

This study was designed to assess the validity and reliability of two medicine ball rotational power tests MB_{vel} and MB_{dis} which utilize proxy measures of velocity and distance, in comparison to the gold-standard criterion reference of three-dimensional motion capture (MoCap) (Vicon Vero, Vicon Motion Systems, Oxford, United Kingdom). A 2kg medicine ball mass was chosen to reflect the average senior professional cricket bat mass of 1-2kg in line with methods used in previous baseball research (Szymanski et al., 2010), as well as to be within the range of medicine ball masses previously used in similar rotational power assessments from 1 – 6kg (Ikeda et al., 2009; Read et al., 2013; Szymanski et al., 2010; Taniyama et al., 2021). Subjects volunteered from the senior women's New South Wales (NSW) state cricket team and attended two testing sessions separated by one week. No familiarization sessions were included due to the subjects' vast previous exposure to the MB_{vel} and MB_{dis} tests respectively, with Cricket NSW utilizing both assessments as part of a regular in-house performance testing battery across the past two seasons. Intra- and inter-day reliability were determined via the Intraclass correlation (ICC), bias and precision were calculated using Bland-Altman plots, and the coefficient of variation (CV) and standard error of mean (SEM) were evaluated for both tests.

Subjects

This study utilized a convenience sample of professional female cricketers due to their availability as part of the Cricket NSW senior women's program. Fifteen cricketers from the NSW professional senior women's state cricket team volunteered to participate in this study (mean ± *SD*: age 23.24 ± 3.76 years, height 169.9 ± 6.3 cm, body mass 71.4 ± 11.9 kg, training age 4.80 ± 3.95 years). All subjects were older than 18.0 years (range: 19.29 to 30.80 years) and were free from injury at the time of data collection. All subjects were professional athletes competing at a senior state or national level and regularly completed comprehensive physical preparation programming including strength and power training utilising medicine ball throw work twice per week. This study was approved by the University of Sydney Human Research Ethics Committee (Project Number 2022/466), and prior to providing informed consent all subjects were presented with information regarding the study protocol, inclusion criteria (senior professional female cricketer, free from injury), as well as the benefits and risks of volunteering.

Procedures

Data collection occurred over two testing sessions separated by seven days. During the first session age, body mass, height, dominant batting hand, number of years played professionally, and highest professional level played, were recorded for all subjects. Both sessions consisted of the same physical performance warm up routine and the same volume of test repetitions on each side (left and right) for MB_{vel} and MB_{dis} conditions. Both sessions were conducted at the same time of day, and subjects were directed to continue with their normal nutrition and hydration schedule.

Each testing session began with subjects completing a specific prescribed warm up routine consisting of dynamic stretching and mobility, general strength movements, and plyometrics (for details see Supplemental Digital Content 1). Subjects then performed a rotational power assessment consisting of 24 total (12 MB_{vel} and 12 MB_{dis}) maximal effort throws of a 2-kilogram medicine ball. Throws were completed in sets of six per round comprising of three left and right sided efforts randomly ordered for each subject. Throws were conducted using a carousel queue where a subject completed one throw and then proceeded to rest whilst the rest of the group completed a single effort each. This method ensured a rest time of 60 - 70 seconds between maximal effort throws inside each set in line with previous medicine ball throw research (Ikeda et al., 2009; Stockbrugger & Haennel, 2001b). Additionally, subjects were allocated three minutes of rest after completing each set for a given condition as an additional safeguard against fatigue over the 24 maximal effort throws required in each session.

The condition for the first set of throws was randomly allocated as either MB_{vel} or MB_{dis}. The following three sets then alternated condition based on the first allocation (for example set 1 = MB_{vel}, therefore set 2 = MB_{dis}, set 3 = MB_{vel}, set 4 = MB_{dis}). The alternating condition design was used as an additional safeguard against fatigue to ensure that upon randomisation neither protocol was allocated consecutively to sets three and four.

For all testing throws across both conditions subjects were instructed to follow the protocol below. A kinogram of the protocol is shown in Figure 1.

1. Subject stands in side-on 'athletic stance' with lateral edge of front shoe aligned with zero-point tape line on laboratory floor, rear arm the assigned pushing arm
2. Subject holds medicine ball at shoulder height in contact with chest, uses front arm to support mass of ball from underneath, rear arm is cocked with hand placed on the back of ball
3. Subject completes throw by rapidly counter-rotating away from throw direction in transverse plane with feet fixed on floor before immediately rotating back and explosively pushing ball forwards, completing any follow through movement of body and feet after ball release

Figure 1. Kinogram displaying the medicine ball rotational power throw for velocity MB_{vel} assessment.

Specific cues were given to subjects for each test type. For MB_{vel} trials subjects were instructed to "explosively push the ball as fast and as hard as possible towards the radar gun". For MB_{dis} trials subjects were instructed to "explosively push the ball as fast and as hard for the longest possible distance".

All trials utilized a three-dimensional 16-camera motion analysis system (Vicon Vantage, Vicon Motion Systems, Oxford, United Kingdom) to record subject hand and medicine ball kinematic data at a sampling rate of 240Hz. Reflective markers were placed on both wrists and hands for all subjects at the ulnar and radial styloids and dorsally at the second and fifth metacarpophalangeal joints using a four-marker hand model, an additional fifth marker was placed on the back of the left hand to differentiate sides. Reflective markers were also placed on the medicine ball using a five-marker model with four markers at an equal distance around the widest circumference of the ball and a fifth marker positioned at a location with a different surface distance to each of the four equally spaced markers. Marker trajectory data were filtered using a low-pass Butterworth filter with a cutoff frequency of 18 Hz and exported to Visual 3D (C-Motion Inc., Germantown, MD) for analysis.

Centre of gravity (CoG) models were created for the medicine ball and both hands. Position, velocity, and projection angle data for all trials were determined using the laboratory coordinate system and two events during each throw: Point of release (P_{rel}) defined as the first frame at which the medicine ball and hand centre of gravity (CoG) models separated and increased distance apart, and point of release +5 frames (P_{rel+5}) as the frame 5 additional frames forward in the trial. Height of release was calculated as the vertical distance from the laboratory floor to medicine ball CoG at P_{rel}. Horizontal (left and right) and vertical (up and down) projection angles were calculated via a five-frame medicine ball CoG trajectory from

P_{rel} to P_{rel+5}. Maximum velocities in each of the x, y, and z (v_x, v_y, v_z) directions were calculated as the peak value of medicine ball CoG velocity averaged over five frames from P_{rel} to P_{rel+5}. The maximum velocity for MB_{vel} trials was calculated as the resultant velocity of $v_x + v_y + v_z$. Throw distance for MB_{dis} trials was calculated as the horizontal distance from P_{rel} to first landing by projectile motion ignoring the effects of air resistance and spin as per similar work completed in shotput (Hubbard et al., 2001; Linthorne, 2001).

In addition, for comparison to field-based measurement techniques, MB_{vel} trials used a radar gun (Stalker ProIIs, Applied Concepts Inc., Plano, TX) set to continuously transmit positioned 5m directly in front of the subject's lead foot at a height of 1.5m to measure the maximum velocity for each throw, and MB_{dis} trials used a tape measure with the zero line at the lateral edge of the lead foot and distance extending straight out along the laboratory floor with visual identification of the distance upon first landing for each throw. Power was not directly measured for either condition with velocity and distance utilized as proxy measures.

Statistical Analysis

All statistical analysis was completed using R (version 4.2.3, Boston, MA). 672 trials were completed during data collection. 45 trials (6.7%) were omitted due to missing data (e.g., marker occlusion), resulting in 627 successful trials (316 MB_{dis} + 311 MB_{vel}) available for analysis. Data were first checked for normality using Shapiro-Wilk testing before the mean and standard deviation (SD) for all outcome variables were calculated (Table 1). An ICC power analysis was conducted using a minimum acceptable reliability = 0.80, expected reliability = 0.90, $\alpha = 0.05$ and $\beta = 0.20$, and showed that a minimum of n = 58 throws per assessment type were required to reach statistical significance.

The coefficient of variation (CV) and standard error of mean (SEM) were calculated for MoCap, radar velocity, and tape measure distance for all trials. Condition accuracy and reliability were determined via Intraclass correlations (ICC) (1, 1) and (3,1) respectively, and interpreted as excellent > 0.9, good 0.75 - 0.9, moderate 0.5 - 0.75 and poor < 0.5 (Koo & Li, 2016). Bias, precision, and upper and lower limits of agreement (LoA) were established using Bland-Altman plots (Bland & Altman, 1999; Giavarina, 2015). Bias was calculated as the mean difference between MoCap and each condition, precision as the standard deviation of the difference between MoCap and each condition. Variance and correlation between MoCap and each condition were calculated using Linear regression (R squared) and Pearson's correlation (*r*). Pearson's r was interpreted as large 0.50 to 0.70, very large 0.70 to 0.90, and nearly perfect > 0.90 (Hopkins, 2000). Data were then split into dominant and non-dominant throws by classifying the assigned rear pushing arm according to each subjects' dominant batting hand before the analysis above was then repeated in full. Significance for all analyses was set a priori at $\alpha = 0.05$.

Table 1. Descriptive statistics of mean (SD) for three-dimensional motion capture (MoCap) outcome measures of resultant velocity, projected distance, horizontal projection angle, vertical projection angle, and height of release for all medicine ball velocity (MB_{vel}) and medicine ball distance (MB_{dis}) trials.

	Resultant Velocity		**Projected Distance**		**Horizontal Projection Angle** (-ve = left of thrower, +ve = right of thrower)		**Vertical Projection Angle** (+ve = up, -ve = down)		**Height of Release**	
	Mean *km·hr^{-1}*	*± SD* *km·hr^{-1}*	*Mean* *m*	*± SD* *m*	*Mean* *Degrees °*	*± SD* *Degrees °*	*Mean* *Degrees °*	*± SD* *Degrees °*	*Mean* *m*	*± SD* *m*
MB_{vel} *n = 311*	35.19	2.20	-	-	0.56	4.01	6.08	3.21	1.52	0.08
Dominant *n = 157*	36.14	2.31	-	-	-1.44	3.53	5.89	3.17	1.51	0.08
Non-Dominant *n = 154*	34.22	2.09	-	-	2.60	3.41	6.27	3.26	1.53	0.09
MB_{dis} *n = 316*	33.93	2.18	10.62	1.23	1.82	3.79	19.22	4.14	1.74	0.11
Dominant	34.97	1.80	11.10	1.06	0.74	3.41	19.24	4.04	1.73	0.11

n = 161										
Non-Dominant *n = 155*	32.85	2.03	10.13	1.20	2.93	3.86	19.20	4.26	1.76	0.11

Results

The radar assessment method demonstrated excellent accuracy (ICC = 0.97 (0.97-0.98)) compared with MoCap, while the distance method showed poor accuracy (ICC = 0.38 (0.28-0.47)). MB_{vel} displayed nearly perfect agreement with MoCap for both bias (-0.09%) and precision (1.49%), whilst MB_{dis} yielded large bias (12.43%) and lower precision (4.55%). The relative variation and standard error of mean were calculated to be CV = 4.19%, SEM = 0.08km·hr^{-1} for MB_{vel} and CV = 9.55%, SEM = 0.05m for MB_{dis}. MB_{vel} demonstrated excellent between-session reliability compared with MoCap (ICC = 0.94 (0.82-0.98)), while MB_{dis} showed moderate reliability (ICC = 0.72 (0.32-0.90)). The side-to-side analysis of MB_{vel} throws follows the same profile as the overall MB_{vel} analysis above for both dominant (ICC = 0.96 (0.95-0.97), bias -0.15%, precision = 1.55%, CV = 2.32%, SEM = 0.07km·hr^{-1}) and non-dominant (ICC = 0.97 (0.96-0.98), bias -0.05%, precision = 1.53%, CV = 2.57%, SEM = 0.07km·hr^{-1}) throws. Across multiple sessions both dominant (ICC = 0.88 (0.69-0.97)) and non-dominant (ICC = 0.93 (0.80-0.98)) MB_{vel} assessments have confirmed good to excellent reliability. The full set of results comparing MoCap to MB_{vel} and MB_{dis} conditions are shown in Table 2, and plots of the Bland-Altman analysis of bias and precision are shown in Figure 2.

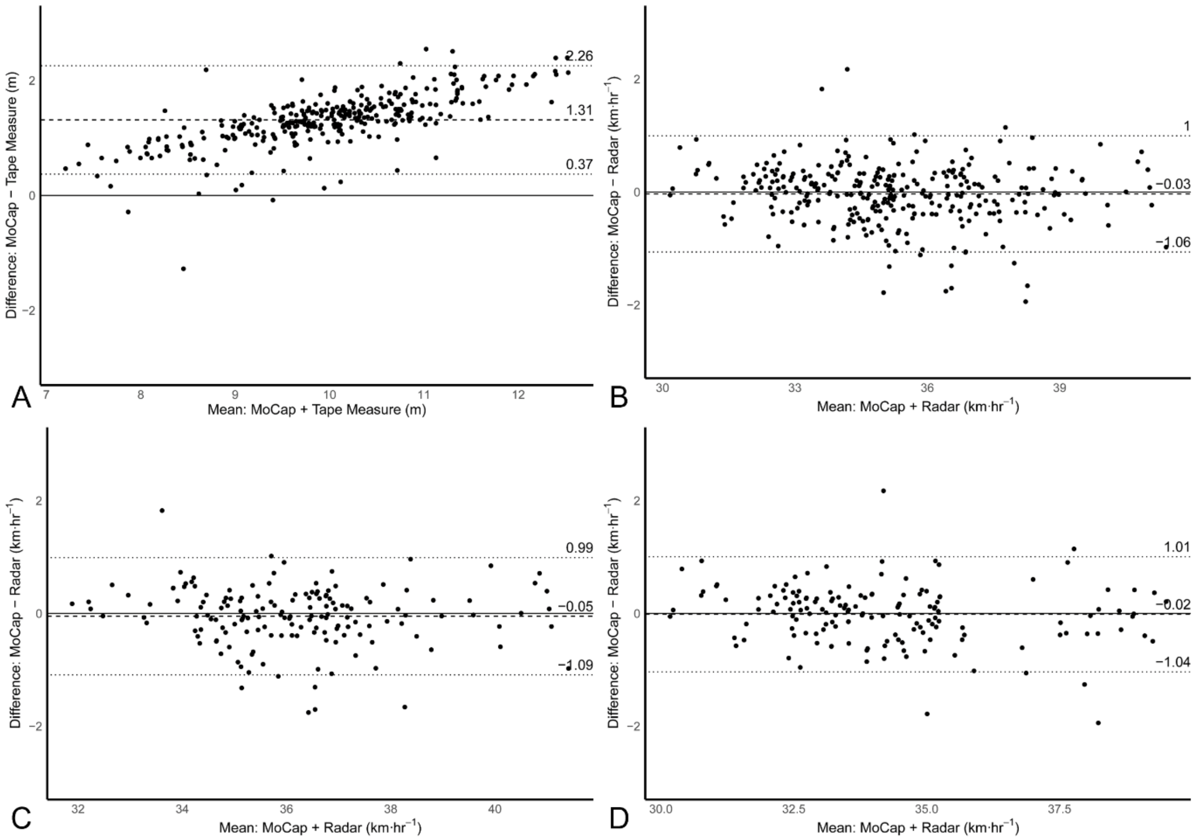
Table 2. Mean ± SD throw velocity for MB_{vel} and throw distance for MB_{dis} by three-dimensional motion capture (MoCap) and radar or tape measure. Coefficient of variation (CV) and standard error of mean (SEM) for MoCap, radar, and tape measure. Assessment accuracy represented by intraclass correlation (ICC). Bias and precision shown by Bland-Altman measures of mean difference and standard deviation of the difference between measures. Variance and correlation represented by linear regression (R^2 and Pearson's r). Assessment reliability represented by intraclass correlation (ICC).

Test Type			**ICC (1, 1)**		**Bland-Altman**		**Linear Regression**	**ICC (3,1)**			
	MoCap	**Radar**	**Accuracy Radar**		**Bias**	**Precision**		**Reliability vs MoCap**		**Reliability vs Radar**	
	Mean ± SD km·hr^{-1}	*Mean ± SD km·hr^{-1}*	*Mean (CI)*	*Classification*	*Mean Diff km·hr^{-1} (%)*	*± SD of Diff km·hr^{-1} (%)*	*R^2 (r)*	*Mean (CI)*	*Classification*	*Mean (CI)*	*Classification*
MB_{vel}											
Overall	35.12 ± 1.47	35.15 ± 1.54	0.97	Excellent	-0.03 (-0.09%)	0.52 (1.49%)	0.95 (0.97)	0.93	Excellent	0.94	Excellent
n = 311	CV = 4.19, SEM = 0.08	CV = 4.38, SEM = 0.09	(0.97-0.98)		LoA: -1.06 - 1.00		p < 0.001	(0.80-0.98)		(0.82-0.98)	
Dominant Hand	36.06 ± 0.83	36.10 ± 0.93	0.96	Excellent	-0.05 (-0.15%)	0.53 (1.55%)	0.92 (0.96)	0.90	Good	0.88	Good
n = 157	CV = 2.32, SEM = 0.07	CV = 2.59, SEM = 0.07	(0.95-0.97)		LoA: -1.09 – 0.99		p < 0.001	(0.72-0.97)		(0.69-0.97)	
Non-Dominant Hand	34.14 ± 0.87	34.16 ± 0.98	0.97	Excellent	-0.02 (-0.05%)	0.52 (1.53%)	0.94 (0.97)	0.94	Excellent	0.93	Excellent

n = 154	CV = 2.57, SEM = 0.07	CV = 2.88, SEM = 0.08	(0.96-0.98)		LoA: -1.04 - 1.01		p < 0.001	(0.81-0.98)		(0.80-0.98)	

			ICC (1, 1)		**Bland-Altman**		**Linear Regression**	**ICC (3,1)**			
	MoCap	**Tape Measure**	**Accuracy Tape Measure**		**Bias**	**Precision**		**Reliability vs MoCap**		**Reliability vs Tape Measure**	
	Mean ± SD m	*Mean ± SD m*	*Mean (CI)*	*Classification*	*Mean Diff m (%)*	*± SD of Diff m (%)*	*R^2 (r)*	*Mean (CI)*	*Classification*	*Mean (CI)*	*Classification*
MB_{dis}											
Overall	10.54 ± 1.00	9.24 ± 0.71	0.38	Poor	1.31 (12.43%)	0.48 (4.55%)	0.90 (0.95)	0.72	Moderate	0.72	Moderate
n = 316	CV = 9.55, SEM = 0.05	CV = 7.69, SEM = 0.04	(0.28-0.47)		LoA: 0.37 - 2.26		p < 0.001	(0.32-0.90)		(0.32-0.90)	

Figure 2. Bland-Altman plots for MB_{dis} and MB_{vel} assessments. Solid line = line of zero difference between measurement systems. Dashed line = bias calculated as the difference between three-dimensional motion capture (MoCap) and tape measure or radar. Dotted lines = upper and lower limits of agreement (LOA) calculated as Bias ± 1.96 · Standard deviation of the difference between measures (precision). A: MoCap versus MB_{dis}, B: MoCap versus MB_{vel}, C: MoCap versus Dominant MB_{vel}, D: MoCap versus Non-Dominant MB_{vel}.



Discussion

The purpose of this study was to assess the validity and reliability of two medicine ball rotational power assessments MB_{vel} and MB_{dis} with the aim of identifying an effective field-based test. The results clearly demonstrate that only MB_{vel} accurately measured rotational power (ICC = 0.97 (0.97-0.98)), and that MB_{dis} lacked the accuracy (ICC = 0.38, (0.28-0.47)) to be utilized in the field. The results further establish the MB_{vel} condition's efficacy, showing accurate assessment of both dominant (ICC = 0.96, (0.95-0.97)) and non-dominant (ICC = 0.97, (0.96-0.98)) throws. When both conditions were assessed for reliability over multiple sessions (Table 2) MB_{vel} (ICC = 0.94, (0.82-0.98)) outperformed MB_{dis} (ICC = 0.72, (0.32-0.90)), and maintained good to excellent reliability for dominant (ICC = 0.88, (0.69-0.97)) and non-dominant (ICC = 0.93, (0.80-0.98)) throws.

Bland-Altman analysis of both conditions (Figure 2) revealed a strong contrast in profiles of bias and precision. Across overall, dominant, and non-dominant analyses MB_{vel} repeatedly demonstrated nearly perfect agreement with MoCap for both bias (-0.05% to -0.15%) and precision (1.49% to 1.55%). Comparing MB_{vel} to common assessments in elite sport settings including counter-movement jump height (Weakley et al., 2023) (bias = -3.05%, precision = 8.52%), and back squat mean concentric bar velocity (Feuerbacher et al., 2023) (bias = -3.64%, precision = 2.05%), the level of error calculated is exceptionally low. It is noted that across all MB_{vel} trials there was a small yet consistent overestimation by radar versus MoCap (Table 2). Given the already established global and multi-sport accuracy and reliability of radar technology (Buchheit et al., 2014; Delgado-García et al., 2019; Feros et al., 2021; González-González et al., 2018; Okoroha et al., 2019; Smith & Burke, 2021) it is unlikely that the bias recorded here represents a true difference between measurement systems. Another potential explanation of the bias may be found in review of calculation differences between systems. Specifically, MoCap resultant velocity was calculated as the average peak velocity over five frames from P_{rel} to P_{rel+5}, whilst radar recorded a maximum instantaneous velocity reached for the full duration of each trial at a collection frequency of 34.7 GHz. The use of instantaneous (absolute maximum) and five frame average (average peak maximum) velocities in this way provide a plausible explanation for the small bias identified.

The difference in results between MB_{vel} and MB_{dis} is significant given the widespread use of the MB_{dis} condition among strength and conditioning professionals (albeit using different throw techniques) both in research settings and across performance environments (Earp & Kraemer, 2010; Ikeda et al., 2009; McMillian et al., 2006; Raeder et al., 2015; Read et al., 2013; Salonia et al., 2004). This is the first study to evaluate the validity and reliability of distance-based medicine ball throws as a measure of rotational power. These findings call into question the accuracy of such approaches, with significant implications for strength and conditioning practitioners currently utilizing this assessment method. The lack of criterion reference validity and reliability research and the recurrent use of distance-based throw assessments in publication have led practitioners to assume that distance-based assessments can accurately measure performance. In the context of the results shown for MB_{dis} above this is not the case, and without known bias and precision, environments utilizing throws for distance should interpret results with caution.

The superior performance of MB_{vel} compared to MB_{dis} can be broken down into two areas, (i) condition specific constraints, and (ii) the measurement systems. Condition specific constraints are best understood by an ecological dynamics approach (Araujo & Davids, 2011; Davids et al., 2008; Kelso, 1995), where the movement outcome (medicine ball throw) is a product of the interaction between constraints of the environment, task, and organism, and subsequent self-organisation of the subject to execute the task. MB_{vel} and MB_{dis} contain two differences in constraints; the condition specific cue either to push as hard and as fast as possible (MB_{vel}), or for the longest distance possible (MB_{dis}), and the measurement equipment as either radar gun or tape measure line. The results in Table 1 demonstrate that these differences contribute to different performance results for each condition. During MB_{dis} trials subjects were unable to optimise their throw trajectory for best possible distance, producing an overall vertical projection profile of 19.2±4.1°, well below values identified in shot put, optimal angle 42° and range of angles for elite throwers 26-41° (Linthorne, 2001). The inability of subjects to throw in the ideal range of trajectories significantly impacts the distance thrown and consequently the MB_{dis} condition's ability to measure true maximum rotational power. Additionally, all types of MB_{dis} throws also displayed a comparatively lower MoCap mean peak resultant velocity versus MB_{vel} throws, despite both conditions being cued as maximum efforts and resultant velocity being summed in all three vector directions. A feasible explanation for these different results could be that the radar gun more effectively constrains subjects to throw maximally at a single target in space compared to the extended tape measure line as a target throwing plane. These findings demonstrate that subjects completing MB_{dis} throws were unable to optimise their task execution producing throws at lower resultant velocities with suboptimal projection angles. The MB_{dis} outcome measures of resultant velocity and distance therefore underrepresent true maximal rotational power expression and show that MB_{dis} is reliant on elements of skill in combination with power to meet task constraints. Conversely, MB_{vel} does not experience this same limitation and is better able to purely measure rotational power expression.

The measurement systems used to assess rotational power for each condition play a key role in contributing to the significantly different accuracy of radar (ICC = 0.97, (0.97-0.98)) and tape measure (ICC = 0.38, (0.28-0.47)). The radar device records an instantaneous maximum velocity without reliance on practitioner input, whereas the tape measure system requires the expert eye of a practitioner to both identify point of landing and estimate distance thrown. The use of expert human eye presents a significant source of potential error given the range of horizontal and vertical projection angles and the subsequent variation in ball trajectories thrown by subjects. During MB_{dis} trials practitioners are required to account for throws projected across a range of distances forward as well as multiple meters to the left or right of the central measurement line. During MB_{vel} trials the radar device performs the equivalent of this task to deal with variation in projection for velocity throws. Whilst neither method can replicate the criterion measurement of resultant velocity from all three vectors with both constrained to the forward direction, the use of human eye for distance trials may explain the contribution of measurement systems to condition accuracy.

As previously mentioned, the ecological validity of physical performance assessments is an important consideration in elite sport environments. Practitioners aim to use assessments that are reflective of an athlete's sporting actions, as seen by the continued use of various medicine ball assessments despite limited or no validity and reliability research available. Practitioners are also often interested in assessing either side-to-side differences or dominant side performance for a given assessment, particularly in unilateral sports such as cricket, tennis, golf, baseball, and softball. This requires the given assessment to have suitable accuracy and reliability on both dominant and non-dominant sides in order to meaningfully compare results and capably detect differences in performance. The MB_{vel} protocol addresses these requirements and provides the most comprehensive assessment of accuracy, bias, precision, and reliability available for rotational power assessments in the literature (Table 2). The MB_{vel} condition is also highly accurate on both sides, with each following the same bias and precision profile as the MB_{vel} overall statistics discussed above, and across multiple testing sessions both have confirmed reliability to repeatedly assess rotational power (Table 2). In comparison, the alternate assessments currently available in the literature; seated cable rotation via external dynamometry (Andre et al., 2012), and kneeling cable lift via linear transducer (Zois et al., 2016) are unable to meet the demands of practitioners in performance settings described above. Both assessments lack ecological validity in their use of seated or kneeling positions and are non-representative of rotational power-based sporting actions completed in standing. Both assessments demonstrate limited accuracy and reliability statistics, with neither utilizing a criterion reference measure, seated cable rotation reporting ICC reliability (0.95-0.97) with no measure of accuracy, and the kneeling cable lift reporting CV (7.4-16.3%) and ICC reliability (0.74-0.94). Furthermore, neither assessment has demonstrated capability to measure side-to-side differences in performance. The MB_{vel} protocol represents a significant progression in the rotational power literature, and in supporting practitioners to accurately assess the capacity in the field.

The MB_{vel} assessment is a new tool for practitioners to utilize in environments where there is a requirement to measure, benchmark, or track change in rotational power performance. This study has built on the pilot work of various velocity-based throw protocols currently in the literature without validation (Freeston et al., 2016; Ikeda et al., 2009; Szymanski et al., 2007; Taniyama et al., 2021), and is the first study that has successfully validated both the accuracy and reliability of a rotational medicine ball throw for velocity in comparison to the criterion reference of MoCap. This is also the first study specifically assessing rotational medicine ball throws in the transverse plane, with previous publications limited to overhead and chest-based throws (Stockbrugger & Haennel, 2001a; van den Tillaar & Marques, 2013). Finally, the MB_{vel} assessment is the first rotational power test in the literature with established accuracy, bias, precision, and reliability across both dominant and non-dominant sides (Table 2).

Practical applications

The MB_{vel} assessment is a valid and reliable way to measure both dominant and non-dominant side rotational power performance in elite sport settings using velocity as a proxy measure. This field-based test requires only a radar gun, tripod, and 2kg medicine ball and permits practitioners to move from laboratory to performance environments whilst still accurately assessing rotational power. In considering the practical interpretation of the results from this study, the MB_{vel} protocol demonstrated a maximum CV of 2.57% across dominant and non-dominant sides, and therefore a meaningful change threshold of ±5.14% for detecting throw speed change. The MBvel protocol produced mean throw speeds from 34.16km/h to 36.10km/h meaning that changes larger than 1.76km/h to 1.86km/h would be considered meaningful. It is important to note that the results of this study show that both the intra-comparison of radar versus radar throw speeds is highly reliable with 2.57% CV, as well as the comparison of throw speeds from radar to motion capture where Bland-Altman analysis shows nearly perfect precision and low bias with limits of agreement ranging from -1.09 to 1.0km/h. The test enables practitioners to describe the rotational power profile of both individual athletes and teams, establish benchmarks specific to a given performance setting, and evaluate the effectiveness of program interventions.

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Chapter Four

The physical determinants of bat speed in elite female cricketers

Author Note

This thesis chapter has been amended after examination and contains minor differences to the published version of this work.

Abstract

This study explored the association between strength and power capacities and bat speed in female cricketers to inform strength and conditioning practices. Twenty-nine professional female cricketers volunteered for three testing sessions. Day 1: participant information, Grip Strength, Medicine Ball Push for Maximum Velocity (MB_{vel}), 10/5 Reactive Strength Index Hop Test. Day 2: Isometric Mid-Thigh Pull (IMTP), Vertical Jump, 1 Repetition-Maximum (1RM) Bench Pull (BP), Maximum Repetition Body Weight Push Up. Day 3: Maximal bat speed for four cricket shots Cut (BS_{cut}), Drive (BS_{drive}), Pull (BS_{pull}), and Slog (BS_{slog}) versus three delivery types (Off-Spin, Medium, Fast). Statistical analysis ($\alpha = 0.05$) included Pearson's (*r)*, Multiple linear regression (R-squared), one-way repeated-measures ANOVA with Tukey HSD analysis. Overall bat speed was associated with absolute 1RM BP ($r = 0.70$, $p < 0.0001$), dominant MB_{vel} ($r = 0.65$, $p < 0.0001$), non-dominant MB_{vel} ($r = 0.60$, $p < 0.0001$), absolute IMTP ($r = 0.47$, $p = 0.01$). Physical capacities regression modelling explained 52.7% of variance in bat speed overall (Adjusted R-squared = 0.5267, Standard Error of Estimate = 2.40, p < 0.0001). BS_{cut} was slower than all shots ($p < 0.0001$). BS_{cut} ($p < 0.0001$), BS_{drive} ($p < 0.0001$), and BS_{pull} ($p < 0.0001$) were slower during Fast versus Off-Spin deliveries. Absolute upper body pulling strength, dominant rotational power, and absolute total body isometric strength are critical qualities for power hitting training in female cricketers. Practitioners may include these findings in their program design to better support female athletes.

Introduction

Power hitting is an important aspect of batting and match success in professional women's cricket for both the 50-over and T20 formats. (Bhardwaj & Dwyer, 2022; Gupta, 2022; Haworth & Mills, 2024) Power hitting is the ability of a batter to strike the ball with high velocity along the ground or through the air across the boundary, scoring either four or six runs (the two highest scoring options). (Peploe et al., 2019) Winning teams have been shown to score runs at a higher rate (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024), hit more boundaries (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024), and accumulate fewer non and single-run scoring shots (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024) than their opposition.

Despite the importance of power hitting for match success in short format women's cricket (Bhardwaj & Dwyer, 2022; Haworth & Mills, 2024) there is limited research to support practitioners beyond biomechanical analysis. This data provides two foundational principles: First, a batter's ability to increase their hitting distance is underpinned by faster bat speed, (Peploe et al., 2018) which leads to faster ball launch velocity, (Peploe et al., 2019) and in combination with the optimal vertical launch angle leads to greater shot distances. (Peploe et al., 2019) Second, female batters exhibit a unique kinematic profile and movement solution when power hitting compared to male batters. (McErlain-Naylor et al., 2021) This difference is likely a combination of multiple factors including differences in anatomy and anthropometry, training environment, and task constraints. (McErlain-Naylor et al., 2021) The evidence for physical capacities and power hitting in cricket relies on the contribution of a single study in male batters which shows a large association between upper body pushing strength and maximum hitting distance. (Taliep et al., 2010) However, this finding may have limited application in women's cricket. The unique hitting technique used by female batters including a bent lead elbow and a close bat to body position (McErlain-Naylor et al., 2021) may render the association for upper body pushing strength not applicable in female environments. Furthermore, it is entirely plausible that the specific power hitting technique employed by female batters may be underpinned by unique physical determinants. These may include a number of physical capacities and therefore research in female power hitting needs to progress to explore a broad range of potential associations.

In comparison, previous work in other bat, club, and racket sports such as baseball (Spaniol et al., 2010; Szymanski et al., 2009) golf (Read et al., 2013; Robinson, Murray, Coughlan, et al., 2024; Robinson, Murray, Ehlert, et al., 2024), softball (Till et al., 2011) and tennis (Hayes et al., 2021) has employed this broad investigative approach with significant results. Rotational power (Hayes et al., 2021; Read et al., 2013; Szymanski et al., 2009), lower body power (Read et al., 2013; Robinson, Murray, Coughlan, et al., 2024; Szymanski et al., 2009; Szymanski et al., 2010), lower body strength (Szymanski et al., 2010), total body force production, (Robinson, Murray, Coughlan, et al., 2024; Robinson, Murray, Ehlert, et al., 2024) and upper body pushing strength (Robinson, Murray, Coughlan, et al., 2024; Szymanski et al., 2009; Szymanski et al., 2010) are consistently associated with bat, clubhead, and racket speed. These findings are pivotal as they enable practitioners to deliver specific programming interventions, explore causal relationships, and target the physical determinants of sport performance. (Spaniol et al., 2010) An example of this is the evidence base for clubhead speed in women's golf where broad explorations of physical capacities (Robinson, Murray, Coughlan, et al., 2024; Robinson, Murray, Ehlert, et al., 2024) have led to specific training interventions and subsequently enhanced clubhead speed and hitting distance. This is best practice strength and conditioning support for elite athletes, and the same approach needs to be adopted for power hitting in female cricket.

This study therefore, sought to utilize a broad explorative approach to assess a wide range of associations between physical capacities and bat speed in elite female cricketers in order to (i) significantly advance the evidence base and inform strength and conditioning practices for this cohort and (ii) help address the underrepresentation of female athletes in cricket research, and sport and exercise science more broadly. (Emmonds et al., 2019)

Methods

Experimental Design

This study was designed to explore the physical determinants associated with bat speed in elite female cricketers using an observational cross-sectional study design. Participants attended three testing sessions each separated by one week during the in-season competition period. The first two sessions involved a battery of anthropometry, strength and power assessments, and the third utilized a novel protocol to assess bat speed. No familiarization sessions were sought due to the participants' significant experience with the assessments, all of which form part of an in-house Cricket New South Wales (CNSW) testing battery.

Participants

This study utilized a convenience sample of professional female cricketers due to their availability as part of the Cricket NSW senior women's team, and the Sydney Sixers and Sydney Thunder Women's Big Bash League teams. Twenty-nine professional cricketers consented to take part in this study (mean±*SD*: age 22.75±5.10 years, height 170.4±6.2 cm, body mass 68.7±9.4 kg, professional experience 4.55±5.04 years). All participants were older than 18.0 years and free from injury at the time of data collection. This study was approved by the University of Sydney Human Research Ethics Committee (Project Number 2019/712), and prior to providing informed consent all participants were presented with information regarding the study protocol, inclusion criteria (senior female cricketer, free from injury), as well as the benefits and risks of volunteering.

Methodology

At the beginning of each testing session a warm-up routine designed to prepare participants for the assessments was delivered (see supplemental file). On Day 1 participant information was recorded including age, batting hand defined as the hand closest to the bat face on handle when batting, number of years played professionally, height, and weight. Participants then completed strength and power assessments including bilateral Grip Strength (GS), Medicine Ball Push for Maximum Velocity (MB_{vel}), and 10/5 Reactive Strength Index (RSI) Hop Test. On Day 2, participants completed Isometric Mid-Thigh Pull (IMTP), Vertical Jump (VJ), 1 Repetition-Maximum (1RM) Bench Pull (BP), and Maximum Repetition Body Weight Push Up. On Day 3, participants were assessed for maximal bat speed across four different shots including Cut (BS_{cut}), Drive (BS_{drive}), Pull (BS_{pull}), and Slog (BS_{slog}). The full details and methodology of the testing framework can be found in the supplemental digital content.

Day 1

Participants completed a Day 1 warm-up routine (supplemental file) and then assessments in the following order:

Grip strength. A hand grip dynamometer (Hydraulic Hand Dynamometer Jamar 5030JI, Bolingbrook, IL, USA) was used to assess participant grip strength following the Canadian National Hockey League combine testing protocol (Chiarlitti et al., 2018). The maximum score in kilograms for each hand was recorded for further analysis.

Medicine Ball Push. Rotational power was assessed using a 2-kilogram medicine ball and a radar gun (Stalker ProIIs, Applied Concepts Inc., Plano, TX), following the published protocol. (Hardy et al., 2024) The maximum speed on each side in $km \cdot hr^{-1}$ was recorded for further analysis.

10/5 Hop Test. Reactive Strength Index (RSI) was assessed following the published protocol (Harper et al., 2011) using a Force Decks FD4000 dual force plate system (Vald Performance, Brisbane, QLD, Australia). The highest peak RSI across the three attempts was recorded for further analysis.

Day 2

Participants completed a Day 2 warm-up routine (supplemental file) and then assessments in the following order:

Isometric Mid-Thigh Pull. Total body isometric strength was assessed following the published protocol (Comfort et al., 2019) using a Force Decks FD4000 dual force plate system (Vald Performance, Brisbane, QLD, Australia) and isometric Vald Performance testing rig. The maximal force generated measured in Newtons (N) across all three attempts was recorded for further analysis.

Vertical Jump. Lower body power was assessed using a Swift Yardstick jump measure system (Sports Imports, Hillard, OH) following the published protocol. (Thomas et al., 1996) Final jump height measured in centimetres (cm) was recorded for further analysis.

Bench Pull. Upper body maximum pulling strength was assessed using the prone laying bench pull protocol (Lum & Aziz, 2020) and the established 1 repetition maximum (1RM) framework. (Seo et al., 2012) The maximum weight successfully lifted, measured in kilograms (kg), was recorded for further analysis.

Push Up. Upper body pushing strength was assessed using the bodyweight push up for maximum repetitions. The testing was conducted using an in-house Cricket New South Wales protocol developed from published literature confirming the validity of the push up as a measure of pushing strength. (Tillaar & Ball, 2020) Participants were instructed to lay prone on the ground self-selecting preferred hand position, aligning the centre of their chest to contact a 5-kilogram weight plate, with feet shoulder-width apart. Participants were then instructed to push up to both arms fully extended, whilst at the same time maintaining a straight line between shoulders, hips, knees, and ankles. Participants were also instructed to ensure trunk control with only minor movement allowed. From the top position participants were to immediately return to the ground and repeat this cycle as many times as possible with no rest in either position. Any repetitions that did not meet the required depth, contained excessive and significant trunk extension resulting in shoulders hips knees and ankles to be miss-aligned, engaged in uneven arm movement with hips assisting by 'kipping', were rejected. Two repeated criteria failures ended the test. The maximum number of successful repetitions was recorded for further analysis.

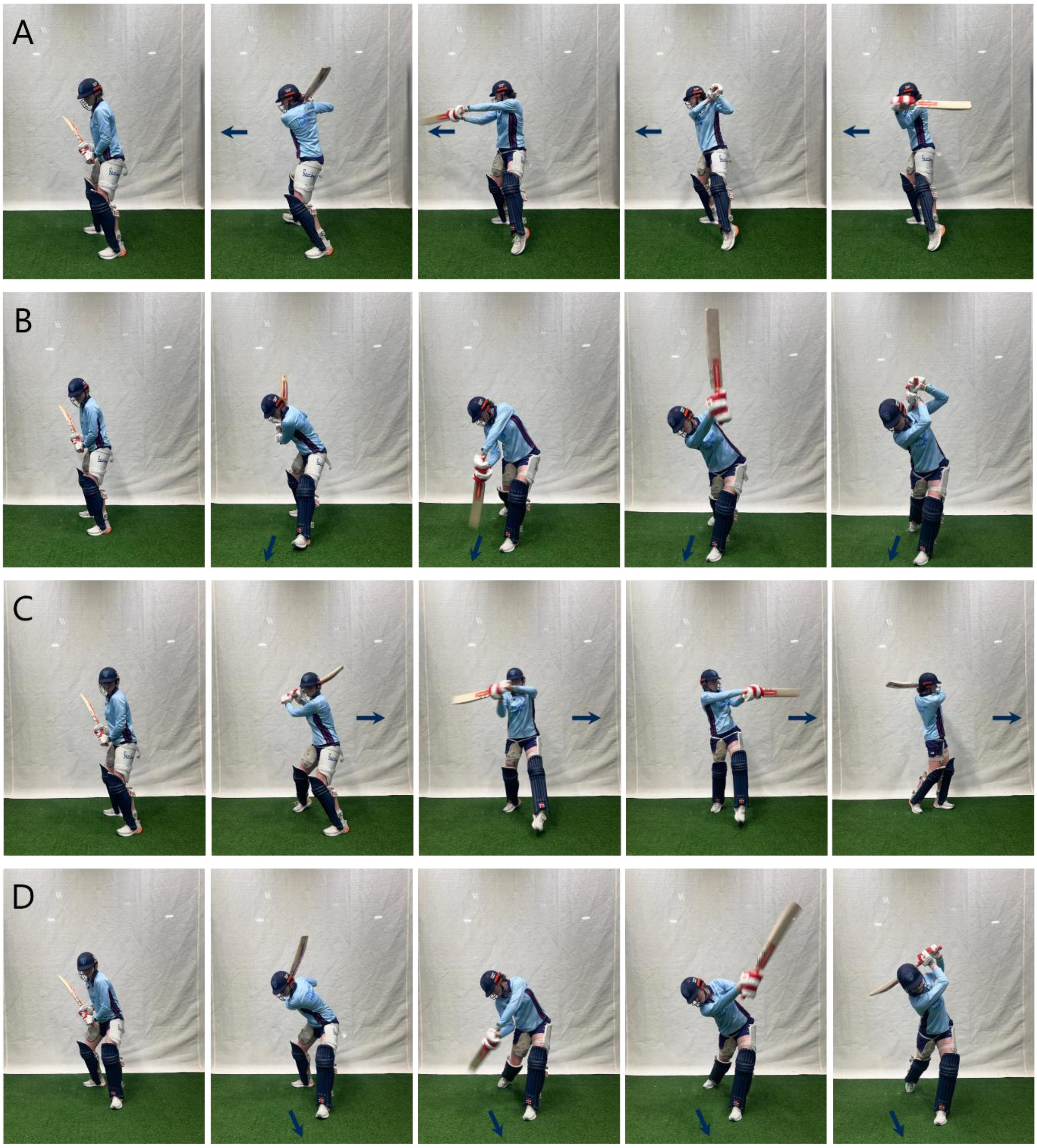
Day 3

Participants completed a Day 3 warm-up routine (supplemental file) and were then assessed for bat speed:

Bat Speed. Bat speed was measured using a validated bat mounted sensor (Blast Baseball, Blast Motion Inc. San Marco, CA). The sensor comprises of an accelerometer, gyroscope and magnetometer device in a unit mounted to the handle of the bat. Bat speed is recorded as the maximal linear speed 15 cm from the tip of the bat along the centre of the bat's long axis at the frame immediately prior to contact. While originally designed for baseball, previous unpublished work (Hardy, June 2025. Accuracy of a bat-mounted sensor for the measurement of bat speed among elite female cricket players [Manuscript submitted for publication]) comparing the device to three-dimensional motion capture shows the sensor is accurate and reliable for application in cricket batting with an overall bias of 2.7%, precision of 5.1%, and good absolute agreement (ICC = 0.86, (0.77-0.92)).

Participants completed testing at the Cricket NSW indoor facility on standard synthetic cricket pitches. Participants were instructed to use their normal matchday protective equipment and bat. Participants performed four different types of maximal effort cricket shots (Cut, Drive, Pull, Slog) whilst facing three different types of delivery (Fast, Medium, Off-Spin). A kinogram of the four different shots can be seen below in Figure 1. The Slog shot was only performed during Off-Spin deliveries, all other shots were performed across all delivery types. Deliveries were performed by a professional level batting coach using a match condition cricket ball. Delivery types were split into designated speed ranges: Fast (100-115 $km \cdot hr^{-1}$), Medium (90-100 $km \cdot hr^{-1}$), and Off-Spin (70-80 $km \cdot hr^{-1}$). Speed for each was recorded using a radar gun (Stalker ProIIs, Applied Concepts Inc., Plano, TX). Only deliveries within the designated ranges were included in the assessment. Participants were required to perform five successful attempts for each shot type to each delivery type for a total of 50 successful shots (15 Cuts, 15 Drives, 15 Pulls, 5 Slogs). A successful shot was defined as the correct shot type performed and batted ball hit in the intended shot direction. All attempts resulting in misses, edges, incorrect shot selection, and incorrect ball direction were rejected. Delivery types were randomised and performed for full sets of shot types (Cut, Drive, Pull, Slog) prior to changing. Shot types were also randomised and completed in blocks of 5 successful attempts for a given shot. Participants rested 10 seconds between shots, 60 seconds between shot types, and 4 minutes between delivery types. These rest periods were chosen specifically to align with the cluster-set method, which has demonstrated efficacy in maintaining power output and velocity during athletic movement. (Tufano et al., 2017) Standardized instructions were given to participants to "hit the ball as hard and as powerfully as you can". Delivery speed ($km \cdot hr^{-1}$), and bat speed ($km \cdot hr^{-1}$) for BS_{cut}, BS_{drive}, BS_{pull}, BS_{slog}, and $BS_{overall}$ (calculated as the maximum bat speed recorded across all four shot types) were recorded for further analysis.

Figure 1. Kinograms displaying the Cut (A), Drive (B), Pull (C), and Slog (D) shot types for the Maximal bat speed assessment. Arrows to represent intended ball trajectory.



Statistical Analysis

Statistical analysis was completed using R (version 4.2.3, Boston, MA). 1501 successful bat speed trials were completed during data collection. 51 trials (3.4%) were omitted due to missing Blast Motion sensor data (error given by smart phone app). All testing data were checked for normality using Shapiro-Wilk testing before mean and standard deviation (SD) were calculated for all outcome data (Table 1). Associations between anthropometry, physical assessments, and bat speed measures were determined using Pearson's correlation (*r*) at a participant level using mean values for each shot and delivery type. Associations were described as trivial (r=0.0-0.09), small (*r*=0.1-0.29), moderate (*r*=0.3-0.49), large (*r*=0.5-0.69), very large (*r*=0.7-0.89), or nearly perfect (*r*=0.9-0.99). (Hopkins et al., 2009) Bonferonni *p*-value corrections (Lydersen, 2024) were applied to associations identified in this study leading to an adjusted significance for correlations set to $\alpha = 0.0038$. Significant associations to bat speed overall were screened for collinearity using variance inflation factor (VIF) < 5 (Vachon et al., 2021) before being used as input variables for multiple linear regression modelling to explore the variance (R-squared) in overall bat speed explained by physical capacities. (Paulo Lopes-Silva et al., 2021) Differences in maximum bat speed between shot types, and delivery types were assessed at a participant level using average values for each shot and delivery type using one-way repeated-measures ANOVA testing and post-hoc Tukey HSD analysis, with significance set to $\alpha = 0.05$.

Table 1. Descriptive statistics of mean, standard deviation (SD), and coefficient of variation (CV) for outcome measures of all anthropometric, strength, power, and bat speed assessments.

Assessment	**Mean**	**±SD**	**CV (%)**
Height (cm)	170.4	6.2	0.7
Weight (kg)	68.7	9.4	0.035
Dominant GS (kg)	46.0	5.8	5.70
Non-Dominant GS (kg)	44.1	5.8	7.60
Dominant MB_{vel} ($km \cdot hr^{-1}$)	37.0	1.7	2.30
Non-Dominant MB_{vel} ($km \cdot hr^{-1}$)	34.3	2.2	2.45
RSI (FT/CT)	2.90	0.38	3.90
Absolute IMTP (N)	2792	326	3.35
Relative IMTP (xBW)	4.2	0.6	3.40
VJ (cm)	46.3	6.2	6.10
Absolute 1RM BP (kg)	57.9	7.2	2.50
Relative 1RM BP (xBW)	0.9	0.2	2.53
Push Up for Maximum Repetitions	23	11	9.1%
BS_{cut} ($km \cdot hr^{-1}$)	73.9	5.9	0.60
BS_{drive} ($km \cdot hr^{-1}$)	84.2	7.0	0.90
BS_{pull} ($km \cdot hr^{-1}$)	86.4	5.3	0.89
BS_{slog} ($km \cdot hr^{-1}$)	85.1	5.9	0.81
$BS_{overall}$ ($km \cdot hr^{-1}$)	88.4	5.6	0.93

Results

Overall bat speed was positively associated with absolute maximum upper body pulling strength, rotational power, and absolute total body isometric strength (absolute 1RM BP; very large, *r*=0.70, *p*<0.0001, dominant MB_{vel}; large, *r*=0.65, *p*<0.0001, non-dominant MB_{vel}; large, *r*=0.60, *p*<0.0001, absolute IMTP; moderate *r*=0.47, *p*=0.006). The full results of the correlation analysis identifying associations to bat speed overall are shown in Table 2.

The multiple regression model explained 52.7% of the variance in bat speed overall using absolute 1RM BP, dominant MB_{vel} and absolute IMTP as predictor variables (Equation 1). All variables passed VIF screening for collinearity (1RM BP = 1.90, absolute IMTP = 1.25, dominant MB_{vel} = 1.97). This model was shown to be statistically significant (F(3,25)=11.39, Adjusted R-squared=0.5267, Standard Error of the Estimate=2.40, *p*<0.0001) with absolute 1RM BP found to be a significant predictor variable (*p*=0.04). Non-dominant MB_{vel} was excluded due to very large association between dominant and non-dominant rotational power test scores (*r*=0.76, *p*<0.0001).

Equation 1:

$$Y = 15.71 + (0.59 * dominant\ MB_{vel}) + (0.0021 * absolute\ IMTP) + (0.20 * absolute\ BP\ 1RM)$$

Across all four shot types Cut, Drive, Pull, and Slog, moderate to large relationships were shown for dominant rotational power and absolute total body isometric strength (dominant MB_{vel}; *r*=0.43–0.60, *p*=0.0001-0.02, absolute IMTP; *r*=0.44–0.50, *p*=0.01-0.02). Drive, Pull, and Slog shots also demonstrated large associations with non-dominant rotational power and absolute maximum upper body pulling strength (non-dominant $MB_{vel;}$ *r*=0.54–0.60, *p*<0.0001, absolute 1RM BP; *r*=0.59–0.62, *p*<0.0001). However, these variables were not associated with bat speed for the cut shot.

Physical capacities associated with the Slog shot were unique, including non-dominant grip strength, relative maximum upper body pulling strength, lower body power, and upper body pushing strength (non-dominant GS; *r*=0.43, *p*=0.02, VJ; *r*=0.43, *p*=0.02, relative 1RM BP; *r*=0.44, *p*=0.02, push up for maximum repetitions; *r*=0.38, *p*=0.04). The full set of associations can be found in Table 3.

Maximum bat speed differed by both shot and delivery type. The Cut shot was slower than all other shots (F(3,112)=24.52, *p*<0.0001), with significant pairwise comparisons and confidence intervals for Cut-Drive (*p*<0.0001, 3.65-8.93) Cut-Pull (*p*<0.0001, 5.19-10.47), and Cut-Slog (*p*<0.0001, 4.16-9.44). The Cut, Drive, and Pull shots were all slower during Fast versus Off-Spin delivery types (Cut; *p*<0.0001, 0.97-6.38, Drive; *p*<0.0001 0.91-7.12, Pull; *p*<0.0001, 3.60-8.93). Additionally, the Pull shot was slower when comparing Fast to Medium (*p*=0.020, 0.39-5.73), and Medium to Off-Spin delivery types (*p*=0.014, 0.54-5.87). The full set of descriptive statistics for bat and ball speeds by shot and delivery type can be found in Table 4, and the group average maximum bat speeds used for ANOVA and Tukey analysis of delivery type can be found in Table 5.

Table 2. Correlation statistics of Pearson's correlation (*r*) and p-value (*p*) with 95% confidence intervals (CI) for maximum bat speed overall versus independent variables of anthropometric, strength, and power assessments.

	Maximum Bat Speed		
Independent Variable	*r*	*p*	CI
Height (cm)	-0.17	0.37	-0.51 to 0.21
Weight (kg)	0.28	0.14	-0.1 to 0.59
Dominant GS (kg)	0.05	0.17	-0.32 to 0.41
Non-Dominant GS (kg)	0.26	0.79	-0.12 to 0.57
Dominant MB_{vel} ($km \cdot hr^{-1}$)	0.65	<0.001*	0.37 to 0.82
Non-Dominant MB_{vel} ($km \cdot hr^{-1}$)	0.60	<0.001*	0.3 to 0.79
RSI (FT/CT)	-0.05	0.80	-0.41 to 0.32
Absolute IMTP (N)	0.47	0.006	0.13 to 0.71
Relative IMTP (xBW)	0.13	0.49	-0.25 to 0.47
VJ (cm)	0.32	0.09	-0.05 to 0.61
Absolute 1RM BP (kg)	0.70	<0.001*	0.45 to 0.85
Relative 1RM BP (xBW)	0.29	0.12	-0.09 to 0.59
Push Up for Maximum Repetitions	0.22	0.26	-0.16 to 0.54

***** $p < 0.0038$

Table 3. Correlation statistics of Pearson's correlation (*r*) and p-value (*p*) with 95% confidence intervals (CI) for maximum bat speed by Cut, Drive, Pull, and Slog shot types versus independent variables of anthropometric, strength, power, and shot type maximum bat speed assessments.

	Cut			Drive			Pull			Slog		
Independent Variable	*r*	*p*	CI	*r*	*p*	CI	*r*	*p*	CI	*r*	*p*	CI
Height (cm)	0.09	0.63	-0.29 to 0.44	-0.12	0.53	-0.47 to 0.26	-0.01	0.95	-0.38 to 0.36	-0.32	0.09	-0.61 to 0.05
Weight (kg)	0.22	0.26	-0.16 to 0.54	0.30	0.11	-0.07 to 0.60	0.35	0.07	-0.02 to 0.64	0.01	0.94	-0.36 to 0.38
Dominant GS (kg)	0.19	0.32	-0.19 to 0.52	0.16	0.40	-0.22 to 0.50	0.01	0.98	-0.36 to 0.38	0.17	0.36	-0.21 to 0.51
Non-Dominant GS (kg)	0.29	0.13	-0.09 to 0.59	0.37	0.05	0.00 to 0.65	0.15	0.45	-0.23 to 0.49	0.43	0.02	0.08 to 0.69
Dominant MB_{vel} (km/hr)	0.43	0.02	0.08 to 0.69	0.49	0.01	0.15 to 0.73	0.60	<0.001*	0.30 to 0.79	0.51	<0.001*	0.18 to 0.74
Non-Dominant MB_{vel} (km/hr)	0.24	0.21	-0.15 to 0.55	0.54	<0.001*	0.22 to 0.76	0.54	<0.001*	0.22 to 0.76	0.60	<0.001*	0.30 to 0.79
RSI (FT/CT)	-0.20	0.30	-0.52 to 0.19	0.03	0.86	-0.34 to 0.40	0.00	0.99	-0.37 to 0.37	0.17	0.39	-0.21 to 0.51
Absolute IMTP (N)	0.44	0.02	0.09 to 0.70	0.50	0.01	0.17 to 0.74	0.49	0.01	0.16 to 0.73	0.46	0.01	0.11 to 0.71

Relative IMTP (xBW)	0.18	0.34	-0.20 to 0.52	0.14	0.46	-0.24 to 0.49	0.09	0.64	-0.29 to 0.44	0.35	0.06	-0.02 to 0.64
VJ (cm)	0.05	0.78	-0.33 to 0.41	0.26	0.18	-0.13 to 0.57	0.24	0.22	-0.15 to 0.55	0.43	0.02	0.08 to 0.69
Absolute 1RM BP (kg)	0.30	0.11	-0.07 to 0.60	0.59	<0.001*	0.29 to 0.78	0.61	<0.001*	0.32 to 0.80	0.62	<0.001*	0.34 to 0.80
Relative 1RM BP (xBW)	0.07	0.73	-0.31 to 0.42	0.22	0.26	-0.17 to 0.54	0.16	0.39	-0.22 to 0.50	0.44	0.02	0.09 to 0.70
Push Up for Maximum Repetitions	0.05	0.80	-0.33 to 0.41	0.07	0.70	-0.31 to 0.42	0.11	0.57	-0.27 to 0.46	0.38	0.04	0.01 to 0.66
BS_{cut} (km·hr^{-1})	-	-	–	0.39	0.04	0.03 to 0.67	0.57	<0.001*	0.27 to 0.78	0.40	0.03	0.04 to 0.67
BS_{drive} (km·hr^{-1})	0.39	0.04	0.03 to 0.67	-	-	–	0.69	<0.001*	0.43 to 0.84	0.63	<0.001*	0.35 to 0.81
BS_{pull} (km·hr^{-1})	0.57	<0.001*	0.27 to 0.78	0.69	<0.001*	0.43 to 0.84	-	-	–	0.62	<0.001*	0.34 to 0.80
BS_{slog} (km·hr^{-1})	0.40	0.03	0.04 to 0.67	0.63	<0.001*		0.62	<0.001*	0.34 to 0.80	-	-	–

***** p < 0.0038

Table 4. Descriptive statistics of mean, standard deviation (SD), minimum (Min), and maximum (Max) for outcome measures of ball speed by delivery type and bat speed by shot type for n = 116 maximum bat speed assessments.

Skills Data		**Mean ± SD** *($km \cdot hr^{-1}$)*	**Min** *($km \cdot hr^{-1}$)*	**Max** *($km \cdot hr^{-1}$)*
Ball Speed by Delivery Type				
	Fast	105.0 ± 3.8	101.0	111.1
	Medium	94.5 ± 1.9	91.6	97.6
	Off-Spin	72.6 ± 2.2	70.0	79.8
Bat Speed by Shot Type				
	Cut	73.9 ± 5.9	62.6	86.7
	Drive	84.2 ± 7.0	70.3	100.3
	Pull	86.4 ± 5.3	75.6	94.3
	Slog	85.1 ± 5.9	70.0	95.4

Table 5. Descriptive statistics of mean and standard deviation (SD), and mean ÷ mean percentages of average maximum bat speed by delivery type and shot type. Significant results denoted by Tukey HSD analysis of one-way repeated-measures ANOVA testing comparing delivery types by shot type.

	Off-Spin	Medium		Fast		
	Mean ± SD	Mean ± SD *($km{\cdot}hr^{-1}$)*	% of Off-Spin Bat Speed	Mean ± SD *($km{\cdot}hr^{-1}$)*	% of Off-Spin Bat Speed	% of Medium Bat Speed
Shot Type						
Cut *n = 87*	72.7 ± 6.2	69.2 ± 6.6	95.2%	66.8 ± 7.9	91.9%**	96.5%
Drive *n = 87*	83.8 ± 7.0	78.5 ± 8.1	93.7%	77.4 ± 8.8	92.4%**	98.6%
Pull *n = 87*	86.6 ± 5.3	81.4 ± 7.0	94.0%**	76.5 ± 7.9	88.3%**	94.0%*
Slog *n = 29*	85.3 ± 5.8	-			-	

* p<0.05, ** p<0.01

Discussion

This is the first study to explore the association between bat speed and physical capacities of strength and power in elite female cricketers. This study was deliberately broad in design to include a comprehensive battery of physical assessments. This was done to ensure that all possible physical factors associated with bat speed were identified. The research team acknowledges that this design has placed some limitations on the statistical analysis, particularly in identifying significant physical capacity associations after *p*-value correction. We also acknowledge that whilst the convenience sample of 29 professional female batters in this study is the largest cohort to be assessed across all published cricket literature, the absolute size of the group is small in statistical terms and has placed some limitations on the interpretation of the outcomes of this research. Within the discussion we have identified a series of correlations, that whilst not statistically significant, we believe to be practically relevant for professional female cricket settings. We anticipate that future research with larger samples across other populations will be needed to clearly determine which capacities have a significant association with bat speed. The results of this study should be interpreted within this context.

Upper body pulling strength, dominant rotational power, and total body isometric strength explained 52.7% of the total variance in bat speed overall. By comparison, full-body biomechanical models have previously explained 77.7% of the total variance in bat speed among a similar cohort. (Peploe et al., 2019) The ability to explain more than half the variance in bat speed using physical variables without any biomechanical features demonstrates how important strength and power qualities are for power hitting in elite female cricketers and highlights the importance of strength and power development among this cohort.

The very large relationship identified for upper body pulling strength and bat speed is a novel finding across all bat, club, and racket sports in the literature to date. Only one previous study has explored this physical capacity, finding no relationship with bat speed among female softball college athletes (n = 19) using a 1RM 1-arm dumbbell row. (Till et al., 2011) Previous research in female golf athletes (n = 19) found a similarly large relationship for the reciprocal upper body pushing capacity of isometric bench press force at 100ms and clubhead speed. (Robinson, Murray, Coughlan, et al., 2024) In combination these findings suggest that maximum upper body strength may be an important quality to consider for hitting sports in line with the physiological underpinning of explosive power by maximum strength. (Suchomel et al., 2016)

The upper body pulling strength finding is consistent with the unique kinematics observed for female batters. Specifically, elite female batters have been shown to flex their lead elbow during downswing. (McErlain-Naylor et al., 2021) Elbow flexion during bat acceleration would theoretically place a high demand on upper body pulling strength to overcome the bat's increasing angular momentum, (McErlain-Naylor et al., 2021) which may explain the association to absolute 1RM BP observed in this study. Whilst this rationale is ecologically valid, it remains unclear whether this finding is unique to female batters, or if the association is a feature of power hitting in cricket generally. Further research within different cricket populations is required to fully understand the role of upper body pulling strength for power hitting.

The large associations for rotational power identified in this study are aligned with the existing evidence base highlighting the importance of rotational power in rotational hitting sports including golf, (Read et al., 2013) baseball, (Spaniol et al., 2010) and tennis. (Hayes et al., 2021) They are also supported by previous kinematic cricket research identifying the contribution of pelvis and upper thorax separation in the transverse plane, known as X-factor, on the generation of rotational power and maximum bat speed during power hitting. (McErlain-Naylor et al., 2021; Peploe et al., 2019) Only one previous study in female softball players has failed to identify rotational power as a key physical capacity. (Till et al., 2011) This research had several limitations which may have precluded the study's ability to identify a significant relationship including use of an unvalidated rotational power assessment and a low sample size of n=19 athletes. The ability to rotate powerfully is clearly an important factor in many bat, club, and racket sports.

Total-body isometric strength has been shown to have a non-significant but practically relevant relationship with bat speed for elite female cricketers. The peak vertical ground reaction forces recorded in the IMTP assessment provide an insight into the ability of participants to maximally apply force to the ground. This finding is consistent with previous work in women's golf where a moderate to large relationship (r=0.38-0.62) was found for clubhead speed and IMTP variables of peak force, and force at 100-300ms. (Robinson, Murray, Coughlan, et al., 2024) The ability to utilize energy from the ground through the kinetic chain has previously been linked to the generation of faster bat and clubhead speeds in both baseball (Szymanski et al., 2009) and golf. (Hellstrom, 2009; Wells et al., 2020) Given that maximal isometric strength is correlated with dynamic 1RM squat and clean performance, (Comfort et al., 2019) these findings also align with previous research showing associations between 1RM power clean, back squat, and clubhead speed in golf, (Oranchuk et al., 2020) and 1RM hang clean and bat speed in softball. (Till et al., 2011)

This investigation has established that a range physical capacities are linked to bat speed. These links include some general associations that are important across all shot types, as well as others that differ by shot. Although not directly measured in this study, the techniques for Cut, Drive, Pull, and Slog shots are all different (Figure 1), including different vertical and horizontal bat swing paths, as well as body and stance orientations. Power hitting therefore is a complex combination of technical and physical determinants. It is likely that technical skill plays a significant role in the generation of bat speed, and that additionally there may be an interaction between different shot techniques, movement demands, and associated physical capacities.

Despite significant differences in movement patterns however, a number of capacities follow the same trend and although not statistically significant they should be considered practically relevant for performance environments. Dominant rotational power and absolute total body isometric strength emerge as foundational qualities with positive relationships to bat speed across all shots. This suggests an almost universal importance of both powerful rotation and ground up energy transfer through the kinetic chain regardless of shot type. Absolute upper body pulling strength builds on the foundational qualities identified above as a specific capacity associated with the fast bat speed shot types; Drive, Pull, and Slog. While further research is needed to establish causal relationships, these capacities likely play a role in enabling greater maximum bat speeds to be produced.

The Slog shot displayed four additional unique associations for bat speed including non-dominant grip strength, lower body power, relative maximum upper body pulling strength, and upper body pushing strength. These results may represent a possible interaction between the specific physical and technical demands of Slog shot power hitting. Unlike the fast bat speed sub-group pattern identified above, the additional associations found for the Slog shot did not correspond to an observed increase in bat speed generated with mean maximum Slog bat speed within 1.4 $km \cdot hr^{-1}$ of both Drive and Pull shots. It may be that in this case the technical demands of performing the Slog shot specifically require these additional associated qualities, and that the unique correlations found are in fact discriminants for Slog shot specific power hitting technique.

Finally, this study is the first to show that female batters produce slower maximum bat speeds when facing deliveries with faster ball speeds. Batters on average experienced reductions in maximum bat speed of 8.1% for Cut, 7.6% for Drive, and 11.7% for Pull when facing the Fast delivery condition (100-115 $km \cdot hr^{-1}$) versus Off-Spin (70-80 $km \cdot hr^{-1}$). This is another example of the impact of the technical demands for power hitting, and the first time that the speed accuracy trade-off phenomenon (Fitts, 1992) has been observed for bat speed in the literature. This finding is significant, with multiple applications to take forward. First, for training environments seeking to profile athletes and measure maximum bat speed the Off-Spin and Medium delivery types are sufficient. Second, there may be a tactical advantage in identifying what a specific batter's reduction in swing speed may look like and how this could influence their shot selection versus fast ball speeds in games. Third, targeted strength and power training of the qualities identified above may drive an increase in maximum bat speed capacity, allowing batters experiencing the same technical limitations to generate faster bat speeds when facing faster ball speeds. This would lead to potentially higher ball exit velocities and greater shot distances for Fast deliveries, advantageous for maximising run scoring during matches. Fourth, batters who display small reductions in maximum bat speed across slow and fast deliveries may have higher elite batting ceilings of performance.

Practical applications

Absolute upper body pulling strength, dominant rotational power, and absolute total body isometric strength are important qualities to consider for professional female cricket environments training power hitting. Practitioners seeking to develop evidence-based programs may include these research findings in their strength and conditioning program design to better orient their support of female athletes. The assessment of these qualities allows the description of the physical capacities related to the power hitting profile of both individual athletes and teams. When assessed repeatedly over time the changes observed may provide insight into the effectiveness of programs seeking to enhance bat speed and power hitting performance.

Conclusions

Multiple strength and power capacities exhibited associations with bat speed overall, and to specific shot types in professional female cricketers. These associations explain a significant portion of the total variance in bat speed and demonstrate that physical capacities play a key role in power hitting. Future research should explore these associations with larger sample sizes, as well as how bat speed may be enhanced by training and assessing these qualities and bat speed over time to establish evidence-based methods.

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Chapter Five

Strength and conditioning methods to enhance power hitting performance

Author Note

This thesis chapter has been amended after examination and contains minor differences to the published version of this work.

Abstract

This study assessed the effect of two strength and power training interventions, conventional strength and power (CSP) and supramaximal accentuated eccentric loading (SAEL) on improving bat speed in professional female cricketers. Ten participants completed volume and load matched strength and power training twice weekly for 9 weeks, interspaced by a 12-week washout period of usual care. Physical assessments were completed at weeks 1, 5, and 9, and included maximal bat speed for four different shots including Cut (BS_{cut}), Drive (BS_{drive}), Pull (BS_{pull}), Slog (BS_{slog}), and combined maximal speed overall ($BS_{overall}$), counter-movement jump height (CMJ_{jh}) and peak power (CMJ_{pp}), 10/5 hop test reactive strength index($RSI_{10/5}$), isometric mid-thigh pull (IMTP), medicine ball rotational power (MB_{vel}), one-repetition-maximum bench pull (1RM BP), and bodyweight. Statistical analysis included two-way repeated-measures ANOVA, paired-sample t-tests, Cohen's D effect sizes, Pearson's *r* with Bonferroni correction ($\alpha = 0.0071$) and stepwise linear regression with Akaike Information Criterion evaluation. Significance set at $\alpha = 0.05$ (excluding Pearson's *r*). Bat speed significantly improved during both SAEL (7.9%) and CSP (5.5%) ($F(2,18) = 40.12$, $p < 0.0001$). IMTP (9.13%, 7.83%), BP 1RM (5.76%, 4.54%), and MB_{vel} (3.65%, 4.82%) also improved for SAEL and CSP respectively. No significant difference between interventions was observed (group x time: $F(1,9) = 0.53$, $p = 0.484$). Regression modelling explained 31% of the total variance in the change in bat speed (Adjusted R-squared = 0.3053, Standard Error of the Estimate = 2.04, $p = 0.010$) with BP 1RM as a significant predictor variable. Bat speed is a modifiable capacity in elite female cricketers that changes over time and demonstrates practically relevant relationships to upper body pulling strength, total body isometric strength, rotational power, and bodyweight are important capacities to consider for practitioners seeking to design power hitting training programs.

Introduction

Short format 20-over (T20) cricket is a physically demanding, fast-paced game that is characterised by high intensity efforts during bowling, fielding, and batting (Scott & Herridge, 2018; Sholto-Douglas et al., 2020). Performance analysis of the T20 format has shown that batting is a critical area where winning teams consistently outperform losing teams (Bhardwaj & Dwyer, 2022; Irvine & Kennedy, 2017; Moore et al., 2012; Petersen et al., 2008). Specifically winning teams adopt a batting style to score runs at a faster rate (Irvine & Kennedy, 2017; Moore et al., 2012), produce more boundary scoring shots (either four or six runs, the two highest possible shot scoring options) (Bhardwaj & Dwyer, 2022; Moore et al., 2012), and produce fewer non and single-run scoring shots (the two lowest possible scoring options) during their batting innings (Irvine & Kennedy, 2017).

A popular method that many teams use to target the batting outcomes identified above is power hitting (Douglas & Tam, 2010; Irvine & Kennedy, 2017; McErlain-Naylor et al., 2021) - a batting method where players maximise their scoring rates by hitting the ball with high velocity through the air or along the ground to score boundaries (four or six runs per shot). This method has previously been shown to be effective in both delivering high run rates and impacting match success for both men's and women's T20 cricket (Bhardwaj & Dwyer, 2022; Irvine & Kennedy, 2017; Moore et al., 2012; Najdan et al., 2014). Despite its importance and widespread use, the physical performance determinants of power hitting in cricket are largely unexplored to date.

Previous physical performance research on power hitting has focused on two areas, biomechanical analysis (McErlain-Naylor et al., 2021; Peploe et al., 2018, 2019) and associations to physical capacities (Hardy et al., 2025; Taliep et al., 2010). Three primary outcomes emerge as important foundations to consider. First, that greater shot distances in power hitting are underpinned biomechanically by faster bat speeds in combination with the optimal vertical launch angle for a given shot (Peploe et al., 2018, 2019). Second, that female batters of a comparable playing level display a different kinematic profile and chosen movement solution to male batters during power hitting (McErlain-Naylor et al., 2021). Third, that specific physical capacities of strength and power are strongly associated with bat speed, and for professional female cricketers these include upper body pulling strength, dominant side rotational power, lower body power, and total body isometric strength (Hardy et al., 2025).

The resultant evidence base and subsequent strength and conditioning support for high-performance cricket environments is modest compared to other ball striking sports. Bat speed in baseball and clubhead speed in golf have both been established as modifiable qualities with demonstrated causal relationships to the physical capacities of rotational power (Choi et al., 2017; Szymanski et al., 2009; Szymanski et al., 2007) lower body power (Oranchuk et al., 2020; Shaw et al., 2022; Spaniol et al., 2010; Uthoff et al., 2021), and lower body strength (Oranchuk et al., 2020; Shaw et al., 2022; Szymanski et al., 2011; Szymanski et al., 2009; Szymanski et al., 2007; Szymanski et al., 2006). These findings have led to the generation of strength and power programs within baseball and golf that have been shown to enhance bat speed and clubhead speed respectively (Choi et al., 2017; Oranchuk et al., 2020; Szymanski et al., 2007). The demonstrated efficacy of these programs has led to widespread adoption in high-performance environments, with a number of approaches utilized including general full body strength training (Oranchuk et al., 2020; Uthoff et al., 2021), maximal upper and lower body strength training (Álvarez et al., 2012; Oranchuk et al., 2020), rotational and sport-specific movement medicine ball power training (Choi et al., 2017; Spaniol et al., 2010; Szymanski et al., 2007), barbell Olympic movement power training (Oranchuk et al., 2020), and loaded jump power training (Álvarez et al., 2012; Oranchuk et al., 2020).

A notable training method absent from the evidence base above that is increasingly used in professional sport settings is supramaximal accentuated eccentric loading (SAEL) (Merrigan et al., 2022; Suchomel et al., 2019). SAEL utilizes eccentric loads that are greater than a given strength movement's concentric 1 repetition-maximum (1RM) load. The eccentric phase of the movement is completed with the additional eccentric loading, which is then removed prior to the concentric phase of movement (Merrigan et al., 2022; Suchomel et al., 2019). Previous studies have demonstrated that SAEL is effective in delivering lasting improvements to jump height, velocity, and power in volleyball (Sheppard et al., 2008; Sheppard et al., 2007) as well as eliciting short term enhancements to serve speed in tennis (Baiget et al., 2025). The ability of SAEL to improve these power-based actions is underpinned physiologically by the method's unique leveraging of eccentric force generation capabilities (Brandenburg & Docherty, 2002; Wagle et al., 2017) in combination with high threshold motor unit recruitment (Brandenburg & Docherty, 2002) to elicit a potent elastic potentiation response (Komi, 1984; Merrigan et al., 2022; Wagle et al., 2017). These mechanisms combine to enable greater concentric or propulsive movement outputs (Merrigan et al., 2022), allowing athletes to train explosive movements at a higher intensity and drive concurrent strength and power adaptations to enhance performance. This ability is highly favourable within the context of bat speed in female cricketers where there are strong associations to upper body strength, rotational and lower body power, and total body isometric strength. Considering both the alignment of SAEL's physiological mechanisms to enhance strength and power qualities, and the previous evidence for the method in improving the full body explosive power tasks of jumping in volleyball and serving in tennis, it is plausible that SAEL could be effective in enhancing bat speed in cricket.

To progress training efficacy in professional female cricket environments, establishing the modifiable potential of bat speed and its casual physical capacities is required. This study therefore sought to establish whether bat speed in professional female cricketers is a modifiable quality through a training intervention, determine which if any of rotational power, upper body pulling strength, and total body isometric force have a causal relationship with bat speed, and, in comparison to traditional strength and power training, examine the efficacy of SAEL as the potentially preferred method to enhance bat speed and power hitting performance.

Methods

Experimental approach to the problem

This study was designed to assess the effect of two strength and power interventions; conventional strength and power (CSP) and supramaximal accentuated eccentric loading (SAEL) on improving bat speed in professional female cricketers. Participants completed both interventions using a crossover randomised controlled trial design. Each intervention was completed over a 9-week period with strength, power, anthropometry, and bat speed assessments at weeks 1, 5, and 9. Between each intervention participants completed a 12-week washout period of usual care programming within their professional sport environment.

Subjects

This study utilized a convenience sample of professional female cricketers due to their availability as part of the Cricket NSW senior women's team. Ten full-time professional cricketers volunteered to participate in this study (mean ± *SD*: age 24.65 ± 4.69 years, height 171.8 ± 7.1 cm, body mass 69.7 ± 9.0 kg, professional experience 6.30 ± 4.42 years) between May 1st 2023 and December 1st, 2024. Participants were included in the study if they were a senior professional female cricketer and free from injury. This study was approved by the University of Sydney Human Research Ethics Committee (Project Number 2023/HE000266), and prior to providing written informed consent all participants were presented with the full information of the research project including the study protocol and the benefits and risks of volunteering.

Procedures

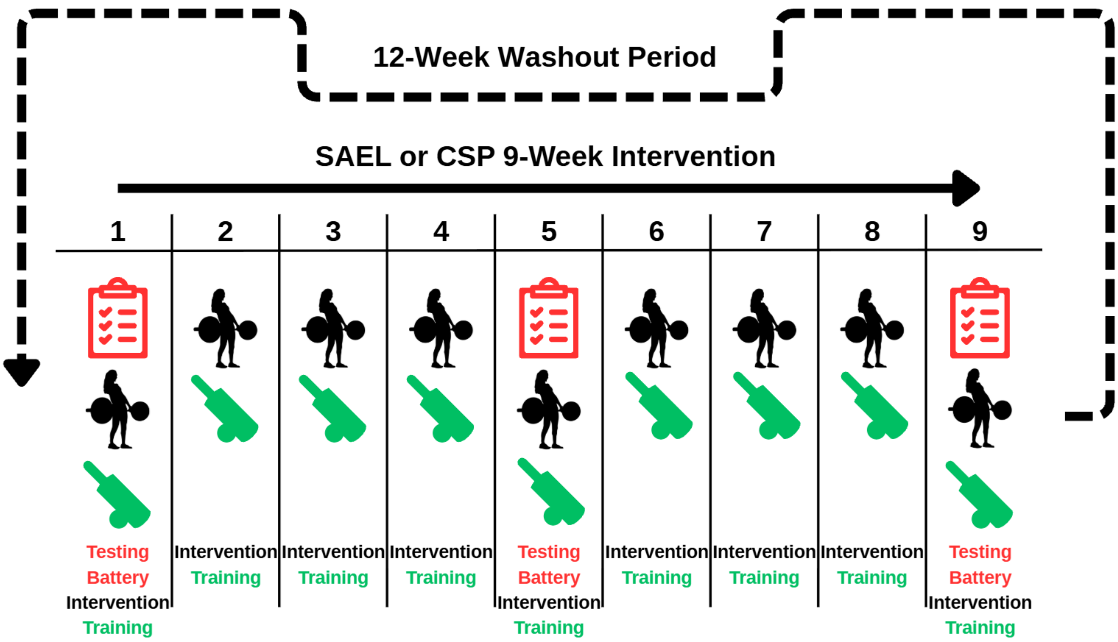
Overview

This study was embedded within the Cricket New South Wales (CNSW) professional women's team high-performance program and took place during the 2023-24 and 2024-25 seasons across the preseason and in-season periods. The study utilized a randomised two-group cross-over design and a 9-week intervention period, the duration of which was chosen to be in line with previous evidence for the required training program length to elicit meaningful change in strength and power capacities (Cormie et al., 2011; Marshall et al., 2021; Merrigan et al., 2022; Newton et al., 2006). Participants were randomly allocated either to CSP or SAEL intervention groups.

Timeline

The first intervention was delivered during the final 9 weeks of the preseason period for each year 2023 and 2024. This was followed by a 12-week washout period where all participants completed the normal requirements of the CNSW high-performance program. The second intervention was then delivered over a 9-week period during in-season. Attendance for all sessions throughout the intervention and washout periods was recorded, with all participants completing all sessions. A full timeline diagram can be seen at Figure 1. For the entire 30-week duration of the study the CNSW high-performance programming was comprehensive across a full-time Monday to Friday schedule and included aerobic conditioning, speed development, strength and power training, technical skill training, and match simulation or match play. A detailed breakdown of the weekly schedule can be found in the supplementary content.

Figure 1. Study design diagram including weekly content, duration, and washout period



Intervention Design

Due to the nature of the professional sport setting a conventional strength and power control group was utilized in place of a pure control group. The delivery of an intervention design where professional athletes were completely excluded from all aspects of high-performance training for the duration of the study was not possible, and the implementation of the CSP group was a key ethical priority of the study to ensure that the professional athletes volunteering all received equal benefit through participation.

The CSP and SAEL interventions were volume, load, and intensity matched to be equivalent programs that utilised different strength methods to target the same physical capacities of upper body pulling strength, and total body force production. Previous research has shown that equivalent improvements in strength are elicited through supramaximal eccentric loading at 120% 1RM and traditional concentric strength training at 85-90% 1RM using the same set and repetition (rep) schemes (Kataoka et al., 2024; Merrigan et al., 2022; Wagle et al., 2021; Wagle et al., 2017). For this reason, the primary upper and lower body strength movements across the two interventions (A1 and B1 in Tables 1 and 2) were prescribed at fixed intensities of 120% 1RM for SAEL and 87% 1RM for CSP to match intensity and subsequent strength improvement. Exposure to these intensities was controlled by using identical set and rep schemes at 3 x 5 for both programs. Both programs utilized equivalent major upper strength movements. The Barbell Bench Pull and Barbell Bent Over Row exercises are both horizontal upper-body pulling movements with demonstrated evidence of comparable movement patterns, joint angles, and force-velocity characteristics in training (Nieto-Acevedo et al., 2023). The lower body strength movements comprising of the Barbell Rack Pull and Barbell Front ½ Squat (to box above knee) were chosen primarily because of their high strength capacity as heavy partial-range exercises. This was a key consideration to ensure that participants would be exposed to the same intensity of lower body load in both interventions. Previous research has also shown that both the rack pull and front squat prtial range exercises elicit equivalent improvements in lower body force production (Nigro & Bartolomei, 2020). The Trap Bar Countermovement Jump and Kettle Bell Speed Squat used identical load at 30% of bodyweight and were both performed using an explosive concentric movement pattern, with the key differences being no controlled eccentric lower or jump for the CSP kettle speed squat. Rotational medicine ball work and bodyweight jumping was identical across both interventions. In terms of whole program design both interventions employed identical set and rep schemes to ensure equivalent exposure to the matched load and intensity of each exercise. All other components of physical training outside of the strength and power programs were delivered identically with matched volumes and loads for all participants across both groups. The CSP and SAEL interventions were completed twice per week on Tuesdays and Fridays during the team's scheduled strength and power training sessions. The strength and power interventions were designed to enhance bat speed by improving upper body pulling strength, rotational power, total body force production, and lower body power. To achieve this both CSP and SAEL programs used a contrast resistance training framework (Seitz & Haff, 2016) where specific combinations of exercises were performed in supersets starting with a high load resistance exercise directly followed by a high velocity plyometric exercise. Contrast training was specifically selected because of the method's established ability to produce improvements in both upper and lower body strength and power using a compact and time efficient framework (Ritchie et al., 2020; Seitz & Haff, 2016).

Within the contrast training framework the SAEL group performed the high load resistance exercises using accentuated eccentric loading at 120% of participants' 1RM scores for Barbell Bench Pull and Rack Pull, and 30% of participant's body weight for loaded jumping (Merrigan et al., 2022; Suchomel et al., 2019). The CSP group used traditional heavy dynamic strength training at 87% of participants 1RM scores for Barbell Bent Over Row and ½ Front Squat (to box above knee) (Thompson et al., 2020), a kettlebell speed squat at 30% of participants' body weight was also programmed to match the loaded jumping content in the SAEL intervention. The rotational power, and bodyweight jumping components of both programs was kept the same. The program prescription of intensity for all movements was static across the 9-week intervention periods with no progression. A detailed breakdown of both programs can be seen below in tables 1 and 2.

Table 1: SAEL contrast training program including exercise order, name, prescribed load, sets, reps (es = each side), rest, and physical capacity targeted. Completely twice weekly.

Order	Exercise	Load	Sets	Reps	Rest	Target Capacity
A1	Barbell Bench Pull Eccentric Lower (partner assisted concentric)	120% of 1RM	3	5	Move immediately to A2	Upper body maximum strength
A2	Rotational Medicine Ball Push (heavy ball)	4kg	3	3es	Move immediately to A3	Rotational power
A3	Rotational Medicine Ball Push (light ball)	1kg	3	3es	90 seconds	Rotational power
B1	Barbell Rack Pull Eccentric Lower (partner assisted concentric)	120% of 1RM	3	5	Move immediately to B2	Total body force production

B2	Trap Bar Eccentric Lower Countermovement Jump	30% of BW	3	5	Move immediately to B3	Lower body power
B3	Bodyweight Countermovement Jump	BW	3	15	90 seconds	Lower body power

Table 2: CSP contrast training program including exercise order, name, prescribed load, sets, reps (es = each side), rest, and physical capacity targeted. Completely twice weekly.

Order	Exercise	Load	Sets	Reps	Rest	Target Capacity
A1	Barbell Bent Over Row	87% of 1RM	3	5	Move immediately to A2	Upper body maximum strength
A2	Rotational Medicine Ball Push (heavy ball)	4kg	3	3es	Move immediately to A3	Rotational power
A3	Rotational Medicine Ball Push (light ball)	1kg	3	3es	90 seconds	Rotational power
B1	Barbell Front ½ Squat (to box above knee)	87% of 1RM	3	5	Move immediately to B2	Total body force production
B2	Kettle Bell Speed Squat	30% of BW	3	5	Move immediately to B3	Lower body power

B3	Bodyweight Countermovement Jump	BW	3	15	90 seconds	Lower body power

Physical Capacity Assessments

A physical testing battery was completed in weeks 1, 5 and 9 in each of the 9-week intervention periods. Testing was completed over 3 separate sessions, with a specific warm up routine completed each day (see supplemental content) to prepare them for the appropriate physical testing. Day 1 assessed bodyweight, height, and maximal bat speed for four different shots including Cut (BS_{cut}), Drive (BS_{drive}), Pull (BS_{pull}), Slog (BS_{slog}), and combined maximal speed overall ($BS_{overall}$). Day 2 assessed Countermovement Jump (CMJ), Isometric Mid-Thigh Pull (IMTP), 10/5 Hop Reactive Strength Index ($RSI_{10/5}$), and Rotational Power Medicine Ball Push (MB_{vel}). Day 3 assessed 1-Repetition Maximum Bench Pull (BP 1RM). To enable accurate prescription of SAEL and CSP programs, load assessments of 5-Repetition Maximum (5RM) Front ½ Squat (to box above knee), 5RM Barbell Rack Pull, and 5RM Barbell Bent Over Row were also completed within the first week during the SAEL and CSP training sessions for all participants. 5RM assessments were specifically chosen for these movements due to participants' limited previous experience in completing 1RM testing for Front ½ Squat (to box above knee), Barbell Rack Pull, and Barbell Bent Over Row.

Week 1, 5, 9 Day 1

Participants completed anthropometric measures of bodyweight and height, a Day 1 warm-up routine (supplemental file), and then the following assessment:

Bat Speed. Bat speed was evaluated using a bat mounted sensor (Blast Baseball, Blast Motion Inc. San Marco, CA) shown to be valid for use in elite women's cricket (Freeston et al., 2025). Maximal speeds for the four shot types Cut, Drive, Pull, and Slog were determined using the protocol developed from our previous work. The authors note that the Fast (100-110 km·hr^{-1}) delivery type assessment was removed for this research project in line with previous findings showing the speed inclusion to be redundant when assessing maximum bat speed. The maximum bat speeds in km·hr^{-1} for BS_{cut}, BS_{drive}, BS_{pull}, BS_{slog}, and the maximum speed overall across the four shots $BS_{overall}$ were recorded for further analysis. CV = 0.9%, SEM = 0.25 km·hr^{-1}

Week 1, 5, 9 Day 2

Participants completed a Day 2 warm-up routine (supplemental file) and then the following assessments:

Countermovement Jump. Lower body power was assessed following the published protocol (Barker et al., 2018) using a Force Decks FD4000 dual force plate system (Vald Performance, Brisbane, QLD, Australia). The highest scores for peak power (CMJ_{pp}) measured in Watts (W) and for jump height (CMJ_{jh}) in centimetres (cm) derived from impulse-momentum were recorded for further analysis. CMJ_{pp} CV = 2.9%, SEM = 27.89W, CMJ_{jh} CV = 0.6%, SEM =0.05cm

10/5 Hop Test. RSI was assessed using the published protocol (Harper et al., 2011), and a Force Decks FD4000 dual force plate system (Vald Performance, Brisbane, QLD, Australia). Maximum peak RSI was recorded for further analysis. CV = 3.8%, SEM = 0.04

Isometric Mid-Thigh Pull. Total body isometric strength was determined using the published protocol (Comfort et al., 2019) using a Force Decks FD4000 dual force plate system (Vald Performance, Brisbane, QLD, Australia) and isometric Vald Performance testing rig. The highest force measured in Newtons (N) was recorded for further analysis. CV = 2.4%, SEM = 22.10N

Medicine Ball Rotational Push. Rotational power was determined using the published protocol (Hardy et al., 2024), a 2-kilogram medicine ball and a radar gun (Stalker ProIIs, Applied Concepts Inc., Plano, TX). The maximum speed for dominant side push in $km \cdot hr^{-1}$ was recorded for further analysis. CV = 2.3%, SEM = 0.28 $km \cdot hr^{-1}$

Week 1, 5, 9 Day 3

Participants completed a Day 3 warm-up routine (supplemental file) and then the following assessments:

Bench Pull. Upper body maximum pulling strength was assessed using the prone laying bench pull protocol (Lum & Aziz, 2020) and the established 1 repetition maximum (1RM) framework (Seo et al., 2012) The maximum weight successfully lifted, measured in kilograms (kg), was recorded for further analysis, and for use as input values for the percentage RM intervention program loads. CV = 2.5%, SEM = 0.45kg

Statistical Analysis

All statistical analysis was completed using R (version 4.2.3, Boston, MA). All outcome data were checked for normality using Shapiro-Wilk testing before the mean and standard deviation (SD) were calculated. The effects of time across baseline (Week 1), intermediate (week 5), and post (week 9), and intervention group between SAEL and CSP were assessed using a two-way repeated measure ANOVA. Change scores for all outcome variables were calculated as post (week 9) minus baseline (week 1). Changes were then quantified for both groups (SAEL, CSP) using Cohen's (*d*), and percentage change. Effect sizes were described as trivial (*d* = 0.0-0.19), small (*d* = 0.2-0.59), moderate (*d* = 0.6-1.19), large (*d* = 1.2-1.99), very large (*d* = 2.0-3.99), or extremely large (d ≥ 4.0) (Hopkins et al., 2009). Effect of intervention order was assessed by linear regression of the change in bat speed versus order. Effect of intervention type on change in all physical capacities was assessed via paired-sample t-tests comparing the change in SAEL versus CSP. Associations between change in bat speed overall and change in bodyweight, and strength and power assessments were calculated using Pearson's (*r*). Associations were described as trivial (r=0.0-0.09), small (r=0.1-0.29), moderate (r=0.3-0.49), large (r=0.5-0.69), very large (r=0.7-0.89), or nearly perfect (r=0.9-0.99) (Hopkins et al., 2009). Bonferonni *p*-value corrections (Lydersen, 2024) were applied to Pearson's *r* associations with an adjusted significance set to α = 0.0071. Stepwise linear regression modelling using backward and forward directional approaches was completed on the change score dataset for change in bat speed overall as the outcome variable. Models were compared by the Akaike Information Criterion (AIC), and the model with the lowest value for AIC was selected in line with previous sport science research (Woods et al., 2015). The Coefficient of Variation (CV) and Standard Error of Measurement (SEM) were calculated for all assessments. Significance for all analyses excluding Pearson's *r* associations was set to a priori at α = 0.05.

Results

Overall, bat speed significantly improved for both interventions from week 1 to 9with increases in speed of 7.9% and 5.5% for SAEL and CSP groups respectively, showing time to have a significant main effect ($F(2,18) = 40.12$, $p < 0.001$). The observed increase was similar between interventions as evidenced by the lack of group x time effect ($F(1,9) = 0.53$, $p = 0.484$). Comparisons of the testing results for both interventions can be found in Tables 3a and 3b where bat speed and physical measures are respectively compared. Attendance for all sessions throughout the intervention and washout periods was recorded, with all participants completing all sessions.

Table 3a. SAEL and CSP intervention group mean and standard deviation (SD) at weeks 1 and 9, for outcome measures of bat speed assessments, group mean percentage change (Δ%) between weeks 1 and 9, cohen's *(d)* effect size, lower and upper confidence intervals (LCI, UCI).

	Supramaximal Accentuated Eccentric Loading						**Conventional Strength and Power**					
Assessment	***Wk 1***	***Wk 9***	***Δ%***	***d***	***LCI***	***UCI***	***Wk 1***	***Wk 9***	***Δ%***	***d***	***LCI***	***UCI***
Bat Speed Overall ($km{\cdot}hr^{-1}$)	82.2 (4.9)	88.8 (6.4)	7.93	0.91*	0.59	1.23	85.1 (7.7)	89.6 (6.9)	5.5	0.60*	0.30	0.89
Cut ($km{\cdot}hr^{-1}$)	75.8 (5.9)	78.4 (6.6)	3.47	0.38	-0.04	0.80	78 (6.7)	80.3 (6.4)	3.14	0.35	-0.89	0.30
Drive ($km{\cdot}hr^{-1}$)	76.5 (4.4)	80.9 (4.6)	5.95	0.99	-0.04	2.02	76.3 (8.3)	77 (6.2)	1.68	0.09	-0.84	0.64
Pull ($km{\cdot}hr^{-1}$)	82.1 (4.9)	86.3 (6.5)	5.13	0.53*	0.17	0.89	83.7 (7.9)	86 (6.6)	2.93	0.28*	0.03	0.53
Slog ($km{\cdot}hr^{-1}$)	79.6 (4.1)	83.7 (5.4)	5.08	0.61*	0.13	1.08	83.6 (7.5)	86.4 (8.3)	3.44	0.35	-0.03	0.74

* = $p < 0.05$

Table 3b. SAEL and CSP intervention group mean and standard deviation (SD) at weeks 1 and 9, for outcome measures of anthropometric, strength, and power assessments, group mean percentage change (Δ%) between weeks 1 and 9, cohen's (*d)* effect size, lower and upper confidence intervals (LCI, UCI).

	Supramaximal Accentuated Eccentric Loading						Conventional Strength and Power					
Assessment	***Wk 1***	***Wk 9***	***Δ%***	***d***	***LCI***	***UCI***	***Wk 1***	***Wk 9***	***Δ%***	***d***	***LCI***	***UCI***
Bodyweight (kg)	69.6 (9.5)	70.4 (9.1)	1.11	0.06*	0.01	0.12	69.4 (9)	69.8 (9.8)	0.55	0.04*	0.01	0.12
BP 1RM (kg)	56.2 (7.72)	58.7 (7.16)	5.76	0.41*	0.30	0.52	56.2 (8.58)	58.6 (7.96)	4.54	0.27*	0.13	0.42
CMJ_{jh} (cm)	26.7 (4.8)	27.5 (4.3)	3.36	-0.16	-0.06	0.39	27.5 (3.5)	27.2 (4.9)	-1.40	-0.05	-0.21	0.32
CMJ_{pp} (W)	2973 (468)	3130 (414)	6.41	0.35*	0.15	0.55	3038 (423)	3056 (458)	0.48	0.04	-0.10	0.18
IMTP (N)	2820 (385)	3035 (389)	9.13	0.65*	0.40	0.89	2793 (335)	3011 (395)	7.83	0.55*	0.28	0.82
MB_{vel} (km·hr^{-1})	38.1 (2.4)	38.9 (2.4)	3.65	0.54*	0.37	0.71	38.11 (1.8)	40 (2.3)	4.82	0.73*	0.48	0.98
$RSI_{10/5}$	2.92 (0.4)	2.97 (0.4)	2.18	0.11	-0.36	0.57	2.98 (0.5)	2.99 (0.35)	0.88	0.01	-0.29	0.26

* = $p < 0.05$

Both SAEL and CSP interventions comparably increased total body isometric strength (9.13% vs. 7.83%), upper body pulling strength (5.76% vs. 4.54%), and rotational power (3.65% vs. 4.82%). There was no significant statistical difference between the magnitude of these changes between interventions; total body isometric strength ($t(9) = 0.42$, $p = 0.68$), upper body pulling strength ($t(9) = 1.00$, $p = 0.35$), rotational power ($t(9) = -1.44$, $p = 0.18$). SAEL generated a larger increase in lower body peak power compared with CSP, (6.41% vs. 0.48%), ($t(9) = 2.57$, $p = 0.03$). The full comparison of physical measures for SAEL and CSP interventions can be found in Table 3b, and the comparison of intervention change data can be found in table 4.

Table 4. Change Scores (Δ) between weeks 1 and 9 for SAEL and CSP interventions ΔSAEL, ΔCSP, the difference between intervention change score ΔSAEL – ΔCSP, t statistic, *p*-value for outcome measures of all anthropometric, strength, power, and bat speed assessments.

	Intervention Change Scores				
Assessment	***ΔSAEL***	***ΔCSP***	***ΔSAEL - ΔCSP***	***t*(9)**	***p***
Bodyweight (kg)	0.706	0.433	0.273	0.407	0.693
Bat Speed Overall ($km{\cdot}hr^{-1}$)	6.563	4.534	2.029	1.529	0.161
Cut ($km{\cdot}hr^{-1}$)	2.621	2.267	0.354	0.19	0.854
Drive ($km{\cdot}hr^{-1}$)	4.354	0.693	3.661	1.255	0.241
Pull ($km{\cdot}hr^{-1}$)	4.281	2.285	1.996	1.165	0.274
Slog ($km{\cdot}hr^{-1}$)	4.098	2.808	1.29	0.701	0.501
CMJ_{pp} (W)	174.1	18.1	156	2.567	0.030*
CMJ_{jh} (cm)	0.78	–0.280	1.06	1.034	0.328
$RSI_{10/5}$	0.046	0.007	0.039	0.293	0.776
IMTP (N)	247.3	218.9	28.4	0.423	0.682
MB_{vel} ($km{\cdot}hr^{-1}$)	1.38	1.85	–0.470	–1.442	0.183
BP 1RM (kg)	3.15	2.4	0.75	0.995	0.346

* = $p < 0.05$

The change in bat speed overall was positively association with the change in absolute upper body pulling strength (BP 1RM; large r = 0.58, p = 0.006). The full set of associations between changes in bat speed overall and physical capacities can be found in table 5.

Table 5. Correlation statistics of Pearson's correlation (*r*) and p-value (*p*) for change (Δ) in bat speed overall versus change in anthropometric, strength, power, and bat speed assessments.

	ΔBat Speed Overall	
Assessment	***r***	***P***
ΔBodyweight (kg)	0.46	0.040
ΔCMJ_{pp} (W)	0.43	0.060
CMJ_{jh} (cm)	-0.01	0.97
$\Delta RSI_{10/5}$	-0.12	0.62
ΔIMTP (N)	0.45	0.045
ΔMB_{vel} ($km \cdot hr^{-1}$)	0.14	0.56
ΔBP 1RM (kg)	0.58	0.006*

* = p < 0.0071

Multiple regression modelling using a forward selection approach explained 31% of the total variance in the change in bat speed overall (F(1, 18) = 9.35, Adjusted R-squared = 0.3053, Standard Error of the Estimate = 2.04, p = 0.010). The forward selection approach where predictor variables were assessed individually before being sequentially added to improve the model demonstrated the lowest AIC value (forward= 96.80, backward = 103.40). The model converged on a single predictor solution that retained BP 1RM as the only variable (Equation 1). Intervention order was shown to have no significant effect on the change in bat speed overall, (F(1, 8) = 1.15, p = 0.3 14).

Equation 1: Linear Regression Model of Change in Bat Speed Overall

$$Change\ In\ Bat\ Speed = 2.40 + (1.14 * 1RM\ BP)$$

Discussion

This is the first study to demonstrate that maximal bat speed is a modifiable capacity in elite female cricketers. Over the 9-week periods both interventions comparably improved bat speed overall, with SAEL and CSP driving increases of 7.93% (d = 0.91) and 5.50% (d = 0.60) respectively (Table 3a). While no cricket comparisons are possible, these changes and effect sizes are larger than those seen previously both in female golf and male baseball research where 12-week strength and conditioning interventions elicited clubhead speed improvements of 3.4 – 3.5% (d = 0.59 – 0.63) in collegiate and professional female golfers (Doan et al., 2006; Kwang Jun, 2010), and 12-week resistance and batting skill interventions resulted in bat speed increases of 3.2 – 6.4% in male high school baseballers (Szymanski et al., 2007; Szymanski et al., 2006; Szymanski et al., 2010). The larger changes seen in this study for bat speed across a shorter intervention period of 9 weeks are likely due to differences in strength and conditioning intervention methodology including the prescription of greater percentage one-repetition-maximum (%1RM) intensities for strength movements and the use of the contrast training framework for session design. Previous baseball research used lower training intensities than the current study (Weeks 1-4 65%, 70%, 75% 1RM, weeks 5-8 70%, 75%, 80% 1RM, and weeks 9-12 75%, 80%, 85% 1RM; (Szymanski et al., 2007; Szymanski et al., 2006; Szymanski et al., 2010). The golf intervention by Doan et al. (2006) did not prescribe any intensities, and the remaining intervention by Kwang Jun (2010) used the following progression: Weeks 1-4 60% 1RM, weeks 5-8 65% 1RM, and weeks 9-12 70% 1RM. Additionally, all of the previous programs used strength-only program sequences for sessions with power work either completed at the end of training or as a separate session. In comparison, this study prescribed 87% and 120% of 1RM for strength movements for weeks 1-9 during the CSP and SAEL interventions and integrated all power exercises into a combined contrast training session designed to leverage the post-activation potentiation of heavy strength training to maximise power adaptations (Seitz & Haff, 2016). In combination the greater intensity and use of integrated training through the contrast framework provide a plausible argument as to why larger improvements for bat speed were seen for this study. Considering the broader context of the established evidence bases for ball-striking sports outside of cricket, the changes seen for bat speed in this study also hold important implications for future performance programs. The findings suggest bat speed in elite female cricket may behave similarly to bat and clubhead speed in baseball and golf as a modifiable and therefore trainable capacity. For elite female cricket environments, two critical applications emerge (i) That with appropriate training programs practitioners can manipulate and enhance bat speed at specific periods of the year to coincide with competition performance demands, and (ii) that longitudinal changes in bat speed are possible through training to enable greater levels of hitting performance.

From a physical capacities perspective, the findings for maximum upper body pulling strength in this project are compelling and provide the foundation for a causal relationship to bat speed. 1RM BP improved similarly across both interventions by 4.54-5.76%, (d = 0.27-0.41), this improvement demonstrated a large significant association (r = 0.58, p = 0.006) to the improvement seen for bat speed, and multiple regression modelling showed that upper body pulling strength as a single predictor variable was able to explain 31% of the total variance in the change in bat speed. These results are consistent with the previous physical capacities research where 1RM BP demonstrated a very large association (r = 0.70, p < 0.0001) to bat speed in 29 elite female cricketers (Hardy et al., 2025). They are also aligned with prior biomechanical research which highlights the unique contribution of the upper body flexors to power hitting kinematics in female batters who opt to flex their lead elbow during downswing (McErlain-Naylor et al., 2021). In combination, these results alongside the findings in the current study suggest that a causal relationship between upper body pulling strength and bat speed in elite female cricketers is likely to exist. Whilst further research should explore the longitudinal changes in upper body pulling strength and bat speed across multiple seasons to determine the stability of this relationship, there are significant implications for practitioners seeking to enhance or maintain bat speed at different periods of the year, as well as a potentially novel application in talent identification. It is feasible that during phases of low batting training exposure such as the off-season and preseason where limited power hitting batting training may undermine bat speed capacity in athletes, practitioners may maintain or elicit improvements in bat speed by targeting upper body pulling strength through physical programming. Upper body pulling strength profiling via 1RM BP may also be used as a potential talent identification tool to help uncover batters who have high upper body pulling strength and potentially high bat speed capacity. These applications together highlight the likely central role of upper body pulling strength in underpinning bat speed for elite female cricketers going forward.

The findings for the physical qualities of bodyweight, total body isometric strength, and lower body power are also important to consider. Whilst the changes in these qualities were not statistically associated to the change in bat speed, we believe that the Pearson's *r* findings demonstrate practically relevant relationships that align with ball-striking research outside of cricket, and that in the case of this study did not demonstrate significance due to sample size and lack of power. The change in bodyweight ($r = 0.46$, $p = 0.04$) showed a moderate association to the change in bat speed and is aligned with previous work in baseball where moderate relationships were demonstrated between bat velocity and body mass ($r = 0.37$-0.44) (Szymanski et al., 2010). Given the demonstrated improvements in upper and lower body strength assessments in this study, it is plausible that bodyweight is acting as a proxy for lean mass which would increase with progressive gains in strength. The change in total body isometric strength (r = 0.45, *p* = 0.045) also demonstrated a moderation association to the change in bat speed. This finding is aligned with previous work in cricket and golf, where moderate to large (*r* = 0.38-0.62) associations between total body isometric strength and bat or clubhead speed have been identified (Hardy et al., 2025; Robinson et al., 2024). These findings have been linked to the ability of athletes to maximally apply force to the ground as part of ground up energy transfer through the kinetic chain during hitting movements (Hellstrom, 2009; Szymanski et al., 2009; Wells et al., 2020). Finally, the change in lower body power showed a moderate association to the change in bat speed (r = 0.43, *p* = 0.06). This is consistent with previous golf research where a large association was seen between clubhead speed and peak power (Robinson et al., 2024). Given the nature of power hitting as a full-body explosive ball-striking task there is clear rationale for the link between lower body peak power and bat speed in cricket. Bodyweight, total body isometric strength, and lower body power all present plausible arguments from the established evidence bases within baseball and golf, and the emerging evidence base within cricket to not be excluded from consideration for power hitting performance in elite female cricketers. Whilst the current study could not confirm the statistical significance of these qualities due the constrained design and small sample, the prior evidence in combination with the sport science rationale suggests that bodyweight, total body isometric strength, and lower body power may form an important part of power hitting performance in elite female cricket and further research is required to fully understand their roles.

The exercise content of both the SAEL and CSP interventions was highly similar by design to ensure equal benefit for all participants. This is largely reflected in the results for changes to physical capacities in Table 3b where bodyweight, upper body pulling strength, total body isometric strength, and rotational power demonstrated a difference in improvement of between 0.55% and 1.3% across both interventions. This finding suggests that the CSP program design was effective in matching the chosen movements, volume, and intensity of the SAEL intervention for these qualities. However, this was not the case for lower body power where SAEL significantly outperformed CSP eliciting an improvement of 6.41% vs. 0.48% for CMJ_{pp} ($t(9) = 2.57$, $p = 0.03$). Given that both interventions employed volume and load matched doses of lower body strength and power, the difference may be due to SAEL's superior ability to elicit high concentric and propulsive outputs via elastic potentiation (Komi, 1984; Merrigan et al., 2022; Wagle et al., 2017), subsequently driving greater changes to lower body power compared to the CSP intervention. This is in line with previous work in volleyball where the SAEL method improved lower body power by an additional 9.4% - 20.0% compared to conventional training (Sheppard et al., 2008; Sheppard et al., 2007). It is unclear as to why SAEL did not produce a larger change for upper body pulling strength and rotational power given that the same physiological rationale above would apply. It is likely that the short length and low sample of this study precluded the effect on upper body strength and power from being detected, and that with greater numbers over a larger intervention the same physiological principles would lead to superior results. Whilst further research is needed to fully understand the efficacy of SAEL in female athletes, this study demonstrates that the method is superior to conventional strength training for the development of lower body power in elite female cricketers.

The decision to design this study without a control group was a constraint resulting from the choice to conduct this study as an embedded project within the senior professional CNSW women's high-performance program. Using a senior professional cohort of cricketers was critical to ensure that the batting skill level assessed was representative of professional women's cricket. Batting at the professional level is a complex and demanding task, and previously it has been demonstrated that significant skill differences exist for amateur versus professional female batters (McErlain-Naylor et al., 2021). Therefore, in order to deliver research outcomes that would be applicable for practitioners within professional female cricket environments the choice was made to embed the study at CNSW. In considering our results, it is likely that the strength and power intervention designs were too similar to detect differences, especially given our sample size. This limitation is inherent to the professional sport setting where practitioners have an ethical obligation to deliver best practice performance support and ensure that program design benefits all athletes equally. Alongside this, it is also important to recognise the additional environmental constraints of conducting research within professional female sports (Cowley et al., 2021; Munro & Christie, 2018). In particular, the small squad sizes of professional female teams such as state cricket where there are 16 senior women's team contracts provides a significant limitation in generating large samples for sport science research (Munro & Christie, 2018). A possible solution to this for future studies could be to coordinate multi-site research partnerships. Within the Australian domestic cricket system this has previously been achieved through a national testing battery for senior programs where states have opted to pilot new bespoke women's physical performance assessments. With the right intervention design and testing framework it is plausible that a multi-site intervention approach could work and allow the recruitment of much larger professional female cricket cohorts such as 50-60 athletes.

We recognise that without a pure control group present within the study design it could be argued that the 5.50-7.93% improvements seen in bat speed were due to components of the high-performance training program outside of the strength and power interventions.

However, considering the physical demands of power hitting as a full body explosive striking task, the broader context of bat and clubhead speed research in rotational hitting sports outside of cricket, and the emerging evidence identifying associations between changes in strength and power capacities and changes in bat speed in this research project, this hypothesis seems unlikely. Therefore, whilst we recognise that the results from this study are not able to establish causal links between physical capacities and bat speed, nor can they determine which of SAEL or CSP is the preferred strength and power training method for bat speed, this research does generate a foundation for future projects to more fully explore this area.

This is the first study to investigate the enhancement of bat speed through strength and power interventions in professional female cricketers. The choice to design and deliver this study embedded within a professional setting resulted in the key benefit of access to a genuinely elite population of female batters. This choice also clearly impacted our sample size within the broader context of statistical analysis. The authors acknowledge that the Cohen's *d* effect size, Pearson's *r* correlation, and linear regression modelling aspects of this analysis are underpowered and require minimum sample sizes of 126 participants to detect effect sizes greater than or equal to $d = 0.50$, and 29 participants to detect correlations greater than or equal to $r = 0.50$ (Hopkins et al., 2009). We recommend that a degree of caution be used when interpreting these preliminary findings in different applied settings. However, in line with previous elite sport research publications with small sample sizes (Doan et al., 2006; Joyce, 2017; Kwang Jun, 2010; Oranchuk et al., 2020; Uthoff et al., 2021) informing parts of applied practice in elite settings and establishing directions for future research projects, it is our opinion that the findings from this project contribute to best practice support of elite female cricket environments. The clear progression on this work will be to design a more robust and powerful study potentially across multiple sites that is capable of effectively discriminating the different contributions of physical training to enhancing bat speed and establishing a set of methods to maximise bat speed and power hitting performance for professional cricketers.

Practical applications

Bat speed is a modifiable capacity in elite female cricketers that changes over time. Upper body pulling strength, total body isometric strength, rotational power, and bodyweight are important capacities to consider for practitioners seeking to design power hitting training programs. Appropriate high-performance training programs across strength and conditioning and technical skills can enhance bat speed at specific periods of the year to coincide with competition performance demands. Longitudinally bat speed can be trained and maximised for individual athletes and teams year on year to enable greater levels of hitting performance.

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Chapter Six

Discussion

Thesis Aims

The purpose of this thesis was to enhance the standard of strength and conditioning support for professional women's cricket by exploring the key area of batting performance through bat speed and establishing an evidence base for the physical determinants of power hitting performance. Despite the evidence that winning teams in short format cricket are differentiated by batting performance and that, specifically, winning teams utilize batting methods such as power hitting to score more runs at a faster rate than their opposition, there is insufficient research to enable an evidence-informed approach to maximising hitting performance in professional female environments (Bhardwaj & Dwyer, 2022; Douglas & Tam, 2010; Haworth & Mills, 2024; Irvine & Kennedy, 2017; McErlain-Naylor et al., 2021). This thesis presents four studies which collectively address this gap, including the validation of a bat-mounted sensor to assess bat speed, the establishment of validity and reliability of a novel rotational power test, evidence for the association between strength and power capacities and bat speed, and evaluation of the efficacy of conventional and specific strength and power interventions to enhance bat speed.

Measuring Bat Speed

The ability to accurately measure bat speed in the field without the requirements of a biomechanics laboratory and three-dimensional optical motion capture (MoCap) was critical to the success of this thesis. No previous research within cricket had explored the sensor-based measurement of bat speed, with all preceding projects relying on laboratory-based study designs. Whilst laboratory measures of bat speed using MoCap are the gold standard for accuracy, a lab-based study design presented multiple barriers including a high time-cost for participants, restricted testing availability to align off-site lab sessions with the full-time professional cricket program, and low practical relevance for expert batting coaches who perceived the laboratory setting as non-representative of elite level batting training and performance. Additionally, within the contexts of professional women's sport and elite sport more broadly small sample sizes are an inherent challenge for researchers. Therefore, the first priority was to explore the efficacy of a bat-mounted sensor as a means to overcome these barriers and enable the research project to be conducted within the field setting of a senior women's high-performance cricket program environment. The first study in this thesis demonstrated that the Blast bat-mounted sensor (Blast Baseball, Blast Motion Inc., San Marcos, CA, USA) measured bat speed in professional female cricketers with an overall bias of 2.7%, precision of 5.1%, and good absolute agreement (ICC = 0.86, 0.77-0.92) in comparison to the criterion reference of MoCap indicating acceptable accuracy for widespread use in the field (Freeston et al., 2025). This finding was important both for this research project and for the broader evolution of professional women's cricket. The validation of the bat-mounted sensor removed the barriers of lab-based MoCap above and unlocked an entirely different study design that could operate in tandem, and embedded with usual high-performance cricket training. Critically, the sensor also allowed scaling of testing with multiple bat speed assessments using multiple sensors delivered simultaneously within a given session. In combination these two factors allowed the research project to seamlessly integrate with the high-performance program and were foundational to the project's success. In the broader context of professional women's cricket the validation of the sensor has provided practitioners with accurate field-based technology to measure the key quality of bat speed for the first time, and in doing so has created the potential for a whole range of new research and innovation projects related to bat-speed. Possible projects might include exploring the acute potentiation of bat speed through specific warm up routines that could inform matchday practices, the measurement of bat speed during match play in combination with scoring outcomes, as well as novel swing speed skill-based training programs where a percentage of maximum bat speed is prescribed for bat swing repetitions in the same was as strength and power movements or sprint training on field.

Measuring Rotational Power

The ability to accurately measure rotational power in the field was also a critical foundation of this thesis. Although no evidence for the quality's association to performance existed for batting in cricket prior to this project, previous work in the ball-striking sports of baseball and golf has showed that both bat speed and clubhead speed have causal relationships with rotational power. Specifically, training intervention studies demonstrated that improvements in rotational power led to improvements in bat and clubhead speed, and subsequently to greater shot distances in both sports. Considering these findings and the overall aim to explore the physical capacities that might inform a deterministic model of bat speed for the explosive rotational hitting task of power hitting in cricket, assessing rotational power was an important consideration. It emerged that, despite rotational power being consistently included in ball-striking research outside of cricket, the field-based assessment of rotational power has been highly variable both in methodology and efficacy. Additionally, no previous field-based measure has ever been validated against the gold-standard criterion reference of MoCap. This may be due in part to the barriers of lab-based study designs highlighted above, however, it is clear that despite the lack of criterion validity and reliability, strength and conditioning practitioners and sports science researchers value the quality of rotational power in ball-striking sports as they continue to include its assessment in research regardless. The unconfirmed utility of the available rotational power measures was an important consideration for this thesis. This project would be the first in the world to explore the physical determinants of power hitting in professional female cricketers and aimed to set the foundation for evolving the strength and conditioning support for hitting in female programs. Therefore, the battery of physical quality assessments needed to have confirmed validity and reliability, especially for rotational power given its likely importance.

The second study of this thesis addressed this gap by confirming the validity and reliability of a new medicine ball rotational power test against the criterion reference of MoCap and comparing the assessment to the commonly used medicine ball throw for distance field measure. The field-based measure of a medicine ball push for maximum velocity (MB_{vel}) proficiently measured rotational power with excellent accuracy (ICC = 0.97 (0.97-0.98)), nearly perfect agreement for both bias (-0.09%) and precision (1.49%), and excellent between-session reliability (ICC = 0.94 (0.82-0.98)) (Hardy et al., 2024). As with the bat sensor, this allowed for the accurate assessment of rotational power within high-performance settings, negating the need for lab-based environments.

The Physical Determinants of Bat Speed

The next step in establishing an evidence base for the physical determinants of power hitting was to explore and identify associations between bat speed and various physical capacities. Associations were important to identify as they represented the first direct evidence in professional women's cricket that supported a deterministic model of bat speed underpinned by physical capacities. Associations were also necessary to guide the subsequent training intervention design for the fourth study of this thesis where causal relationships between bat speed and physical capacities were explored. The research progression from association to intervention has previously been utilized to good effect in both baseball and golf, where associations to bat and clubhead speed have informed intervention design and led to the establishment of causal relationships between physical capacities and bat or clubhead speed.

The third study of this thesis replicated the approach taken by baseball and golf and confirmed for the first time that physical capacities are strongly associated with bat speed in professional female cricketers (Hardy et al., 2025). A convenience sample of twenty-nine professional female batters was utilized to explore thirteen different qualities of strength, power, and anthropometry, with Pearson's *r* associations showing that upper body pulling strength (r = 0.70), dominant rotational power (r = 0.65), and total body isometric strength (r = 0.47) were all associated with bat speed. Multiple regression modelling of these associations explained 52.7% of the total variance in bat speed overall. A convenience sample of players from the Cricket NSW senior women's team, and the Sydney Sixers and Sydney Thunder Women's Big Bash League teams was chosen in this case to ensure that exclusively professional level female batters were included within the study cohort to accurately reflect the research aims regarding professional women's cricket. This broad study design to explore many variables relative to the small sample size was a deliberate choice for two reasons: (i) To deliver practically relevant findings back into the senior women's high-performance program on the relevance of the current battery of physical assessments used by the state program, and (ii) to ensure that a wide net was cast to capture and explore range of different physical factors given the current paucity of hitting research within cricket. Whilst this decision limited the statistical power of the study, this was outweighed by the value of informing strength and conditioning practices in the applied high-performance setting and creating a foundation to guide future research directions.

Strength and Conditioning Methods to Enhance Power Hitting Performance

In order to genuinely enhance the standard of strength and conditioning support for power hitting in professional women's cricket this thesis needed to deliver practically relevant findings that demonstrate how bat speed can be improved through strength and power programming. In line with the established progression of association to intervention from baseball and golf literature, the fourth study of this thesis built on the association outcomes from study three and utilized a training intervention design.

The design and execution of scientific evaluation often competes with the demands of high-performance sport and makes applied research very challenging. It was essential for this study that participants were elite professional female cricketers in order to deliver representative research outcomes that reflect the specialist skill level and attributes of this cohort that are not seen in sub-elite populations (Hardy et al., 2025; McErlain-Naylor et al., 2021). Within this context a control group in the usual sense was not possible given the disadvantage towards the aim of improved performance. This was compounded by small available populations (state female contract list). This is an example of where best-practice research methods are not aligned with the practical realities of professional sporting environments. These specialist populations are essential for high-performance sport research to be accepted for their validity and therefore rather than conforming to traditional research design requirements researchers should construct alternative methods to include them.

The fourth study of this thesis did this by using a crossover randomised controlled trial design where participants completed two different strength and power training interventions that were volume, load, and intensity matched. Despite the similarity of the intervention arms and the limited sample size, the study generated a number of key findings. For the first time in the cricket literature bat speed was confirmed to be a modifiable and therefore trainable capacity. Both interventions demonstrated strong efficacy and elicited improvements of 5.50-7.93% (*d* = 0.60-0.91) in bat speed across a 9-week period. These are larger changes than those seen previously for intervention studies of a similar length in baseball and golf where bat speed and clubhead speed improved by 3.2-6.4% and 3.4-3.5% respectively (Doan et al., 2006; Kwang Jun, 2010; Szymanski et al., 2007; Szymanski et al., 2006; Szymanski et al., 2010). The changes seen in bat speed across each intervention were associated with the corresponding changes in the physical capacities of upper body pulling strength (r = 0.58), bodyweight (r = 0.46), and total body isometric strength (r = 0.45), and multiple regression analysis showed that 31% of the total variance in change in bat speed was explained by the change in upper body pulling strength. Whilst remaining cognisant of the study limitations above, this evidence was still important to consider. The confirmation of bat speed as a trainable quality that can be measured in the field is highly valuable within the context of professional cricket environments seeking to maximise hitting performance in order to win short format cricket. The efficacy of both interventions generating large associated changes in bat speed and target physical qualities has established (albeit underpowered) the first causal evidence for physical capacities enhancing bat speed in professional female cricketers. Together, these findings provide a practical framework for practitioners seeking to enhance bat speed, and the foundation for future projects to expand the evidence for this critical area.

Power Hitting Research in Professional Cricket

Prior to this thesis, only four studies across the professional cricket sports science and sport medicine literature had examined power hitting including three biomechanical investigations and a single exploration of physical capacities. Despite the modest size of this evidence base, these studies produced several important findings: (i) bat speed explains 83% of the total variance in ball launch speed for shots with central impacts on or near the "sweet spot" region of the bat, (ii) shot carry distance is underpinned by ball launch angle and ball launch speed, with ball launch speed itself underpinned by bat speed, (iii) elite female batters exhibit a different kinematic profile and movement solution compared to male batters when power hitting, (iv) hitting distance is positively associated with upper body pushing strength in male batters. In combination, these studies set the foundation for power hitting research by identifying bat speed as a determinant of power hitting shot distance and a critical quality to explore, highlighting sex-specific movement solutions and the potential for sex-specific physical capacity associations, and providing preliminary evidence to indicate the link between physical capacities and power hitting.

This thesis built on this foundational work and has progressed the evidence base for power hitting through the findings across four empirical studies. Bat speed can now be measured in field settings without the requirement of MoCap after the successful validation of the Blast bat-mounted sensor. Rotational power can now also be assessed in the field using a highly accurate and reliable protocol that has been validated against the criterion reference of MoCap. The physical capacities of upper body pulling strength, dominant rotational power, and total body isometric strength are all associated with bat speed and explain more than 50% of the total variance in bat speed overall. Bat speed is a modifiable capacity that increases with targeted training. The changes seen in bat speed across training interventions are associated with the corresponding changes in the physical capacities of upper body pulling strength, bodyweight, and total body isometric strength, and 31% of the total variance in change in bat speed is explained by the change in upper body pulling strength indicating its critical importance for power hitting performance.

Practical Applications

The findings of this thesis have important practical implications for practitioners in professional women's cricket environments worldwide. The validation of field-based measures for bat speed and rotational power has shifted the power hitting assessment setting from the laboratory to the field, and has equipped practitioners with accurate, reliable, and scalable tools to monitor these qualities in high-performance settings. Notably, bat speed has now been established as a modifiable capacity that can be enhanced through training. This has two key applications: first, practitioners can strategically target bat speed development during specific periods of the year to coincide with competition demands, and second, that longitudinal changes in bat speed are possible to enable greater levels of hitting performance. The identification of upper body pulling strength, total body isometric strength, rotational power, and bodyweight as key associations to bat speed provides clear priorities for strength and conditioning program design. Regular assessment of these physical capacities alongside bat speed allows practitioners to profile both individuals and teams, evaluate the effectiveness of training programs, and deliver evidence-based interventions aimed at supporting power hitting performance in short format cricket.

Future Directions

This thesis has established bat speed as a modifiable capacity underpinned by specific physical qualities and has validated field-based tools that enable the accurate measurement of both bat speed and rotational power. Alongside these findings four key future directions have emerged. First, in order to develop a robust and reliable evidence base more research both exploring the associations between bat speed and physical capacities, and investigating the causal links between strength and conditioning interventions and bat speed is needed. Bat speed research in professional women's cricket should strive to emulate the benchmark set by clubhead speed in golf where the volume of both association and training intervention studies has sufficient depth and breadth to conduct meaningful systematic reviews and meta-analyses. Second, future research should consider longitudinal investigations that tie changes in bat speed to changes in on-field performance across single and multiple seasons. Establishing this link would effectively allow practitioners to measure how much on-field performance improves with every $1km \cdot hr^{-1}$ increase in bat speed, as well as contextualizing the improvements of the underpinning physical capacities trained within the performance program. Longitudinal research would also enable the exploration of a potential ceiling effect for bat speed in elite female cricketers as programs pursue higher levels of performance year on year with specific power hitting training. Third, future research should explore the efficacy of power hitting training where delivery speed is specifically prescribed to address the speed accuracy trade-off phenomenon seen for elite female batters in chapter four of this thesis. Fast bowling is a critical part of short format cricket that elite female batters regularly compete against in match. Projects demonstrating how deficits in maximum bat speed when facing fast deliveries can be addressed would be compelling for performance environments to consider. Fourth, conducting research within professional women's sporting environments comes with a number of challenges including small squad sizes. Future research projects should explore how multi-site collaborations might lead to powerful insights and scalable study designs. The ability to double or triple the professional player sample size for a given study across two or three teams would be compelling given the specialist nature of the elite female cricket population. There is significance in the potential of professional women's sporting teams helping each other and collaborating to raise the standard for all women in sport.

Self-Reflection

Conducting this thesis as an embedded project within a professional women's cricket environment resulted in several achievements, as well as some challenges to navigate. Most notable is the contribution this research has made to women's sport. Aside from the drive to impact and improve batting performance, this thesis also served the higher purpose of making a meaningful contribution to the progression of professional women's sport. Currently, women make up just 6% of single-sex studies and only 34% of all participants in sport science and sport medicine research. As a result, for many aspects of women's high-performance programs, practitioners are guessing by extrapolating male or youth studies, or going off practical experience and gutfeel. Designing and delivering a PhD research project that was built around and for professional female cricketers, represented a concrete way to add momentum to the advancement of women's sport not just for the applied environment at Cricket New South Wales (CNSW) but for all women's cricket programs. Another achievement of this thesis is the successful translation of the academic research findings into meaningful practical applications. Bat speed and rotational power assessments are now a standard part of the CNSW high-performance testing battery and are periodically delivered within the senior female program across each season. The strength and conditioning program has reoriented physical benchmarking to include the absolute rather than relative measures of isometric mid-thigh pull and 1-repitition-maximum bench pull due to their strong association with bat speed. Bat speed is comprehensibly monitored for specific batters within the senior female team and technical coaches regularly utilize the sensor measurements to combine technical and physical feedback. However, being embedded in a professional women's program was not without its challenges. The choice to conduct the study with professional female cricketers meant that our prospective sample size across all studies was limited due to the small squad sizes in professional women's cricket. The full-time nature of the high-performance program was also a barrier to success with only small additional time periods available with the players across their schedule of commitments. These two factors had a strong influence both on our initial pursuit of field-based measures for bat speed and rotational power, as well as later in the thesis the study design for chapters three and four. Ultimately, these challenges were successfully met and resulted in the successful validation of measures for both bat speed and rotational power, and subsequently fully embedded study designs for chapters three and four.

Over the course of the last three years the PhD has also had a profound impact on the development of my skillset and philosophy as a practitioner in professional sport. The process of designing and leading two validation studies for this thesis has given me a deep and thorough understanding of what field-based measurement tools actually need to be capable of to be utilised for assessments in high-performance. Consequently, I have applied this thinking across both the CNSW high-performance testing battery and our medical screening testing to critically evaluate the measures and what they imply. This information has also been communicated to wider high-performance staff and to athletes to elevate the level of our sport science practice. Conducting studies three and four as embedded projects within the CNSW professional women's program has taught me that it is entirely possible to concurrently run applied PhD level research alongside high-performance team programming in professional sport, albeit with highly flexible timelines and an agile research team. Delivering these two studies greatly enhanced my skillset in strategic thinking as I sought to merge the goals, timelines, and requirements of high-performance and research to deliver outcomes for both. This improvement in skillset has also had an impact on my overall philosophy around the purpose of strength and conditioning coaches in high-performance environments. Alongside the goals of maximising team performance and enabling every athlete to reach their full potential, I also now believe that delivering a broader impact to the sport as a whole through practice, innovation, or research is important to consider. Strength and conditioning roles within professional sporting programs are privileged positions that have access to some of the most talented sportspeople in the world. These programs have an enormous opportunity not only to gain performance insights for their athletes and teams, but also to contribute to the broader progression of sport as a whole.

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Chapter Seven

Appendix

Appendix One: Chapter Three Supplemental Digital Content

Specific Warm Up Routine

Order	Exercise	Reps
1	Reverse Lunge and Reach	5es
	Leg Swings	15es
	Thoracic Windmill Rotations	20
	Walking Lunge and Twist	5es
2	Speed Squat	10
	Jump Squat	10
	Medicine Ball Slam Left/Right	5es
3	Banded Rip Switch	8es
	Single Arm Split Stance Cable Pull	6es
4	Speed Squat	10
	Jump Squat	10
	Medicine Ball Slam Left/Right	5es
5	Banded Rip Switch	8es
	Single Arm Split Stance Cable Pull	6es

Es = each side

Appendix Two: Chapter Four Supplemental Digital Content

Strength and Power Assessment Specific Warm Up Routine Day 1 (Grip Strength, Medicine Ball Push, 10/5 Hop Test)

Order	Exercise	Reps
1	Watt Bike Steady State Ride @ 50-60% self-selected intensity	4min
2	Walking Hamstring Stretch	10m
	Walking Quad Stretch	10m
	Walking Sumo Squat Stretch	10m
	Jog	30m
3	KB Swing	10
	Banded Low Row (feet square)	10
	KB Goblet Squat	10
	Banded Face Pull	10
4	Low Skip	10m
	Carioca slow-paced L	10m
	Carioca slow-paced R	10m
	Skip on 45 angle	30m
5	Skipping Rope	50
	MB Scoop Toss (3kg, vertical)	4
	Medicine Ball Slam Left/Right (3kg)	6es
6	Double Leg Pogo Hop	10m
	Carioca fast-paced L	10m
	Carioca fast-paced R	10m
	Run	30m
7	Skipping Rope	50
	MB Scoop Toss (3kg, vertical)	4
	Medicine Ball Slam Left/Right (3kg)	6es

Strength and Power Assessment Specific Warm Up Routine Day 2 (Isometric Mid-Thigh Pull, Vertical Jump, Bench Pull, Push Up)

Order	Exercise	Reps
1	Watt Bike 30 sec @ 50-60%, 60 sec @ 70-80%, 30sec @ 90%+ self-selected intensity	2min
2	Walking Hamstring Stretch	10m
	Walking Quad Stretch	10m
	Walking Sumo Squat Stretch	10m
	Jog	30m
3	KB Swing	10
	Banded Low Row (feet square)	10
	KB Goblet Squat	10
	Banded Face Pull	10
5	Skipping Rope	50
	Medicine Ball Slam Left/Right (3kg)	6es
6	KB Swing	10
	Banded Low Row (feet square)	10
	KB Goblet Squat	10
	Banded Face Pull	10
7	BB Double Leg RDL @ 50%, 75%, 80%+	8,6,4
	Counter-Movement Jump @ 50%, 75%, 90%+	2,2,2

Maximum Bat Speed Assessment Specific Warm Up Routine Day 3

Order	Exercise	Reps
1	Watt Bike @ 50-60% self-selected intensity	5min
2	Walking Hamstring Stretch	10m
	Walking Quad Stretch	10m
	Walking Sumo Squat Stretch	10m
	Jog	30m
3	KB Swing	10m
	Banded Low Row (feet square)	10m
	KB Goblet Squat	10m
	Banded Face Pull	30m
4	Low Skip	10m
	Carioca slow-paced L	10m
	Carioca slow-paced R	10m
	Skip on 45 angle	30m
5	Fast Skip	10m
	Carioca fast-paced L	10m
	Carioca fast-paced R	10m
	Run	30m
6	Ground Based Dynamic Stretches (calf pumps, hamstring kicks, back rolls, side laying archers, yoga push ups, athlete choice	3min
7	Skills batting warm up including coach underarm and overarm throws, players to complete their normal pre-match batting warm up routine	10min

Testing Battery Protocol

Day 1 – Subject Information, Anthropometry, Strength and Power Assessments. Participants completed a specific Day 1 warm up (see supplemental content) before completing assessments in the numbered order. Three minutes of passive rest were taken between each different assessment from 3. Grip Strength onwards.

1. Height:

Height was measured by stretch stature, using a portable stadiometer (Seca 213, Seca GmbH, Hamburg, Germany). Participant stood barefoot, with heels together, and head positioned in the Frankfurt plane. Two height measurements were taken, and a third measure was used if the first two measurements were different by more than 0.4 cm as per previous sport science research (Buchheit & Mendez-Villanueva, 2013). The median value was recorded for further analysis.

2. Weight:

Participant bodyweight was assessed using a scale (WS150R, Wildcat, Mettler Toledo, Greifensee, Switzerland) with maximum capacity 150kg and readability 0.02kg. Participants stood barefoot in training shorts and training shirt only. One measurement was taken and recorded for further analysis.

3. Grip Strength:

A hand grip dynamometer (Hydraulic Hand Dynamometer Jamar 5030JI, Bolingbrook, IL, USA) was used to assess subject grip strength following the Canadian National Hockey League combine testing protocol (Chiarlitti et al., 2018).

For all participants the dynamometer handle was set to the second position (Trampisch et al., 2012). Participants were directed to fully extend their testing arm above their head with no elbow flexion, squeeze the dynamometer as hard as possible, and slowly bring their arm down to their side maintaining no elbow flexion. Each hand was measured three times alternating left and right assessments with 60 seconds of rest between attempts. Strong verbal encouragement was provided using the cue "crush the dyno, go as hard as you can".

The maximum score in kilograms for each hand was recorded for further analysis.

4. Medicine Ball Push.

Rotational power was assessed using a novel protocol recently validated against the criterion reference of three-dimensional motion capture shown to have established accuracy and reliability (Hardy et al., 2024).

Participants were instructed to stand side-on in an athletic stance with the rear arm the assigned pushing arm. Participants held a 2kg medicine ball at shoulder height in contact with their chest, the front arm supporting the ball from underneath and the rear arm cocked with the hand on back of the ball. Participants completed the medicine ball push by rapidly counter-rotating away from the throw direction in the transverse plane with feet fixed on floor before immediately rotating back and explosively pushing the ball forwards to the intended target. The speed of each attempt was measured using a radar gun (Stalker ProIIs, Applied Concepts Inc., Plano, TX) positioned 5m directly in front of the participant's lead foot at a height of 1.5m. Participants were cued to "explosively push the ball as fast and as hard as possible towards the radar gun". Three attempts on each side left and right were completed in an alternating order with 60 seconds of rest between each.

The maximum speed on each side in $km \cdot hr^{-1}$ was recorded for further analysis.

5. 10/5 Hop Test.

Reactive Strength Index (RSI) was assessed in accordance with the 10/5 hop test protocol (Harper et al., 2011).

Participants were instructed to maintain hands on hips for the duration of the assessment. Standing on a Force Decks FD4000 dual force plate system (Vald Performance, Brisbane, QLD, Australia), participants completed 10 maximal continuous pogo hops and were cued to "jump as high as possible and spend as little time as possible on the force plates". Three attempts were completed with 90 seconds of rest between each. RSI was calculated as flight time divided by contact time for all hops.

The highest RSI from a single hop in each attempt was recorded as the peak RSI for each attempt. The highest peak RSI across the three attempts was recorded for further analysis.

Day 2 – Strength and Power Assessments. Participants completed a specific Day 2 warm up (see supplemental content) before completing assessments in the numbered order. Three minutes of passive rest were taken between each different assessment from 1. Isometric Mid-Thigh Pull.

1. Isometric Mid-Thigh Pull. Total body isometric strength was assessed using the Isometric Mid-Thigh pull protocol (Comfort et al., 2019).

To determine bar height participants were directed to assume the body position required at the start of the second pull during an Olympic clean movement on the isometric testing rig and were instructed to take all "slack" out of their body position e.g., remove shoulder girdle protraction and elevation, elbow flexion. Height of the stationary bar was then set through an iterative process, aiming to replicate the subject from viewing side-on having an upright torso, slight flexion at the hip 140°-150°, flexion at the knee 125°-145° with knees underneath and in front of the bar, some dorsiflexion at the ankle, the shoulder girdle retracted and depressed, shoulders in line with or slightly behind the vertical plane of the bar and feet centred underneath. Athlete subjective preference was used when two bar heights replicated very similar positions. Participants used lifting straps and chalk to ensure grip strength was not a limiting factor in maximal force expression.

Three maximal effort attempts were conducted with 60 seconds of rest between trials. Participants were cued on maximal efforts to start by assuming the practiced pull position and removing all slack before "pushing your feet into the force plates as hard and as fast as possible". Strong verbal encouragement was provided during for all maximal efforts.

The maximal force generated measured in Newtons (N) across all three attempts was recorded for further analysis.

2. Vertical Jump:

Lower body power was assessed by the standing vertical jump protocol (Thomas et al., 1996).

Participants were asked to stand in their preferred jumping stance with feet approximately hip width apart directly below the Swift Yardstick jump measure system (Sports Imports, Hillard, OH), with their chosen reach arm oriented closest to the Swift apparatus. From a stationary position standing fully upright with head and eyes looking straight ahead, participants were instructed to reach up and touch the highest vane possible to calibrate standing reach height. Participants then completed maximal jump height testing. Jump height was recorded as the highest vane displaced subtracted by the standing reach height. Starting from a stationary position in the same jump stance participants were cued to maximally jump "Fast down, fast up, jump and reach as high as you can", reach up and displace the highest possible vane on the measurement system. 30 seconds rest separated each attempt, and a final jump height was attained when a participant failed to improve their height on 2 consecutive attempts. Strong verbal encouragement was provided for all efforts.

Final jump height measured in centimetres (cm) was recorded for further analysis.

3. Bench Pull:

Upper body maximum pulling strength was assessed using the prone laying bench pull protocol (Lum & Aziz, 2020) and the 1 repetition maximum (1RM) framework described by Seo et al. (2012).

The bench pull movement was completed "from hang". The subject laying prone on the bench received the barbell lifted by 2 spotters, the barbell was supported by the spotters until instruction to release was given by the subject who, gripping the bar in an overhand position with straight arms momentarily hung with the barbell before maximally pulling upwards until contact between the bottom of the bench and the barbell was made. Participants used chalk to ensure maximal grip strength was achieved. Participants then completed 1RM testing with increasing bar weights each followed by 90-120 seconds of rest. Attempts were rejected if the bench pull movement involved any of significant back arching, leg movement, uneven pulling, or if the subject failed to make contact between the bench and the bar.

The maximum weight successfully lifted, measured in kilograms (kg), was recorded for further analysis.

4. Push Up:

Upper body pushing strength was assessed using the bodyweight push up for maximum repetitions.

The testing was conducted in accordance with an in-house Cricket New South Wales protocol developed from previously published literature confirming the validity of the push up as a measure of pushing strength (Tillaar & Ball, 2020). Participants were instructed to lay prone on the ground self-selecting preferred hand position, aligning the centre of their chest to make contact with a 5-kilogram weight plate, and choosing to either to have feet together or shoulder-width apart. Participants were then instructed to push up from this depth to both arms fully extended, whilst at the same time maintaining a straight line between shoulders, hips, knees, and ankles. Participants were also instructed to ensure strong trunk control with only minor movement allowed. From the top position participants were to immediately return to the ground and repeat this cycle as many times as possible with no rest in either the top or ground positions. Strong verbal encouragement was delivered for the duration of the test. Any repetitions that did not meet the required depth, contained excessive and significant trunk extension resulting in shoulders hips knees and ankles to be miss-aligned, engaged in uneven arm movement with hips assisting by 'kipping', were rejected. Participants were strongly encouraged to repeat a repetition if they failed any criteria outlined above, with 2 repeated criteria failures ending the test.

The maximum number of successful repetitions from one effort was recorded for further analysis.

Day 3 – Bat Speed Assessment. Participants completed a specific Day 3 warm up (see supplemental content) before completing the maximal bat speed assessment.

1. Bat Speed:

Maximal bat speed was measured using a validated bat mounted sensor (Blast Baseball, Blast Motion Inc. San Marco, CA).

Participants completed testing at the Cricket NSW high-performance indoor facility on standard synthetic cricket pitches. Participants were instructed to use their full set of matchday batting protective equipment and bat.

Participants performed four different types of maximal effort cricket shots (Cut, Drive, Pull, Slog) whilst facing three different types of delivery (Fast, Medium, Off-Spin). The Slog shot was only performed during Off-Spin deliveries, all other shots were performed across all delivery types. Deliveries were performed by a professional level batting coach using a match condition cricket ball. Delivery types were split into designated speed ranges as Fast (100-115 $km{\cdot}hr^{-1}$), Medium (90-100 $km{\cdot}hr^{-1}$), and Off-Spin (70-80 $km{\cdot}hr^{-1}$), with speed for each delivery recorded using a radar gun (Stalker ProIIs, Applied Concepts Inc., Plano, TX). Only deliveries within the designated ranges were included in the bat speed assessment.

Participants were required to perform five successful attempts for each shot type to each delivery type for a total of 50 successful shots (15 Cuts, 15 Drives, 15 Pulls, 5 Slogs) for the session. A successful shot was defined as the correct shot type performed and batted ball powerfully hit in the intended shot direction. All attempts resulting in misses, edges, incorrect shot selection, and incorrect ball direction were rejected.

Delivery types were randomised and performed for a full set of shot types (Cut, Drive, Pull, Slog) prior to changing. Shot types were also randomised and completed in blocks of 5 successful attempts for a given shot, with 10 seconds rest between shots, 60 seconds rest between shot types, and 4 minutes rest between delivery types. Prior to commencing standardized instructions were given to participants to "hit the ball as hard and as powerfully as you can". The delivery speed in km·hr^{-1} for all successful attempts, and bat speed in km·hr^{-1} for BS_{cut}, BS_{drive}, BS_{pull}, BS_{slog}, and $BS_{overall}$ (calculated as the maximum bat speed recorded across all four shot types for each participant) were recorded for further analysis.

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Appendix Three: Publications

Sports Biomechanics

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Accuracy of a bat-mounted sensor for the measurement of bat speed among elite female cricket players

J. Freeston, S. G. J. Hardy, E. Ho, P. Sinclair, S. Chalmers, M. Hollings & J. T. Andersen

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RESEARCH ARTICLE

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Accuracy of a bat-mounted sensor for the measurement of bat speed among elite female cricket players

J. Freeston [a,b], S. G. J. Hardy [a,c], E. Ho[a], P. Sinclair [a], S. Chalmers [a,d], M. Hollings [a] and J. T. Andersen [a,e,f]

[a]Sydney School of Health Sciences, Faculty of Medicine and Health, The University of Sydney, Australia; [b]Cleveland Guardians Baseball Club, Cleveland, USA; [c]Cricket New South Wales, Sydney, Australia; [d]Allied Health and Human Performance, University of South Australia, Adelaide, Australia; [e]Biomechanics, Physical Performance, and Exercise (BioPPEx) Research Group, Macquarie University, Sydney, Australia; [f]Faculty of Medicine, Health, and Human Sciences, Macquarie University, Sydney, Australia

ABSTRACT
Currently, there are no validated field-based measures of bat speed in cricket. This study sought to validate a baseball bat-mounted sensor for use in cricketers. Nine professional female cricketers (19.9 ± 2.8 years, 166.6 ± 4.8 cm, 68.7 ± 8.6 kg) performed 40 swings across four shot types (Cut, Drive, Pull, Slog-Sweep). Bat speed from a bat-mounted sensor was compared to optical motion capture (MoCap). Bat speed differed between shot types and ranged from 52.8 to 87.9 km/h. Device accuracy was determined by Bland-Altman bias and precision. The Drive shot had the smallest bias (−1.0 km/h; 1.4%), followed by the Slog-Sweep (2.0 km/h; 2.7%), Pull (2.0 km/h; 2.8%) then Cut shot, (2.5 km/h; 3.9%). The Cut shot had the greatest precision (2.7 km/h; 4.1%), followed by Pull (3.4 km/h; 4.7%), Slog-Sweep (4.0 km/h; 5.3%) and Drive (4.4 km/h; 6.3%). Kendall's tau analysis showed that proportional errors increased with higher bat speeds for all shots except Pull, ($p < 0.05$). The evidence supports use of the sensor for bat speed among female cricket players for all shots between speeds of 52.8–87.9 km/h. Caution is warranted for additional shot types, and speeds outside the explored range.

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Introduction

In cricket, batters score runs using a number of different strategies to play shots and hit the ball to various areas of the field. Shot distance is an important outcome for run scoring, with both of the two highest scores available from a single shot requiring the ball to be propelled the maximum distance over the field boundary either along the ground for four runs or in the air for six runs (either score known as 'boundaries'). Although many different shots are possible, four commonly played when aiming to hit boundaries are known as the Cut, Drive, Pull, and Slog-Sweep (see supplementary online content) (Foysal

CONTACT J. Freeston jonathan.freeston@sydney.edu.au

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et al., 2019; Jamil et al., 2022; Stuelcken et al., 2005). The approach to maximise scoring boundaries is known within cricket as power hitting (Jamil et al., 2022), a strategy often employed in the shortest format of the sport T20 cricket where previous performance analysis has shown that winning teams score runs at a higher rate and accumulate more boundaries whilst batting (Douglas & Tam, 2010; Moore et al., 2012; Petersen et al., 2008).

While our understanding of determinants of power hitting are still emerging, two foundational tenets have been established in the cricket literature: (i) ball exit velocity is critical for shot distance, and (ii) ball exit velocity is primarily underpinned by bat swing speed Peploe et al., 2018, 2019). This same principle has previously been established in baseball (Nathan, 2003) where bat swing speed has been shown to be a critical factor in determining the velocity of the struck baseball. The enhancement of bat swing speed in particular is identified as a critical area of training focus for players and coaches in maximising shot distances in cricket (McErlain-Naylor et al., 2021; Peploe et al., 2018, 2019).

Research into validated methods for measuring bat swing speed in cricket has been limited to lab-based motion capture solutions with no validated on-field measure currently available. This has contributed to a slower rate of progress in terms of clinical practice and research relating to bat swing speed in cricket compared with its baseball and softball counterparts. Research investigating commercially available bat swing sensors such as the work in baseball by Morishita and Jinji (2022) and Lyu and Smith (2018), and in softball by Stewart et al. (2021) provide a foundation to aid the creation of new and enhanced training practices, as well as guide practitioners on the current limitations of the available technologies. Validated, field-based measures of bat speed in baseball and softball have led to the development of multiple research areas including specific bat swing speed match warm-ups (De Renne et al., 1992; Montoya et al., 2009; Southard & Groomer, 2003; Szymanski et al., 2011), strength and conditioning programs designed to enhance bat swing speed (Ab Razak et al., 2022; Kobak et al., 2018; Mace & Allen, 2020; Miyaguchi & Demura, 2012; Szymanski et al., 2009; Szymanski et al., 2010), a comprehensive understanding of the relationship between anthropometric measurements and bat swing speed (Lowe et al., 2010; Till et al., 2011), as well as performance benchmarking of bat swing speeds (Spaniol, 2009). The validation of a device capable of measuring bat swing speed in cricket presents an opportunity to evolve the clinical practice and research of the sport in several areas, similar to those observed in baseball and softball.

The aim of this study, therefore, was to determine the accuracy of a bat-mounted sensor to measure bat swing speed during four different cricket shots (drive, cut, pull, slog-sweep) over a range of swing intensities. We hypothesised that shot types with similar bat swing paths to a baseball swing—specifically, the Cut and the Pull—would produce more accurate bat speed results than shot types with dissimilar bat angles to a baseball swing—that is, the Drive and the Slog-Sweep.

Materials and methods

Participants

Nine professional state and national level female cricketers (age: 19.9 ± 2.8 years; height: 166.6 ± 4.8 cm; mass: 68.7 ± 8.6 kg) from Cricket NSW volunteered for the study. Based on the available sample size, it was determined that we could detect r^2 values of ≥ 0.63 with 80% power and a 0.05 alpha level for associations between the bat-mounted sensor and optical motion capture (GPower 3.1.9.7). Participants were free from injury or musculoskeletal complaints at the time of the study. Prior to taking part, participants were made aware of the experimental procedures (including the benefits and risks of the investigation) and written consent was obtained. This study complied with the ethical guidelines for human research by the Australian National Health and Medical Research Council and was approved by the University Human Research Ethics Committee (Project Number 2019/712).

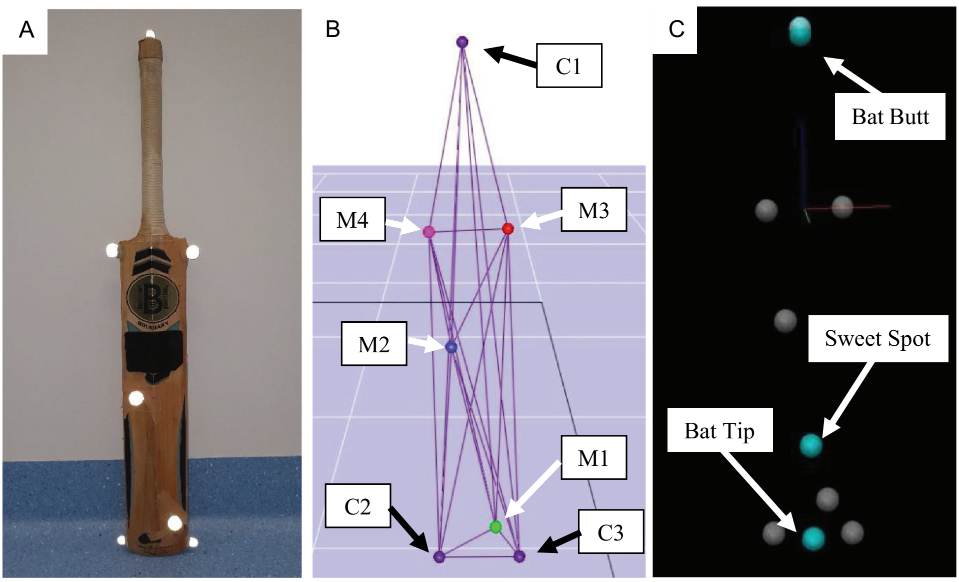
Procedures

Participants attended a single testing session at an indoor biomechanics laboratory. They were assessed for their height (Seca 222 stadiometer, Seca, Hamburg, Germany) and mass (WS150R, Wildcat, Mettler Toledo, Greifensee, Switzerland) before completing a specific warm-up comprising 10 min of batting skills.

Participants each performed a total of 40 bat swings against a cricket ball placed on a stationary tee with a modifiable height. Ten shots were executed for each of the following batting shot types: Cut, Drive, Pull, and Slog-Sweep. For the Cut shot, a batting tee was placed at approximately hip-height at a self-selected distance on the off-side of the body (i.e., the right-hand-side for right-handed batters; left-hand-side for left-handed batters). For the Drive shot (characterised by a vertical bat swing), the ball was placed on a small tee located approximately 10 cm off the ground directly in front of the batter. For the Pull shot, the ball was placed at approximately shoulder-height at a self-selected distance away on the on-side of the body (i.e., the left-hand-side for right-handed batters; the right-hand-side for left-handed batters). Finally, for the Slog-Sweep, the ball was placed at a height approximately corresponding to the mid-point between the knee and hip on the on-side of the body. For each shot type, batters were instructed to swing 'as hard as possible' at maximal intensity for five shots and additional five shots were played at a self-selected intensity equivalent to approximately 80% of maximal perceived exertion. The order of shots was randomised in blocks of five, with each shot separated by approximately 10 s to minimise the fatigue effect and to mimic training and game scenarios.

The bat-mounted sensor (Blast Baseball, Blast Motion Inc., San Marcos, CA, USA) is a wireless, portable baseball bat swing analyser comprising a bat-mounted dual three axis accelerometer, gyroscope, and magnetometer device with a sampling rate of 500 Hz and smartphone app 'Blast Baseball' developed by the manufacturer. The sensor is also equipped with a proprietary dynamic calibration algorithm that runs continuously whilst in use to filter measurements and adjust for sensor drift. The sensor was mounted onto the participant's preferred bat at the butt-end of the handle using a rubberised sensor casing designed by the manufacturer. At ball contact, the sensor records gyroscope, accelerometer, and magnetometer data that are immediately transferred to the phone application via Bluetooth. Maximal linear speed at the 'sweet spot' of the bat, which the manufacturer defines as 15 cm (6 inches) from the tip of the bat along the centre of the bat's long axis, is then calculated. Bat length, measured from the butt-end of the handle to the tip of the bat using a standard tape measure, and bat mass using a scale (WS30R, Wildcat, Mettler Toledo, Greifensee, Switzerland) with maximum capacity 30 kg and readability 0.005 kg were input to the app to enable the calculation.

Bat speed at this same estimated sweet spot was also determined via three-dimensional optical motion capture (MoCap) (Cortex 3.3, Motion Analysis Corporation, USA) using a 14-camera system collecting at 240 Hz. Bat marker data were unfiltered to avoid unwanted changes to bat speed data (Orishimo et al., 2023; Tabuchi et al., 2007). The bat was modelled in Visual 3D (v.6.0, C-Motion, Germantown, MD, USA) using seven markers, which were placed at the locations outlined in Figure 1(A). M1-M4 were used to track the bat for each shot, whilst C1-C3 were for calibration purposes and removed before beginning the swing trials. C1 was placed on top of the bat-mounted sensor and a corrected bat butt location was calculated as a virtual marker offset from C1 to account for the thickness of the sensor and its casing (Figure 1(C)). The bat tip was modelled as the point along the bat's long axis at the bat length distance away from the bat butt. The bat's sweet spot was located using the definition from the manufacturer.: 15 cm from the tip of the bat along the bat's long axis in the centre of the bat (Figure 1(C)). Bat speed was



Marker	Location
M1	Back of bat, on the right side of the spine, approximately 0.15m from bat tip
M2	Back of bat, on the left side of the spine, approximately 0.30m from the base of handle
M3	On the edge of the right side of bat, at the end closest to base of handle
M4	On the edge of the left side of the bat at the end closest to the base of handle
C1	Calibration marker (removed during swing trials) on the butt of the bat
C2	Calibration marker (removed during swing trials) on the edge of left side of bat tip
C3	Calibration marker (removed during swing trials) on the edge of the right side of bat tip

Figure 1. Optical motion capture markers (A), 3D marker reconstruction (B) and virtual markers (C) used to calculate bat speed. Marker locations are described in the table.

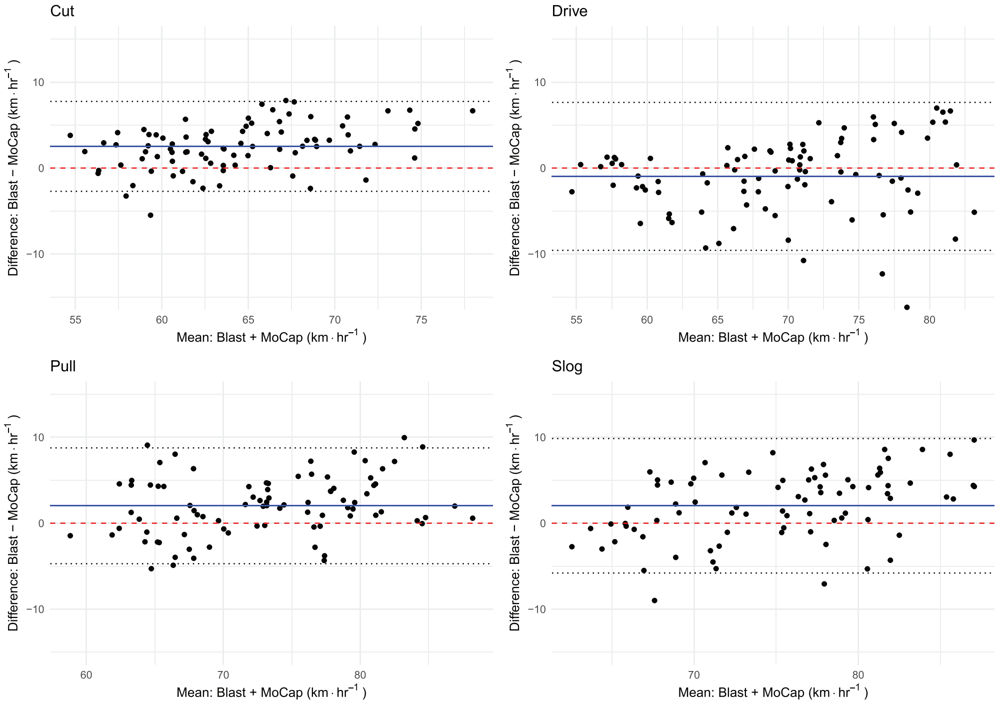


Figure 2. Bland-Altman plots of bat speed estimates between the BM_{sensor} and optical motion capture for the Cut, Drive, Pull, and Slog-Sweep. The blue line indicates the bias while the dashed line represents the upper and lower limits of agreement (LoA). Precision was calculated as the standard deviation of the difference between methods.

calculated using the sweet-spot positional data averaged across the first five frames after bat-ball contact. A cricket ball was wrapped in retroreflective tape and tracked using MoCap. The time of bat-ball contact was defined by the last frame before the ball's displacement changed from its initial resting position on a stationary tee.

Statistical analyses

Statistical analysis was conducted using R (RCoreTeam, 2023) Each shot was treated as an individual observation since the aim of this study was to evaluate the validity of the sensor outputs. 17 (4.7%) trials were missed by MoCap (e.g., marker occlusion), of which, 9 (2.5%) were also missed by the sensor (e.g., error given by the smart phone app).

Differences in mean bat speed between the different shot types Drive, Cut, Pull, and Slog-Sweep were assessed using a one-way repeated-measures ANOVA. Mean, standard deviation, coefficient of variation (CV) and standard error of mean (SEM) were calculated for all sensor and MoCap bat speeds. Device accuracy was determined via Bland-Altman analysis of bias and precision (Bland & Altman, 1999; Giavarina, 2015) in line with previous sports research assessing accuracy (MacDougall et al., 2024; Santos et al., 2024; Zacca et al., 2023). MoCap was used as the gold-standard criterion reference 'true' measurement. Bias was calculated by assessing the mean difference between the two methods, and precision by calculating the standard deviation of the difference between methods, upper and lower limit of agreement (LoA) were calculated for both. Kendall's tau (Goedhart & Rishniw, 2021) was used to assess the variation of sensor measurement error with bat speed magnitude. Intraclass correlation (2, 1) was used to assess the absolute agreement between sensor and MoCap measurement systems, and was interpreted as excellent > 0.9, good 0.75–0.9, moderate 0.5–0.75 and poor < 0.5 (Koo & Li, 2016). Linear regression using R squared and Pearson's correlation (*r*) was used, and Pearson's r was interpreted as large 0.50 to 0.70, very large 0.70 to 0.90, and nearly perfect > 0.90 (Hopkins, 2000). Significance was set a priori at $\alpha = 0.05$.

Results

Maximum bat speed as measured by the MoCap system was highest for the Pull shot (Max 87.9 km/h; Min 59.6 km/h; Range 28.4 km/h), followed by Drive (Max 86.5 km/h; Min 55.1 km/h; Range 31.4 km/h), Slog (Max 84.9 km/h; Min 63.9 km/h; Range 21.0 km/h) and Cut (Max 74.6 km/h; Min 52.8 km/h; Range 21.8 km/h), (Table 1). These differences were statistically significant, ($F(3, 682) = 80.0$, $p = 0.00$), consequently, bias and precision results are presented in absolute terms and as percentage errors.

Bland-Altman analysis of sensor accuracy (Figure 2) revealed revealed that the Drive shot had the smallest bias (−1.0 km/h; 1.4%) and was the only shot type to be underestimated by the sensor. All other shot types were overestimated by the sensor, with the Cut shot having the largest bias (2.5 km/h; 3.9%), followed by Pull (2.0 km/h; 2.8%) and then Slog-Sweep (2.0 km/h; 2.7%). The Cut shot had the greatest precision (2.7 km/h; 4.1%), followed by Pull (3.4 km/h; 4.7%), Slog-Sweep (4.0 km/h; 5.3%) and Drive (4.4 km/h; 6.3%). Assessment of Kendall's tau correlation coefficient showed that sensor measurement error increased with increasing bat speed for Cut (0.22, $p = 0.00$), Drive (0.23, $p = 0.00$), and Slog-Sweep (0.21, $p = 0.01$), but not for Pull (Table 1). Intraclass correlation showed the Pull shot to have the highest level of absolute agreement (0.89) followed by the Cut (0.87), Drive (0.84) then Slog-Sweep (0.82) (Table 1).

Correlations were significant for all shot types but were stronger for Pull and Cut ($R^2 = 0.80$ and 0.79 respectively) than for Slog-Sweep and Drive ($R^2 = 0.72$ and 0.71 respectively). ($p = 0.00$) (Table 1).

Discussion and implications

This is the first study to describe the accuracy of a bat-mounted sensor for the measurement of bat speed across four different shot types in cricket. Differences in overall accuracy resulted from different degrees of bias (1.4–3.9%) and precision (4.1–6.3%) for each shot type. While no previous study has explored the use of a bat-mounted sensor to measure bat speed in cricket, the results of the current study are partially comparable to publications in baseball. Morishita and Jinji (2022) described the accuracy of four commercially available sensors relative to motion capture during a baseball batting task as having precision levels of 8–10%. This previous study's methodology did not allow for between study comparisons of bias as this was reported as a ratio scale after antilog. The sensor precision determined in the current study strongly outperforms the level found by Morishita and Jinji (2022) and may be explained by methodological differences in the baseball study including a smaller number of participants, ($n = 7$), fewer swings taken

Table 1. Mean (SD) bat speed from the MIMU sensor and optical motion capture. Sensor accuracy represented by Bland-Altman bias as mean difference and precision as standard deviation of difference between measures, respectively. Assessment of heteroscedasticity represented by Kendall's tau correlation coefficient (τ). Absolute agreement of measurements represented by intraclass correlation coefficient (ICC). Linear regression (R^2 and Pearson's r) show the Strength of the relationship between measures for each shot type. Number of shots included in each analysis (n) is also listed.

Shot Type	Bat Speed		Bland-Altman		Kendall's Tau	ICC (2, 1) Absolute Agreement		Linear Regression
	Sensor	MoCap	Bias	Precision				
	Mean (SD) (km/h)	*Mean (SD) (km/h)*	*Mean Diff km/h (%)*	*SD of Diff km/h (%)*	*τ*	*Mean (CI)*	*Classification*	*R^2 (r)*
Cut	65.6 (5.8)	63.1 (4.8)	2.5 (3.9%)	2.7 (4.1%)	0.22**	0.87	Good-Excellent	0.79 (0.89) **
n = 86	CV = 0.6, SEM = 1.9	CV = 0.5, SEM = 1.6	LoA: −2.7 to 7.8		p = 0.00	(0.81 to 0.92)		p = 0.00
Drive	69.0 (8.2)	69.6 (7.1)	−1.0 (1.4%)	4.4 (6.3%)	0.23**	0.84	Good	0.71 (0.84) **
n = 90	CV = 0.9, SEM = 2.7	CV = 0.8, SEM = 2.4	LoA: −9.6 to 7.6		p = 0.00	(0.77 to 0.89)		p = 0.00
Pull	74.0 (7.8)	72.1 (7.0)	2.0 (2.8%)	3.4 (4.7%)	0.02	0.89	Good-Excellent	0.80 (0.89) **
n = 86	CV = 0.9, SEM = 2.6	CV = 0.8, SEM = 2.3	LoA: −4.7 to 8.8		p = 0.81	(0.83 to 0.92)		p = 0.00
Slog-Sweep	76.0 (7.6)	74.0 (6.0)	2.0 (2.7%)	4.0 (5.3%)	0.21*	0.82	Moderate-Good	0.72 (0.85) **
n = 81	CV = 0.8, SEM = 2.5	CV = 0.7, SEM = 2.0	LoA: −5.8 to 9.9		p = 0.01	(0.74 to 0.88)		p = 0.00

*$p < 0.05$.
**$p < 0.01$.

with the sensor (5–10 swings per participant per sensor; *n* = 35–70 swings total), significantly higher bat speeds, (average = 108.3 km/h) as well as the bat type (baseball bat) and bat swing path. Lyu and Smith (2018) produced similar findings in their comparison of three commercially available sensors to high-speed video capture during a baseball hitting task finding an average sensor bias of 8%. Due to the statistical analysis choice to use the concordance correlation coefficient by the authors we were not able to directly compare precision. Again, the level of bias (2.7% average) found in the current study significantly outperforms the 8% average determined by Lyu and Smith (2018) and may result from similar methodological differences to those identified for Morishita and Jinji (2022) above including a smaller number of participants, (*n* = 8), significantly higher bat speeds, (average = 102.6 km/h), bat type (baseball bat), and bat swing path. Although the evidence base for bat swing sensor accuracy in cricket is still emerging, the bias and precision results found in this study suggest that sensor application to assess bat speed in cricket settings is viable.

According to the Intraclass Correlation, the sensor showed 'Good to Excellent' absolute agreement for the Pull and Cut, 'Good' absolute agreement for the drive, and 'Moderate to Good' absolute agreement for the Slog-Sweep (Koo & Li, 2016) compared with the Gold-Standard criterion reference of Motion Capture. These findings support our hypothesis that the sensor is most valid for cricket shot types that more closely resemble that of baseball batting, i.e., the pull and cut shots which have a predominantly horizontal bat swing plane (Sawicki et al., 2003; Williams et al., 2019). Interestingly, sensor absolute agreement was greater for the drive shot compared with the slog-sweep, despite the drive shot having a predominantly vertical bat path, while the mixed horizontal and vertical bat path of the slog-sweep was associated with poorer sensor absolute agreement. Further research is required to better understand the role of bat swing plane on sensor-derived measurements of bat speed in cricket.

Previous research on baseball bat swing sensors has reported that accuracy decreases at higher swing speeds due, amongst other reasons, to saturation of the accelerometer sensors used in that study (Lyu & Smith, 2018; Morishita & Jinji, 2022). This is reflected in the results for Kendall's Tau shown in Table 1 where Cut, Drive, and Slog-Sweep measurement error increased with increasing bat speed. This effect was not present for Pull. This lack of consistent pattern of accuracy varying with velocity for all shot types is most likely because the swinging a heavy cricket bat by female players produced substantially slower swing speeds than for baseball. Rather than velocity, the plane of motion appeared to have more effect, with precision being higher for the cut and pull shots which followed a horizontal plane more similar to that of a baseball swing.

The IMUs within bat swing sensors integrate data from accelerometers (linear acceleration), gyroscopes (angular velocity) and magnetometers (angular displacement) using a data fusion algorithm to account for inaccuracies within each individual sensor (Caruso et al., 2021). These fusion algorithms require specific tuning for different activities to best account for the different contributions of angular velocity and linear acceleration to the overall movement (Nazarahari & Rouhani, 2021). It is therefore possible that the more vertical swing patterns of the drive and slog-sweep shots had quite a different interaction between gravity and the linear acceleration of the bat, resulting in a sensor tune that was less suitable for a device designed primarily for baseball. Similarly, movement of the instantaneous centre of rotation during a swing may change the relative contribution between linear motion of the hand and angular motion of the bat, altering the relative magnitudes of each sensor and thus potentially changing the ideal tuning parameters for a sensor fusion algorithm.

Given the lack of field-based methods currently available to measure bat speed in cricket, we suggest that the evidence presented here is sufficient to recommend use of the sensor to quantify bat speed among elite female cricket players, particularly for the Cut, Drive and Pull shots. While caution is advised for the use of the sensor to quantify bat speed for the slog-sweep shot given its lower overall absolute agreement. Previous research describing the maximal bat speeds of elite female cricket players when performing the Drive shot against a bowling machine were also within the bat speed ranges achieved here, supporting the wider application of the sensor within this player group, (81.4 km/h; McErlain-Naylor et al. (2021) Notably however, while previous research has shown that sub-maximal bat speeds for elite male cricket players fall within this range, (76.3 km/h; Stuelcken et al. (2005) maximal bat speeds for elite male players are significantly higher than those explored here, (97.2 km/h; Chris Peploe et al. (2018, 2019) 102.2 km/h; McErlain-Naylor et al. (2021) Given that the measurement error increased with increasing bat speed for Cut, Drive, and Slog-Sweep, it is unclear what accuracy the device has beyond the speeds explored in the current study. Additional research is therefore needed to determine the accuracy of the sensor for use in other amateur and professional settings outside of elite female cricket, where population speed ranges differ to those explored in this study.

The current study had several limitations. Firstly, the findings of this study are limited to a laboratory setting when hitting a stationary ball off a tee; therefore, the ability of the sensor to detect bat speed in practice and game settings should be explored. Secondly, the study was limited to cricket players achieving bat speeds between 52.8 and 87.9 km/h. Given that measurement error increased with increasing bat speed, the performance of the sensor above and below this range is unclear. Thirdly, the sweet spot of the bat was estimated at 15 cm from the bat tip in accordance with the manufacturer definition. However, the sweet spot of a cricket bat varies slightly between implements and is usually slightly further from the tip than this, about 17.5 cm (Peploe et al., 2018, 2019), which means that bat speed values presented here may have been slightly overestimated. This consistent estimate was necessary however, to ensure that the comparisons between measurements were not affected by different definitions for calculating bat speed. Finally, in deciding to maximise data accuracy by using a five-frame average of the MoCap data post contact to calculate bat swing speed there may be some small reduction in maximal speed recorded for the study. This could explain some of the difference in swing speed seen between the sensor and MoCap.

A number of future directions for research remain. Firstly, continued improvements to the bat-mounted sensor and its related algorithm are required. This is particularly important to improve the sensor accuracy for the slog-sweep shot, as well as reduce the increase in measurement error with increasing bat speed. This would increase the utility of the device to players capable of achiever higher bat speeds beyond those explored here. Secondly, future research should explore bat speed across each of the major shot types among a larger group of players to establish normative reference data. The current study showed significant differences in bat speed between shots however, describing normative ranges was beyond the scope of the study and should be explored with a larger, more representative sample. This information would be helpful for practitioners to describe individual player capabilities against normative standards, as well as help with shot selection in situations where optimising bat speed is critical.

Conclusions

This is the first study to describe the accuracy of a bat-mounted sensor for the measurement of bat speed in cricket. The sensor demonstrated across shot averages of 2.7% for bias (Cut 3.9%, Drive 1.4%, Pull 2.8%, Slog-Sweep 2.7%) and 5.1% for precision (Cut 4.1%, Drive 6.3%, Pull 4.7%, Slog-Sweep 5.3%). Absolute agreement between MoCap and the sensor was shown to be 'Good to Excellent' for Pull and Cut, 'Good' for Drive, and 'Moderate to Good' for Slog-Sweep. The evidence supports the use of the sensor to measure bat speed among elite female cricket players for these shots between speeds of 52.8–87.9 km/h, but caution is warranted for its application for the slog-sweep shot and for speeds outside of the explored range.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

J. Freeston http://orcid.org/0000-0003-4383-1712
S. G. J. Hardy http://orcid.org/0000-0002-9949-1000
P. Sinclair http://orcid.org/0000-0002-3957-9561
S. Chalmers http://orcid.org/0000-0003-1901-6910
M. Hollings http://orcid.org/0000-0003-1083-1062
J. T. Andersen http://orcid.org/0000-0002-3424-9205

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Criterion Validity and Reliability of a New Medicine Ball Rotational Power Test

Sean G.J. Hardy,[1,2] Oscar W. Stelzer-Hiller,[1] Kate M. Edwards,[1] and Jonathan Freeston[1,3]

[1]Sydney School of Health Sciences, Faculty of Medicine and Health, The University of Sydney, Sydney, Australia; [2]Cricket New South Wales, New South Wales, Australia; and [3]Cleveland Guardians Baseball Club, Cleveland, Ohio

Abstract

Hardy, SGJ, Stelzer-Hiller, OW, Edwards, KM, and Freeston, J. Criterion validity and reliability of a new medicine ball rotational power test. *J Strength Cond Res* 39(3): e429–e435, 2025—This study assessed the validity and reliability of 2 medicine ball rotational power assessments, the novel push for maximum velocity by radar (MB_{vel}), and the commonly used push for maximum distance by tape measure (MB_{dis}), against the criterion reference 3-dimensional motion capture (MoCap) to identify the best-practice field-based assessment. Fifteen professional female cricketers volunteered for 2 testing sessions each comprising of a specific warm-up and 24 (12 MB_{vel}, 12 MB_{dis}) maximal throws of a 2-kilogram medicine ball. Radar velocity and tape measure distance were compared with MoCap velocity and projectile motion calculated distance overall, and by dominant and nondominant sides. Statistical analysis included intraclass correlations (ICCs) for accuracy (1, 1) and reliability (3,1), Bland-Altman plots for bias precision and limits of agreement, linear regression (R^2) for variance, and Pearson's (r) for correlation. Significance was set $\alpha = 0.05$. MB_{vel} demonstrated excellent accuracy (ICC = 0.97 [0.97–0.98]), and nearly perfect agreement for bias (−0.09%) and precision (1.49%). Side-to-side analysis showed the same profile for MB_{vel} dominant (ICC = 0.96 [0.95–0.97], bias −0.15%, precision = 1.55%) and nondominant sides (ICC = 0.97 [0.96–0.98], bias −0.05%, precision = 1.53%). MB_{vel} demonstrated excellent reliability overall (ICC = 0.94 [0.82–0.98]) for dominant (ICC = 0.88 [0.69–0.97]) and nondominant sides (ICC = 0.93 [0.80–0.98]). MB_{dis} showed poor accuracy (ICC = 0.38 [0.28–0.47]), large bias (12.43%), lower precision (4.55%), and moderate reliability (ICC = 0.72 [0.32–0.90]). The MB_{vel} assessment validly and reliably measures rotational power performance, enabling practitioners to profile, benchmark, and assess the quality in the field.

Key Words: velocity, field-based, athlete assessment, plyometrics, bat and club sports, velocity-based training

Introduction

Rotational power is associated with performance in a number of sports including baseball, cricket, European handball, golf, tennis, and water-polo (12,17,36,40). The physical quality plays an important role in underpinning multiple athletic tasks across sports including throwing (12,17) and performing bat, club, or racket shots (29,34,36,40). Strength and conditioning programs within these sports commonly use various methods to develop and enhance rotational power to drive athletic performance (5,8,25,27,28,34) including heavy lower and upper-body strength training, plyometric exercises, and medicine balls throws (11,31,34).

Medicine ball throws are the most widely studied method of developing rotational power in athletes across a variety of age groups and performance settings (1,5,8,34). There is strong evidence for both the efficacy of medicine ball throws for power training (1,5,8,34) and the ecological validity of completing high velocity multiplanar movements that are reflective of actions performed in a sport setting (8). For example, the medicine ball rotational throw exercise allows a cricket athlete to take a side-on athletic stance akin to their batting stance in match, hold a 1- or 2-kg medicine ball similar to their individual bat mass, complete a reactive counter-rotation, and explosively throw the ball using a comparable movement pattern with similar timing to the on-field execution of powerfully hitting a ball. Such is the versatility of medicine ball throws that strength and conditioning coaches across various sports use some version of a rotational medicine ball throw to target a variety of sporting actions including batting and overhead throwing in baseball (34,36), pace bowling in cricket (21), and ground stroke play in tennis (29). Given the popularity, efficacy, and effectiveness of medicine ball training for sport-specific movements, the ability to accurately assess medicine ball training would be highly advantageous for practitioners across environments.

The valid and reliable assessment of rotational power is critical to strength and conditioning practice among rotational athletes. Periodic assessment of this physical capacity allows practitioners to describe and benchmark individual and team performance, and evaluate the effectiveness of rotational power training programs. For practitioners seeking to use field-based assessments, the proxy measures of medicine ball throws for maximum distance by visual inspection (17,23,28,30,33,37) and throws for maximum velocity by radar device (12,34,36) are the dominant choices, followed by cable pulley rotations for power by linear position transducer (40) and external dynamometer (1). Although laboratory-based testing has the ability to quantify rotational power, research to date has centered on the motion capture and subsequent kinematic outcomes of athletes completing sporting movements rather than specifically designed rotational power assessments (22,26,34).

Address correspondence to Sean G.J. Hardy, shar7470@uni.sydney.edu.au.

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Despite the seemingly broad array of available testing options, the current set of rotational power assessments are deficient in their ability to support elite sport performance. The field-based assessments use throw methods without criterion reference validity and reliability, spurious performance data, or protocols requiring seated or kneeling positions wholly unreflective of many sporting actions that practitioners are seeking to support. Laboratory-based testing yields highly accurate information but requires specialist equipment and a significant time cost, both of which are not feasible for practitioners in elite environments.

Given that rotational power is an important quality in many sports that practitioners regularly seek to enhance to drive athletic performance, there is a clear need to establish an accurate and reliable way to measure this capacity, to better support strength and conditioning programs through evidence-based practice. Therefore, the purpose of this study was to assess the validity and reliability of both a novel rotational power test the medicine ball push for maximum velocity (MB_{vel}) and the commonly used assessment the medicine ball push for distance (MB_{dis}) and identify the best-practice field-based measure to assess rotational power by proxy.

Methods

Experimental Approach to the Problem

This study was designed to assess the validity and reliability of 2 medicine ball rotational power tests MB_{vel} and MB_{dis}, which use proxy measures of velocity and distance, in comparison with the gold-standard criterion reference of three-dimensional motion capture (MoCap) (Vicon Vero; Vicon Motion Systems, Oxford, United Kingdom). A 2-kg medicine ball mass was chosen to reflect the average senior professional cricket bat mass of 1–2 kg in line with methods used in previous baseball research (35), and to be within the range of medicine ball masses previously used in similar rotational power assessments from 1 to 6 kg (17,28,35,36). Subjects volunteered from the senior women's New South Wales (NSW) state cricket team and attended 2 testing sessions separated by 1 week. No familiarization sessions were included because of the subjects' vast previous exposure to the MB_{vel} and MB_{dis} tests, respectively, with Cricket NSW using both assessments as part of a regular in-house performance testing battery across the past 2 seasons. Intra- and interday reliability were determined via the intraclass correlation (ICC), bias and precision were calculated using Bland-Altman plots, and the coefficient of variation (CV) and SEM were evaluated for both tests.

Subjects

Fifteen cricketers from the NSW professional senior women's state cricket team volunteered to participate in this study (mean ± *SD*: age 23.24 ± 3.76 years, height 169.9 ± 6.3 cm, body mass 71.4 ± 11.9 kg, training age 4.80 ± 3.95 years). All subjects were older than 18.0 years (range: 19.29–30.80 years) and were free from injury at the time of data collection. All subjects were professional athletes competing at a senior state or national level and regularly completed comprehensive physical preparation programming including strength and power training using medicine ball throw work twice per week. This study was approved by the University of Sydney Human Research Ethics Committee (Project Number 2022/466), and before providing informed consent, all subjects were presented with information regarding the study protocol, inclusion criteria (senior professional female cricketer, free from injury), and the benefits and risks of volunteering.

Procedures

Data collection occurred over 2 testing sessions separated by 7 days. During the first session, age, body mass, height, dominant batting hand, number of years played professionally, and highest professional level played were recorded for all subjects. Both sessions consisted of the same physical performance warm-up routine and the same volume of test repetitions on each side (left and right) for MB_{vel} and MB_{dis} conditions. Both sessions were conducted at the same time of day, and subjects were directed to continue with their normal nutrition and hydration schedule.

Each testing session began with subjects completing a specific prescribed warm-up routine consisting of dynamic stretching and mobility, general strength movements, and plyometrics (for details see Supplemental Digital Content 1, http://links.lww.com/JSCR/A554). Subjects then performed a rotational power assessment consisting of 24 total (12 MB_{vel} and 12 MB_{dis}) maximal effort throws of a 2-kg medicine ball. Throws were completed in sets of 6 per round comprising of 3 left-and right-sided efforts randomly ordered for each subject. Throws were conducted using a carousel queue where a subject completed 1 throw and then proceeded to rest, whereas the rest of the group completed a single effort each. This method ensured a rest time of 60–70 seconds between maximal effort throws inside each set in line with previous medicine ball throw research (17,33). In addition, subjects were allocated 3 minutes of rest after completing each set for a given condition as an additional safeguard against fatigue over the 24 maximal effort throws required in each session.

The condition for the first set of throws was randomly allocated as either MB_{vel} or MB_{dis}. The following 3 sets then alternated condition based on the first allocation (for example, set 1 = MB_{vel}, therefore, set 2 = MB_{dis}, set 3 = MB_{vel}, set 4 = MB_{dis}). The alternating condition design was used as an additional safeguard against fatigue to ensure that upon randomization neither protocol was allocated consecutively to sets 3 and 4.

For all testing throws across both conditions, subjects were instructed to follow the protocol below. A kinogram of the protocol is shown in Figure 1.

- Subject stands in side-on "athletic stance" with lateral edge of front shoe aligned with zero-point tape line on laboratory floor, rear arm the assigned pushing arm
- Subject holds medicine ball at shoulder height in contact with chest, uses front arm to support mass of ball from underneath, rear arm is cocked with hand placed on the back of ball
- Subject completes throw by rapidly counter-rotating away from throw direction in transverse plane with feet fixed on floor before immediately rotating back and explosively pushing ball forwards, completing any follow through movement of body and feet after ball release

Specific cues were given to subjects for each test type. For MB_{vel} trials, subjects were instructed to "explosively push the ball as fast and as hard as possible towards the radar gun." For MB_{dis} trials, subjects were instructed to "explosively push the ball as fast and as hard for the longest possible distance."

All trials used a three-dimensional 16-camera motion analysis system (Vicon Vantage; Vicon Motion Systems) to record subject hand and medicine ball kinematic data at a sampling rate of 240 Hz. Reflective markers were placed on both wrists and hands for all subjects at the ulnar and radial styloids and dorsally at the

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Figure 1. Kinogram displaying the medicine ball rotational power throw for velocity MB_{vel} assessment.

second and fifth metacarpophalangeal joints using a 4-marker hand model, and an additional fifth marker was placed on the back of the left hand to differentiate sides. Reflective markers were also placed on the medicine ball using a 5-marker model with 4 markers at an equal distance around the widest circumference of the ball and a fifth marker positioned at a location with a different surface distance to each of the 4 equally spaced markers. Marker trajectory data were filtered using a low-pass Butterworth filter with a cutoff frequency of 18 Hz and exported to Visual 3D (C-Motion, Inc., Germantown, MD) for analysis.

Center of gravity (CoG) models were created for the medicine ball and both hands. Position, velocity, and projection angle data for all trials were determined using the laboratory coordinate system and 2 events during each throw: point of release (P_{rel}) defined as the first frame at which the medicine ball and hand CoG models separated and increased distance apart, and point of release +5 frames (P_{rel+5}) as the frame 5 additional frames forward in the trial. Height of release was calculated as the vertical distance from the laboratory floor to medicine ball CoG at P_{rel}. Horizontal (left and right) and vertical (up and down) projection angles were calculated via a 5-frame medicine ball CoG trajectory from P_{rel} to P_{rel+5}. Maximum velocities in each of the x, y, and z (v_x, v_y, v_z) directions were calculated as the peak value of medicine ball CoG velocity averaged over 5 frames from P_{rel} to P_{rel+5}. The maximum velocity for MB_{vel} trials was calculated as the resultant velocity of $v_x + v_y + v_z$. Throw distance for MB_{dis} trials was calculated as the horizontal distance from P_{rel} to first landing by projectile motion ignoring the effects of air resistance and spin as per similar work completed in shot put (16,20).

In addition, for comparison with field-based measurement techniques, MB_{vel} trials used a radar gun (Stalker ProIIs; Applied Concepts, Inc., Plano, TX) set to continuously transmit positioned 5 m directly in front of the subject's lead foot at a height of 1.5 m to measure the maximum velocity for each throw, and MB_{dis} trials used a tape measure with the zero line at the lateral edge of the lead foot and distance extending straight out along the laboratory floor with visual identification of the distance upon first landing for each throw. Power was not directly measured for either condition with velocity and distance used as proxy measures.

Statistical Analyses

All statistical analysis was completed using *R* (version 4.2.3; RStudio, Boston, MA). A total of 672 trials were completed during data collection. And 45 trials (6.7%) were omitted because of missing data (e.g., marker occlusion), resulting in 627 successful trials (316 MB_{dis} + 311 MB_{vel}) available for analysis. Data were first checked for normality using Shapiro-Wilk testing before the mean and *SD* for all outcome variables were calculated (Table 1). An ICC power analysis was conducted using a minimum acceptable reliability = 0.80, expected reliability = 0.90, $\alpha = 0.05$, and $\beta = 0.20$ and showed that a minimum of $n = 58$ throws per assessment type were required to reach statistical significance.

The CV and *SEM* were calculated for MoCap, radar velocity, and tape measure distance for all trials. Condition accuracy and reliability were determined via ICCs (1, 1) and (3,1), respectively, and interpreted as excellent >0.9, good 0.75–0.9, moderate 0.5–0.75, and poor <0.5 (19). Bias, precision, and upper and lower limits of agreement were established using Bland-Altman plots (3,13). Bias was calculated as the mean difference between MoCap and each condition, precision as the *SD* of the difference between MoCap and each condition. Variance and correlation between MoCap and each condition were calculated using linear regression (R^2) and Pearson's correlation (r). Pearson's r was interpreted as large 0.50–0.70, very large 0.70–0.90, and nearly perfect >0.90 (15). Data were then split into dominant and nondominant throws by classifying the assigned rear pushing arm according to each subjects' dominant batting hand before the analysis above was then repeated in full. Significance for all analyses was set a priori at $\alpha = 0.05$.

Results

The radar assessment method demonstrated excellent accuracy (ICC = 0.97 [0.97–0.98]) compared with MoCap, whereas the distance method showed poor accuracy (ICC = 0.38 [0.28–0.47]). MB_{vel} displayed nearly perfect agreement with MoCap for both bias (−0.09%) and precision (1.49%), whereas MB_{dis} yielded large bias (12.43%) and lower precision (4.55%). The relative variation and *SEM* were calculated to be CV = 4.19%, *SEM* = 0.08 $km \cdot h^{-1}$ for MB_{vel} and CV = 9.55%, *SEM* = 0.05 m for MB_{dis}. MB_{vel} demonstrated excellent between-session reliability compared with MoCap (ICC = 0.94 [0.82–0.98]), whereas MB_{dis} showed moderate reliability (ICC = 0.72 [0.32–0.90]). The side-to-side analysis of MB_{vel} throws follows the same profile as the overall MB_{vel} analysis above for both dominant (ICC = 0.96 [0.95–0.97], bias −0.15%, precision = 1.55%, CV = 2.32%, *SEM* = 0.07 $km \cdot h^{-1}$) and nondominant (ICC = 0.97 [0.96–0.98], bias −0.05%, precision = 1.53%, CV = 2.57%, *SEM* = 0.07 $km \cdot h^{-1}$) throws. Across multiple sessions, both dominant (ICC = 0.88 [0.69–0.97]) and nondominant (ICC = 0.93 [0.80–0.98]) MB_{vel} assessments have confirmed good to excellent reliability. The full set of results comparing MoCap to MB_{vel} and MB_{dis} conditions are shown in Table 2, and plots of the Bland-Altman analysis of bias and precision are shown in Figure 2.

Discussion

The purpose of this study was to assess the validity and reliability of 2 medicine ball rotational power assessments MB_{vel} and MB_{dis} with the aim of identifying an effective field-based test. The results

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Table 1

Descriptive statistics of mean ± *SD* for 3-dimensional motion capture (MoCap) outcome measures of resultant velocity, projected distance, horizontal projection angle, vertical projection angle, and height of release for all medicine ball velocity (MBvel) and medicine ball distance (MBdis) trials.

	Resultant velocity Mean ± *SD* ($km \cdot hr^{-1}$)	Projected distance Mean ± *SD* (m)	Horizontal projection angle (−ve = left of thrower, +ve = right of thrower) Mean ± *SD* (°)	Vertical projection angle (+ve = up, −ve = down) Mean ± *SD* (°)	Height of release Mean ± *SD* (m)
MB_{vel} (*n* = 311)	35.19 ± 2.20	—	0.56 ± 4.01	6.08 ± 3.21	1.52 ± 0.08
Dominant (*n* = 157)	36.14 ± 2.31	—	−1.44 ± 3.53	5.89 ± 3.17	1.51 ± 0.08
Nondominant (*n* = 154)	34.22 ± 2.09	—	2.60 ± 3.41	6.27 ± 3.26	1.53 ± 0.09
MB_{dis} (*n* = 316)	33.93 ±2.18	10.62 ± 1.23	1.82 ± 3.79	19.22 ± 4.14	1.74 ± 0.11
Dominant (*n* = 161)	34.97 ± 1.80	11.10 ± 1.06	0.74 ± 3.41	19.24 ± 4.04	1.73 ± 0.11
Nondominant (*n* = 155)	32.85 ± 2.03	10.13 ± 1.20	2.93 ± 3.86	19.20 ± 4.26	1.76 ± 0.11

clearly demonstrate that only MB_{vel} accurately measured rotational power (ICC = 0.97 [0.97–0.98]), and that MB_{dis} lacked the accuracy (ICC = 0.38 [0.28–0.47]) to be used in the field. The results further establish the MB_{vel} condition's efficacy, showing accurate assessment of both dominant (ICC = 0.96 [0.95–0.97]) and nondominant (ICC = 0.97 [0.96–0.98]) throws. When both conditions were assessed for reliability over multiple sessions (Table 2), MB_{vel} (ICC = 0.94 [0.82–0.98]) outperformed MB_{dis} (ICC = 0.72 [0.32–0.90]) and maintained good to excellent reliability for dominant (ICC = 0.88 [0.69–0.97]) and nondominant (ICC = 0.93 [0.80–0.98]) throws.

Bland-Altman analysis of both conditions (Figure 2) revealed a strong contrast in profiles of bias and precision. Across overall, dominant, and nondominant analyses, MB_{vel} repeatedly demonstrated nearly perfect agreement with MoCap for both bias (−0.05 to −0.15%) and precision (1.49–1.55%). Comparing MB_{vel} with common assessments in elite sport settings including countermovement jump height (39) (bias = −3.05%, precision = 8.52%) and back squat mean concentric bar velocity (10) (bias = −3.64%, precision = 2.05%), the level of error calculated is exceptionally low. It is noted that across all MB_{vel} trials, there was a small yet consistent overestimation by radar versus MoCap (Table 2). Given the already established global and multisport accuracy and reliability of radar technology (4,7,9,14,24,32), it is unlikely that the bias recorded here represents a true difference between measurement systems. Another potential explanation of the bias may be found in review of calculation differences between systems. Specifically, MoCap resultant velocity was calculated as the average peak velocity over 5 frames from P_{rel} to $P_{rel\,+\,5}$, whereas radar recorded a maximum instantaneous velocity reached for the full duration of each trial at a collection frequency of 34.7 GHz. The use of instantaneous (absolute maximum) and 5-frame average (average peak maximum) velocities in this way provide a plausible explanation for the small bias identified.

The difference in results between MB_{vel} and MB_{dis} is significant given the widespread use of the MB_{dis} condition among strength and conditioning professionals (albeit using different throw techniques) both in research settings and across performance environments (8,17,23,27,28,30). This is the first study to evaluate the validity and reliability of distance-based medicine ball throws as a measure of rotational power. These findings call into question the accuracy of such approaches, with significant implications for strength and conditioning practitioners currently using this assessment method. The lack of criterion reference validity and reliability research and the recurrent use of distance-based throw assessments in publication have led practitioners to assume that distance-based assessments can accurately measure performance. In the context of the results shown for MB_{dis} above, this is not the case, and without known bias and precision, environments using throws for distance should interpret results with caution.

The superior performance of MB_{vel} compared with MB_{dis} can be broken down into 2 areas: (a) condition specific constraints and (b) the measurement systems. Condition specific constraints are best understood by an ecological dynamics approach (2,6,18), where the movement outcome (medicine ball throw) is a product of the interaction between constraints of the environment, task, and organism, and subsequent self-organization of the subject to execute the task. MB_{vel} and MB_{dis} contain 2 differences in constraints: the condition specific cue either to push as hard and as fast as possible (MB_{vel}) or for the longest distance possible (MB_{dis}), and the measurement equipment as either radar gun or tape measure line. The results in Table 1 demonstrate that these differences contribute to different performance results for each condition. During MB_{dis} trials, subjects were unable to optimize their throw trajectory for best possible distance, producing an overall vertical projection profile of 19.2 ± 4.1°, well below values identified in shot put, optimal angle 42°, and range of angles for elite throwers 26–41° (20). The inability of subjects to throw in the ideal range of trajectories significantly impacts the distance thrown and consequently the MB_{dis} condition's ability to measure true maximum rotational power. In addition, all types of MB_{dis} throws also displayed a comparatively lower MoCap mean peak resultant velocity versus MB_{vel} throws, despite both conditions being cued as maximum efforts and resultant velocity being summed in all 3 vector directions. A feasible explanation for these different results could be that the radar gun more effectively constrains subjects to throw maximally at a single target in space compared with the extended tape measure line as a target throwing plane. These findings demonstrate that subjects completing MB_{dis} throws were unable to optimize their task execution producing throws at lower resultant velocities with suboptimal projection angles. The MB_{dis} outcome measures of resultant velocity and distance, therefore, underrepresent true maximal rotational power expression and show that MB_{dis} is reliant on elements of skill in combination with power to meet task constraints. Conversely, MB_{vel} does not experience this same limitation and is better able to purely measure rotational power expression.

The measurement systems used to assess rotational power for each condition play a key role in contributing to the significantly different accuracy of radar (ICC = 0.97 [0.97–0.98]) and tape

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Table 2
Mean ± *SD* throw velocity for MB_{vel} and throw distance for MB_{dis} by three-dimensional motion capture (MoCap) and radar or tape measure.*

Test type	MoCap Mean ± *SD* (km·h^{-1})	Radar Mean ± *SD* (km·h^{-1})	ICC (1, 1) Accuracy radar Mean (CI)	ICC (1, 1) Accuracy radar Classification	Bland-Altman Bias Mean diff, km·h^{-1} (%)	Bland-Altman Precision ±*SD* of diff, km·h^{-1} (%)	Linear regression R^2 (*r*)	ICC (3,1) Reliability vs. MoCap Mean (CI)	ICC (3,1) Reliability vs. MoCap Classification	ICC (3,1) Reliability vs. radar Mean (CI)	ICC (3,1) Reliability vs. radar Classification
MB_{vel}											
Overall	35.12 ± 1.47	35.15 ± 1.54	0.97	Excellent	−0.03 (−0.09%)	0.52 (1.49%)	0.95 (0.97)	0.93	Excellent	0.94	Excellent
n = 311	CV = 4.19, SEM = 0.08	CV = 4.38, *SEM* = 0.09	0.97–0.98		LoA: −1.06 to 1.00		*p* = 0.00	0.80–0.98		0.82–0.98	
Dominant hand	36.06 ± 0.83	36.10 ± 0.93	0.96	Excellent	−0.05 (−0.15%)	0.53 (1.55%)	0.92 (0.96)	0.90	Good	0.88	Good
n = 157	CV = 2.32, *SEM* = 0.07	CV = 2.59, *SEM* = 0.07	0.95–0.97		LoA: −1.09 to 0.99		*p* = 0.00	0.72–0.97		0.69–0.97	
Nondominant hand	34.14 ± 0.87	34.16 ± 0.98	0.97	Excellent	−0.02 (−0.05%)	0.52 (1.53%)	0.94 (0.97)	0.94	Excellent	0.93	Excellent
n = 154	CV = 2.57, *SEM* = 0.07	CV = 2.88, *SEM* = 0.08	0.96–0.98		LoA: −1.04 to 1.01		*p* = 0.00	0.81–0.98		0.80–0.98	

Test type	MoCap Mean ± *SD* (m)	Tape measure Mean ± *SD* (m)	ICC (1, 1) Accuracy tape measure Mean (CI)	ICC (1, 1) Accuracy tape measure Classification	Bland-Altman Bias Mean diff m (%)	Bland-Altman Precision ±*SD* of diff m (%)	Linear regression R^2 (*r*)	ICC (3,1) Reliability vs. MoCap Mean (CI)	ICC (3,1) Reliability vs. MoCap Classification	ICC (3,1) Reliability vs. tape measure Mean (CI)	ICC (3,1) Reliability vs. tape measure Classification
MB_{dis}											
Overall	10.54 ± 1.00	9.24 ± 0.71	0.38	Poor	1.31 (12.43%)	0.48 (4.55%)	0.90 (0.95)	0.72	Moderate	0.72	Moderate
n = 316	CV = 9.55, *SEM* = 0.05	CV = 7.69, *SEM* = 0.04	0.28–0.47		LoA: 0.37–2.26		*p* = 0.00	0.32–0.90		0.32–0.90	

*Coefficient of variation (CV) and SEM for MoCap, radar, and tape measure. Assessment accuracy represented by intraclass correlation (ICC). Bias and precision shown by Bland-Altman measures of mean difference and *SD* of the difference between measures. Variance and correlation represented by linear regression (R^2 and Pearson's *r*). Assessment reliability represented by ICC.

measure (ICC = 0.38 [0.28–0.47]). The radar device records an instantaneous maximum velocity without reliance on practitioner input, whereas the tape measure system requires the expert eye of a practitioner to both identify point of landing and estimate distance thrown. The use of expert human eye presents a significant source of potential error given the range of horizontal and vertical projection angles and the subsequent variation in ball trajectories thrown by subjects. During MB_{dis} trials, practitioners are required to account for throws projected across a range of distances forward and multiple meters to the left or right of the central measurement line. During MB_{vel} trials, the radar device performs the equivalent of this task to deal with variation in projection for velocity throws. Although neither method can replicate the criterion measurement of resultant velocity from all 3 vectors with both constrained to the forward direction, the use of human eye for distance trials may explain the contribution of measurement systems to condition accuracy.

As previously mentioned, the ecological validity of physical performance assessments is an important consideration in elite sport environments. Practitioners aim to use assessments that are reflective of an athlete's sporting actions, as seen by the continued use of various medicine ball assessments despite limited or no validity and reliability research available. Practitioners are also often interested in assessing either side-to-side differences or dominant side performance for a given assessment, particularly in unilateral sports such as cricket, tennis, golf, baseball, and softball. This requires the given assessment to have suitable accuracy and reliability on both dominant and nondominant sides to meaningfully compare results and capably detect differences in performance. The MB_{vel} protocol addresses these requirements and provides the most comprehensive assessment of accuracy, bias, precision, and reliability available for rotational power assessments in the literature (Table 2). The MB_{vel} condition is also highly accurate on both sides, with each following the same bias and precision profile as the MB_{vel} overall statistics discussed above, and across multiple testing sessions, both have confirmed reliability to repeatedly assess rotational power (Table 2). In comparison, the alternate assessments currently available in the literature: seated cable rotation via external dynamometry (1) and kneeling cable lift via linear transducer (40) are unable to meet the demands of practitioners in performance settings described above. Both assessments lack ecological validity in their use of seated or kneeling positions and are nonrepresentative of rotational power-based sporting actions completed in standing. Both assessments demonstrate limited accuracy and reliability statistics, with neither using a criterion reference measure, seated cable rotation reporting ICC reliability (0.95–0.97) with no measure of accuracy, and the kneeling cable lift reporting CV (7.4–16.3%) and ICC reliability (0.74–0.94). Furthermore, neither assessment has demonstrated capability to measure side-to-side differences in performance. The MB_{vel} protocol represents a significant progression in the rotational power literature, and in supporting practitioners to accurately assess the capacity in the field.

The MB_{vel} assessment is a new tool for practitioners to use in environments where there is a requirement to measure, benchmark, or track change in rotational power performance. This study has built on the pilot work of various velocity-based throw protocols currently in the literature without validation (12,17,34,36) and is the first study that has successfully validated both the accuracy and reliability of a rotational medicine ball throw for velocity in comparison with the criterion reference of MoCap. This is also the first study specifically assessing rotational medicine ball throws in the transverse plane, with previous

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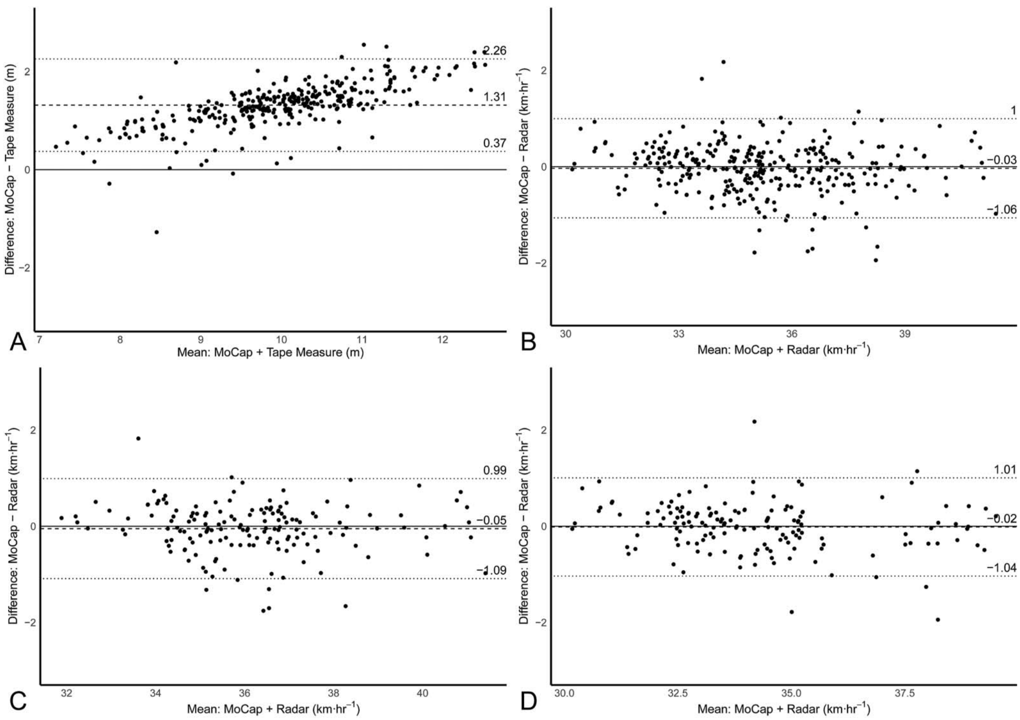

Figure 2. Bland-Altman plots for MB_{dis} and MB_{vel} assessments. Solid line = line of zero difference between measurement systems. Dashed line = bias calculated as the difference between 3-dimensional motion capture (MoCap) and tape measure or radar. Dotted lines = upper and lower limits of agreement (LoA) calculated as bias ± 1.96 · *SD* of the difference between measures (precision). A) MoCap versus MB_{dis}, (B) MoCap versus MB_{vel}, (C) MoCap versus dominant MB_{vel}, and (D) MoCap versus nondominant MB_{vel}.

publications limited to overhead and chest-based throws (33,38). Finally, the MB_{vel} assessment is the first rotational power test in the literature with established accuracy, bias, precision, and reliability across both dominant and nondominant sides (Table 2).

Practical Applications

The MB_{vel} assessment is a valid and reliable way to measure both dominant and nondominant side rotational power performance in elite sport settings using velocity as a proxy measure. This field-based test requires only a radar gun, tripod, and 2-kg medicine ball and permits practitioners to move from laboratory to performance environments while still accurately assessing rotational power. The test enables practitioners to describe the rotational power profile of both individual athletes and teams, establish benchmarks specific to a given performance setting, and evaluate the effectiveness of program interventions.

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ORIGINAL INVESTIGATION

The Physical Determinants of Bat Speed in Elite Female Cricketers

Sean G.J. Hardy,[1,2] **Kate M. Edwards,**[1] **and Jonathan Freeston**[1,3]
[1]Sydney School of Health Sciences, Faculty of Medicine and Health, University of Sydney, Sydney, NSW, Australia;
[2]Cricket New South Wales, Sydney, NSW, Australia; [3]Cleveland Guardians Baseball Club, Cleveland, OH, USA

Purpose: This study explored the association between strength and power capacities and bat speed in female cricketers to inform strength and conditioning practices. ***Methods:*** Twenty-nine professional female cricketers volunteered for 3 testing sessions. Day 1: participant information, grip strength, medicine-ball push for maximum velocity, 10/5 Reactive Strength Index Hop Test. Day 2: isometric midthigh pull, vertical jump, 1-repetition-maximum (1RM) bench pull, and maximum-repetition body-weight push-up. Day 3: maximal bat speed for 4 cricket shots—cut (BS_{cut}), drive (BS_{drive}), pull (BS_{pull}), and slog (BS_{slog})—versus 3 delivery types (off-spin, medium, and fast). Statistical analysis ($\alpha = .05$) included Pearson r, multiple linear regression (R-squared), and 1-way repeated-measures analysis of variance with Tukey HSD analysis. ***Results:*** Overall bat speed was associated with absolute 1RM bench pull ($r = .70$, $P < .0001$), dominant medicine-ball push for maximum velocity ($r = .65$, $P < .0001$), nondominant medicine-ball push for maximum velocity ($r = .60$, $P < .0001$), and absolute isometric midthigh pull ($r = .47$, $P = .01$). Physical capacities regression modeling explained 52.7% of variance in bat speed overall (adjusted R-squared = .5267, standard error of estimate = 2.40, $P < .0001$). BS_{cut} was slower than all shots ($P < .0001$). BS_{cut} ($P < .0001$), BS_{drive} ($P < .0001$), and BS_{pull} ($P < .0001$) were slower during fast versus off-spin deliveries. ***Conclusions:*** Absolute upper-body pulling strength, dominant rotational power, and absolute total-body isometric strength are critical qualities for power-hitting training in female cricketers. Practitioners may include these findings in their program design to better support female athletes.

Keywords: correlation, power hitting, bat and club sports, velocity, strength and power training

Power hitting is an important aspect of batting and match success in professional women's cricket for both the 50-over and T20 formats.[1–3] Power hitting is the ability of a batter to strike the ball with high velocity along the ground, or through the air across the boundary, scoring either 4 or 6 runs (the 2 highest scoring options).[4] Winning teams have been shown to score runs at a higher rate,[1,3] hit more boundaries,[1,3] and accumulate fewer non and single-run scoring shots[1,3] than their opposition.

Despite the importance of power hitting for match success in short format women's cricket,[1,3] there is limited research to support practitioners beyond biomechanical analysis. This data provides 2 foundational principles: First, a batter's ability to increase their hitting distance is underpinned by faster bat speed,[5] which leads to faster ball launch velocity,[4] and in combination with the optimal vertical launch angle leads to greater shot distances.[4] Second, female batters exhibit a unique kinematic profile and movement solution when power hitting compared with male batters.[6] This difference is likely a combination of multiple factors, including differences in anatomy and anthropometry, training environment, and task constraints.[6] The evidence for physical capacities and power hitting in cricket relies on the contribution of a single study in male batters which shows a large association between upper body pushing strength and maximum hitting distance.[7] However, this finding may have limited application in women's cricket. The unique hitting technique used by female batters, including a bent lead elbow and a close bat to body position[6] may render the association for upper body pushing strength not applicable in female environments. Furthermore, it is entirely plausible that the specific power hitting technique employed by female batters may be underpinned by unique physical determinants. These may include a number of physical capacities; and therefore, research in female power hitting needs to progress to explore a broad range of potential associations.

In comparison, previous work in other bat, club, and racket sports, such as baseball,[8,9] golf,[10–12] softball,[13] and tennis[14] has employed this broad investigative approach with significant results. Rotational power,[9,10,14] lower body power,[9–11,15] lower body strength,[15] total body force production,[11,12] and upper body pushing strength[9,11,15] are consistently associated with bat, clubhead, and racket speed. These findings are pivotal as they enable practitioners to deliver specific programming interventions, explore causal relationships, and target the physical determinants of sport performance.[8] An example of this is the evidence base for clubhead speed in women's golf where broad explorations of physical capacities[11,12] have led to specific training interventions and subsequently enhanced clubhead speed and hitting distance. This is best-practice strength and conditioning support for elite athletes, and the same approach needs to be adopted for power hitting in female cricket.

This study therefore, sought to explore the associations between physical capacities and bat speed in elite female cricketers in order to (1) significantly advance the evidence base and inform strength and conditioning practices for this cohort and (2) help address the underrepresentation of female athletes in cricket research, and sport and exercise science more broadly.[16]

Edwards https://orcid.org/0000-0003-3429-5989
Freeston https://orcid.org/0000-0003-4383-1712
Hardy (shar7470@uni.sydney.edu.au) is corresponding author, https://orcid.org/0000-0002-9949-1000

Methods

Experimental Design

This study was designed to explore the physical determinants associated with bat speed in elite female cricketers using an observational cross-sectional study design. Participants attended 3 testing sessions each separated by 1 week during the in-season competition period. The first 2 sessions involved a battery of anthropometry, strength and power assessments, and the third utilized a novel protocol to assess bat speed. No familiarization sessions were sought due to the participants' significant experience with the assessments, all of which form part of an in-house Cricket New South Wales testing battery.

Participants

Twenty-nine professional cricketers from the Cricket New South Wales women's team, the Sydney Sixers, and Sydney Thunder Women's Big Bash League teams consented to take part in this study (mean [SD]: age 22.75 [5.10] y, height 170.4 [6.2] cm, body mass 68.7 [9.4] kg, professional experience 4.55 [5.04] y). All participants were older than 18.0 years and free from injury at the time of data collection. This study was approved by the University of Sydney Human Research Ethics Committee (Project Number 2019/712), and prior to providing informed consent, all participants were presented with information regarding the study protocol, inclusion criteria (senior female cricketer, free from injury), as well as the benefits and risks of volunteering.

Methodology

At the beginning of each testing session, a warm-up routine designed to prepare participants for the assessments was delivered (see Supplementary Material S1 [available online]). On day 1, participant information was recorded including age; batting hand, defined as the hand closest to the bat face on handle when batting; number of years played professionally; height; and weight. Participants then completed strength and power assessments including bilateral Grip Strength, medicine ball push for maximum velocity (MB_{vel}), and 10/5 Reactive Strength Index Hop Test. On day 2, participants completed isometric mid-thigh pull (IMTP), vertical jump, 1 repetition-maximum (1RM) bench pull (BP), and maximum repetition body weight push up. On day 3, participants were assessed for maximal bat speed across 4 different shots including Cut (BS_{cut}), Drive (BS_{drive}), Pull (BS_{pull}), and Slog (BS_{slog}). The full details and methodology of the testing framework can be found in the supplemental digital content.

Day 1

Participants completed a day 1 warm-up routine (Supplementary Material S2 [available online]) and then assessments in the following order:

Grip Strength. A handgrip dynamometer (Hydraulic Hand Dynamometer Jamar 5030JI) was used to assess participant grip strength following the Canadian National Hockey League combine testing protocol.[17] The maximum score in kilograms for each hand was recorded for further analysis.

Medicine-Ball Push. Rotational power was assessed using a 2-kg medicine ball and a radar gun (Stalker ProIIs, Applied Concepts Inc), following the published protocol.[18] The maximum speed on each side in kilometer per hour was recorded for further analysis.

10/5 Hop Test. Reactive Strength Index was assessed following the published protocol[19] using a Force Decks FD4000 dual force plate system (Vald Performance). The highest peak Reactive Strength Index across the 3 attempts was recorded for further analysis.

Day 2

Participants completed a day 2 warm-up routine (Supplementary Material S3 [available online]) and then assessments in the following order:

Isometric Midthigh Pull. Total body isometric strength was assessed following the published protocol[20] using a Force Decks FD4000 dual force plate system (Vald Performance) and isometric Vald Performance testing rig. The maximal force generated measured in Newtons (N) across all 3 attempts was recorded for further analysis.

Vertical Jump. Lower-body power was assessed using a Swift Yardstick jump measure system (Sports Imports) following the published protocol.[21] Final jump height measured in centimeters (cm) was recorded for further analysis.

Bench Pull. Upper-body maximum pulling strength was assessed using the prone lying bench pull protocol[22] and the established 1 repetition maximum (1RM) framework.[23] The maximum weight successfully lifted, measured in kilograms (kg), was recorded for further analysis.

Push-Up. Upper-body pushing strength was assessed using the bodyweight push up for maximum repetitions. The testing was conducted using an in-house Cricket New South Wales protocol developed from published literature confirming the validity of the push up as a measure of pushing strength.[24] Participants were instructed to lay prone on the ground self-selecting preferred hand position, aligning the center of their chest to contact a 5-kg weight plate, with feet shoulder-width apart. Participants were then instructed to push up to both arms fully extended, while at the same time maintaining a straight line between shoulders, hips, knees, and ankles. Participants were also instructed to ensure trunk control with only minor movement allowed. From the top position, participants were to immediately return to the ground and repeat this cycle as many times as possible with no rest in either position. Any repetitions that did not meet the required depth, contained excessive and significant trunk extension resulting in shoulders hips knees and ankles to be miss-aligned, engaged in uneven arm movement with hips assisting by "kipping," were rejected. Two repeated criteria failures ended the test. The maximum number of successful repetitions was recorded for further analysis.

Day 3

Participants completed a day 3 warm-up routine (Supplementary Material S4 [available online]) and were then assessed for bat speed. Bat speed was measured using a validated bat-mounted sensor (Blast Baseball, Blast Motion Inc). The sensor comprises an accelerometer, gyroscope, and magnetometer device in a unit mounted to the handle of the bat. Bat speed is recorded as the maximal linear speed 15 cm from the tip of the bat along the center of the bat's long axis at the frame immediately prior to contact. While originally designed for baseball, previous unpublished work (Hardy, June 2025. Accuracy of a bat-mounted sensor for the measurement of bat speed among elite female cricket players) comparing the device to 3-dimensional motion capture shows the sensor is accurate and reliable for application in cricket batting with an overall bias of 2.7%, precision of 5.1%, and good absolute agreement (intraclass correlation coefficient = .86 [.77–.92]).

Participants completed testing at the Cricket NSW indoor facility on standard synthetic cricket pitches. Participants were instructed to use their normal matchday protective equipment and bat. Participants performed 4 different types of maximal effort cricket shots (Cut, Drive, Pull, Slog) while facing 3 different types of delivery (Fast, Medium, Off-Spin). A kinogram of the 4 different shots can be seen below in Figure 1. The Slog shot was only performed during Off-Spin deliveries, all other shots were

Figure 1 — Kinograms displaying the cut (A), drive (B), pull (C), and slog (D) shot types for the maximal-bat-speed assessment. Arrows represent intended ball trajectory.

performed across all delivery types. Deliveries were performed by a professional level batting coach using a match condition cricket ball. Delivery types were split into designated speed ranges: Fast (100–115 km·hr^{-1}), Medium (90–100 km·hr^{-1}), and Off-Spin (70–80 km·hr^{-1}). Speed for each was recorded using a radar gun (Stalker ProIIs, Applied Concepts Inc). Only deliveries within the designated ranges were included in the assessment. Participants were required to perform 5 successful attempts for each shot type to each delivery type for a total of 50 successful shots (15 Cuts, 15 Drives, 15 Pulls, 5 Slogs). A successful shot was defined as the correct shot type performed and batted ball hit in the intended shot direction. All attempts resulting in misses, edges, incorrect shot selection, and incorrect ball direction were rejected. Delivery types were randomized and performed for full sets of shot types (Cut, Drive, Pull, Slog) prior to changing. Shot types were also randomized and completed in blocks of 5 successful attempts for a given shot. Participants rested 10 seconds between shots, 60 seconds between shot types, and 4 minutes between delivery types. These rest periods were chosen specifically to align with the cluster-set method, which has demonstrated efficacy in maintaining power output and velocity during athletic movement.[25] Standardized instructions were given to participants to "hit the ball as hard and as powerfully as you can." Delivery speed (in kilometer per hour) and bat speed (in kilometer per hour) for BS_{cut}, BS_{drive}, BS_{pull}, BS_{slog}, and $BS_{overall}$ (calculated as the maximum bat speed recorded across all 4 shot types) were recorded for further analysis.

Statistical Analysis

Statistical analysis was completed using R (version 4.2.3). One thousand five hundred and one successful bat speed trials were completed during data collection. Fifty one trials (3.4%) were omitted due to missing Blast Motion sensor data (error given by smart phone app). All testing data were checked for normality using Shapiro–Wilk testing before mean (SD) were calculated for all outcome data (Table 1). Associations between anthropometry, physical assessments, and bat speed measures were determined using Pearson correlation (r). Associations were described as trivial ($r = .0$–$.09$), small ($r = .1$–$.29$), moderate ($r = .3$–$.49$), large ($r = .5$–$.69$), very large ($r = .7$–$.89$), or nearly perfect ($r = .9$–$.99$).[26] Bonferroni P-value corrections[27] were applied to associations identified in this study leading to an adjusted significance for correlations set to $\alpha = .0038$. Significant associations to bat speed overall were screened for collinearity using variance inflation factor <5[28] before being used as input variables for multiple linear regression modeling to explore the variance (R-squared) in overall bat speed explained by physical capacities.[29] Differences in maximum bat speed between shot types, and delivery types were assessed using 1-way repeated-measures analysis of variance testing and post hoc Tukey HSD analysis, with significance set to $\alpha = .05$.

Results

Overall bat speed was positively associated with absolute maximum upper body pulling strength, rotational power, and absolute total body isometric strength (absolute 1RM BP; very large, $r = .70$, $P < .0001$, dominant MB_{vel}; large, $r = .65$, $P < .0001$, nondominant MB_{vel}; large, $r = .60$, $P < .0001$, absolute IMTP; moderate $r = .47$, $P = .006$). The full results of the correlation analysis identifying associations to bat speed overall are shown in Table 2.

The multiple regression model explained 52.7% of the variance in bat speed overall using absolute 1RM BP, dominant MB_{vel}, and absolute IMTP as predictor variables (Equation 1). All variables passed variance inflation factor screening for collinearity

Table 1 Descriptive Statistics for Outcome Measures of all Anthropometric, Strength, Power, and Bat-Speed Assessments

Assessment	Mean	SD	CV, %
Height, cm	170.4	6.2	0.7
Weight, kg	68.7	9.4	0.035
Dominant GS, kg	46.0	5.8	5.70
Nondominant GS, kg	44.1	5.8	7.60
Dominant MB_{vel}, km·hr^{-1}	37.0	1.7	2.30
Nondominant MB_{vel}, km·hr^{-1}	34.3	2.2	2.45
Reactive Strength Index (FT/CT)	2.90	0.38	3.90
Absolute IMTP, N	2792	326	3.35
Relative IMTP (×BW)	4.2	0.6	3.40
Vertical jump, cm	46.3	6.2	6.10
Absolute 1RM BP, kg	57.9	7.2	2.50
Relative 1RM BP (×BW)	0.9	0.2	2.53
Push-up for maximum repetitions	23	11	9.1
BS_{cut}, km·hr^{-1}	73.9	5.9	0.60
BS_{drive}, km·hr^{-1}	84.2	7.0	0.90
BS_{pull}, km·hr^{-1}	86.4	5.3	0.89
BS_{slog}, km·hr^{-1}	85.1	5.9	0.81
$BS_{overall}$, km·hr^{-1}	88.4	5.6	0.93

Abbreviations: BP, bench pull; BS_{cut}, bat speed for cut; BS_{drive}, bat speed for drive; $BS_{overall}$, bat speed for overall; BS_{pull}, bat speed for pull; BS_{slog}, bat speed for slog; BW, body weight; CV, coefficient of variation; FT/CT, flight time/contact time; GS, grip strength; IMTP, isometric midthigh pull; MB_{vel}, medicine-ball push for maximum velocity; 1RM, 1-repetition maximum.

Table 2 Correlation Statistics for Maximum Bat Speed Overall Versus Independent Variables of Anthropometric, Strength, and Power Assessments

	Maximum bat speed	
Independent variable	r	P
Height, cm	−.17	.37
Weight, kg	.28	.14
Dominant GS, kg	.05	.17
Nondominant GS, kg	.26	.79
Dominant MB_{vel}, km·hr^{-1}	.65	<.001*
Nondominant MB_{vel}, km·hr^{-1}	.60	<.001*
Reactive Strength Index (FT/CT)	−.05	.80
Absolute IMTP, N	.47	.006
Relative IMTP (×BW)	.13	.49
Vertical jump, cm	.32	.09
Absolute 1RM BP, kg	.70	<.001*
Relative 1RM BP (×BW)	.29	.12
Push-up for maximum repetitions	.22	.26

Abbreviations: BP, bench pull; BW, body weight; GS, grip strength; IMTP, isometric midthigh pull; MB_{vel}, medicine-ball push for maximum velocity; 1RM, 1-repetition maximum.
*$P < .0038$.

(1RM BP = 1.90, absolute IMTP = 1.25, dominant MB_{vel} = 1.97). This model was shown to be statistically significant ($F_{3, 25}$ = 11.39, adjusted R-squared = .5267, standard error of the estimate = 2.40, P < .0001) with absolute 1RM BP found to be a significant predictor variable (P = .04). Nondominant MB_{vel} was excluded due to very large association between dominant and nondominant rotational power test scores (r = .76, P < .0001).

$$Y = 15.71 + (0.59 \times \text{dominant}\, MB_{vel}) + (0.0021 \times \text{absolute IMTP}) + (0.20 \times \text{absolute BP1RM}). \quad (1)$$

Across all 4 shot types Cut, Drive, Pull, and Slog, moderate to large relationships were shown for dominant rotational power and absolute total body isometric strength (dominant MB_{vel}: r = .43–.60, P = .0001–.02; absolute IMTP: r = .44–.50, P = .01–.02). Drive, Pull, and Slog shots also demonstrated large associations with nondominant rotational power and absolute maximum upper body pulling strength (nondominant MB_{vel}: r = .54–.60, P < .0001; absolute 1RM BP: r = .59–.62, P < .0001). However, these variables were not associated with bat speed for the cut shot.

Physical capacities associated with the Slog shot were unique, including nondominant grip strength, relative maximum upper body pulling strength, lower body power, and upper body pushing strength (nondominant grip strength: r = .43, P = .02; vertical jump: r = .43, P = .02; relative 1RM BP: r = .44, P = .02; push up for maximum repetitions: r = .38, P = .04). The full set of associations can be found in Table 3.

Maximum bat speed differed by both shot and delivery type. The Cut shot was slower than all other shots ($F_{3, 112}$ = 24.52, P < .0001), with significant pairwise comparisons and confidence intervals for Cut-Drive (P < .0001, 3.65–8.93), Cut-Pull (P < .0001, 5.19–10.47), and Cut-Slog (P < .0001, 4.16–9.44). The Cut, Drive, and Pull shots were all slower during Fast versus Off-Spin delivery types (Cut: P < .0001, 0.97–6.38; Drive: P < .0001, 0.91–7.12; Pull: P < .0001, 3.60–8.93). Additionally, the Pull shot was slower when comparing Fast with Medium (P = .020, 0.39–5.73), and Medium with Off-Spin delivery types (P = .014, 0.54–5.87). The full set of descriptive statistics for bat and ball speeds by shot and delivery type can be found in Table 4, and the group average maximum bat speeds used for analysis of variance and Tukey analysis of delivery type can be found in Table 5.

Table 4 Descriptive Statistics for Outcome Measures of Ball Speed by Delivery Type and Bat Speed by Shot Type for 116 Assessments of Maximum Bat Speed

Skills data	Mean (SD), km·hr^{-1}	Min, km·hr^{-1}	Max, km·hr^{-1}
Ball speed by delivery type			
Fast	105.0 (3.8)	101.0	111.1
Medium	94.5 (1.9)	91.6	97.6
Off-spin	72.6 (2.2)	70.0	79.8
Bat speed by shot type			
Cut	73.9 (5.9)	62.6	86.7
Drive	84.2 (7.0)	70.3	100.3
Pull	86.4 (5.3)	75.6	94.3
Slog	85.1 (5.9)	70.0	95.4

Table 3 Correlation Statistics for Maximum Bat Speed by Cut, Drive, Pull, and Slog Shot Types Versus Independent Variables

	Cut shot		Drive shot		Pull shot		Slog Shot	
Independent variable	r	P	r	P	R	P	r	P
Height, cm	.09	.63	–.12	.53	–.01	.95	–.32	.09
Weight, kg	.22	.26	.30	.11	.35	.07	.01	.94
Dominant GS, kg	.19	.32	.16	.40	.01	.98	.17	.36
Nondominant GS, kg	.29	.13	.37	.05	.15	.45	.43	.02
Dominant MB_{vel}, km·hr^{-1}	.43	.02	.49	.01	.60	<.001*	.51	<.001*
Nondominant MB_{vel}, km·hr^{-1}	.24	.21	.54	<.001*	.54	<.001*	.60	<.001*
Reactive Strength Index, FT/CT)	–.20	.30	.03	.86	.00	.99	.17	.39
Absolute IMTP, N	.44	.02	.50	.01	.49	.01	.46	.01
Relative IMTP (×BW)	.18	.34	.14	.46	.09	.64	.35	.06
Vertical jump, cm	.05	.78	.26	.18	.24	.22	.43	.02
Absolute 1RM BP, kg	.30	.11	.59	<.001*	.61	<.001*	.62	<.001*
Relative 1RM BP (×BW)	.07	.73	.22	.26	.16	.39	.44	.02
Push up for maximum repetitions	.05	.80	.07	.70	.11	.57	.38	.04
BS_{cut}, km·hr^{-1}	—	—	.39	.04	.57	<.001*	.40	.03
BS_{drive}, km·hr^{-1}	.39	.04	—	—	.69	<.001*	.63	<.001*
BS_{pull}, km·hr^{-1}	.57	<.001*	.69	<.001*	—	—	.62	<.001*
BS_{slog}, km·hr^{-1}	.40	.03	.63	<.001*	.62	<.001*	—	—

Abbreviations: BP, bench pull; BS_{cut}, bat speed for cut; BS_{drive}, bat speed for drive; $BS_{overall}$, bat speed for overall; BS_{pull}, bat speed for pull; BS_{slog}, bat speed for slog; BW, body weight; CV, coefficient of variation; GS, grip strength; IMTP, isometric midthigh pull; MB_{vel}, medicine-ball push for maximum velocity; 1RM, 1-repetition maximum.
*P < .0038.

Table 5 Descriptive Statistics of Average Maximum Bat Speed by Delivery Type and Shot Type

Shot type	Off-spin, Mean (SD)	Medium		Fast		
		Mean (SD), km·h^{-1}	% of off-spin bat speed	Mean (SD), km·h^{-1}	% of off-spin bat speed	% of medium bat speed
Cut (n = 87)	72.7 (6.2)	69.2 (6.6)	95.2%	66.8 (7.9)	91.9%**	96.5%
Drive (n = 87)	83.8 (7.0)	78.5 (8.1)	93.7%	77.4 (8.8)	92.4%**	98.6%
Pull (n = 87)	86.6 (5.3)	81.4 (7.0)	94.0%**	76.5 (7.9)	88.3%**	94.0%*
Slog (n = 29)	85.3 (5.8)		—		—	

Significant results denoted by Tukey HSD analysis of 1-way repeated-measures analysis of variance testing comparing delivery types by shot type.
$^{*}P < .05$. $^{**}P < .01$.

Discussion

This is the first study to explore the association between bat speed and physical capacities of strength and power in elite female cricketers. This study was deliberately broad in design to include a comprehensive battery of physical assessments. This was done to ensure that all possible physical factors associated with bat speed were identified. The research team acknowledges that this design has placed some limitations on the statistical analysis, particularly in identifying significant physical capacity associations after *P*-value correction. Within the discussion we have identified a series of correlations, that while not statistically significant, we believe to be practically relevant for professional female cricket settings. We anticipate that future research with larger samples across other populations will be needed to clearly determine which capacities have a significant association with bat speed. The results of this study should be interpreted within this context.

Upper body pulling strength, dominant rotational power, and total body isometric strength explained 52.7% of the total variance in bat speed overall. By comparison, full-body biomechanical models have previously explained 77.7% of the total variance in bat speed among a similar cohort.[4] The ability to explain more than half the variance in bat speed using physical variables without any biomechanical features demonstrates how important strength and power qualities are for power hitting in elite female cricketers and highlights the importance of strength and power development among this cohort.

The very large relationship identified for upper body pulling strength and bat speed is a novel finding across all bat, club, and racket sports in the literature to date. Only one previous study has explored this physical capacity, finding no relationship with bat speed among female softball college athletes (n = 19) using a 1RM 1-arm dumbbell row.[13] Previous research in female golf athletes (n = 19) found a similarly large relationship for the reciprocal upper body pushing capacity of isometric bench press force at 100 milliseconds and clubhead speed.[11] In combination, these findings suggest that maximum upper body strength may be an important quality to consider for hitting sports in line with the physiological underpinning of explosive power by maximum strength.[30]

The upper body pulling strength finding is consistent with the unique kinematics observed for female batters. Specifically, elite female batters have been shown to flex their lead elbow during downswing.[6] Elbow flexion during bat acceleration would theoretically place a high demand on upper body pulling strength to overcome the bat's increasing angular momentum,[6] which may explain the association to absolute 1RM BP observed in this study. While this rationale is ecologically valid, it remains unclear whether this finding is unique to female batters, or if the association is a feature of power hitting in cricket generally. Further research within different cricket populations is required to fully understand the role of upper body pulling strength for power hitting.

The large associations for rotational power identified in this study are aligned with the existing evidence base highlighting the importance of rotational power in rotational hitting sports including golf,[10] baseball,[8] and tennis.[14] They are also supported by previous kinematic cricket research identifying the contribution of pelvis and upper thorax separation in the transverse plane, known as X-factor, on the generation of rotational power and maximum bat speed during power hitting.[4,6] Only one previous study in female softball players has failed to identify rotational power as a key physical capacity.[13] This research had several limitations which may have precluded the study's ability to identify a significant relationship including use of an unvalidated rotational power assessment and a low sample size of n = 19 athletes. The ability to rotate powerfully is clearly an important factor in many bat, club, and racket sports.

Total body isometric strength has been shown to have a nonsignificant but practically relevant relationship with bat speed for elite female cricketers. The peak vertical ground reaction forces recorded in the IMTP assessment provide an insight into the ability of participants to maximally apply force to the ground. This finding is consistent with previous work in women's golf where a moderate to large relationship ($r = .38–.62$) was found for clubhead speed and IMTP variables of peak force, and force at 100 to 300 milliseconds.[11] The ability to utilize energy from the ground through the kinetic chain has previously been linked to the generation of faster bat and clubhead speeds in both baseball[9] and golf.[31,32] Given that maximal isometric strength is correlated with dynamic 1RM squat and clean performance,[20] these findings also align with previous research showing associations between 1RM power clean, back squat, and clubhead speed in golf,[33] and 1RM hang clean, and bat speed in softball.[13]

This investigation has established that a range of physical capacities are linked to bat speed. These links include some general associations that are important across all shot types, as well as others that differ by shot. Although not directly measured in this study, the techniques for Cut, Drive, Pull, and Slog shots are all different (Figure 1), including different vertical and horizontal bat swing paths, as well as body and stance orientations. Power hitting therefore is a complex combination of technical and physical determinants. It is likely that technical skill plays a significant role in the generation of bat speed, and that additionally there may be an interaction between different shot techniques, movement demands, and associated physical capacities.

Despite significant differences in movement patterns however, a number of capacities follow the same trend and although not statistically significant they should be considered practically relevant for performance environments. Dominant rotational power and absolute total body isometric strength emerge as foundational qualities that are important for bat speed across all shots. This suggests an almost universal importance of both powerful rotation and ground up energy transfer through the kinetic chain regardless of shot type. Absolute upper body pulling strength builds on the foundational qualities identified above as a specific capacity important for the fast bat speed shot types; Drive, Pull, and Slog. While further research is needed, this capacity may play a role in enabling greater maximum bat speeds to be produced.

The Slog shot displayed 4 additional unique associations for bat speed, including nondominant grip strength, lower body power, relative maximum upper body pulling strength, and upper body pushing strength. These results may represent a possible interaction between the specific physical and technical demands of Slog shot power hitting. Unlike the fast bat speed subgroup pattern identified above, the additional associations found for the Slog shot did not correspond to an observed increase in bat speed generated with mean maximum Slog bat speed within 1.4 $km{\cdot}hr^{-1}$ of both Drive and Pull shots. It may be that in this case the technical demands of performing the Slog shot specifically require these additional associated qualities, and that the unique correlations found are in fact discriminants for Slog shot specific power hitting technique.

Finally, this study is the first to show that female batters produce slower maximum bat speeds when facing deliveries with faster ball speeds. Batters on average experienced reductions in maximum bat speed of 8.1% for Cut, 7.6% for Drive, and 11.7% for Pull when facing the Fast delivery condition (100–115 $km{\cdot}hr^{-1}$) versus Off-Spin (70–80 $km{\cdot}hr^{-1}$). This is another example of the impact of the technical demands for power hitting, and the first time that the speed accuracy trade-off phenomenon[34] has been observed for bat speed in the literature. This finding is significant, with multiple applications to take forward. First, for training environments seeking to profile athletes and measure maximum bat speed the Off-Spin and Medium delivery types are sufficient. Second, there may be a tactical advantage in identifying what a specific batter's reduction in swing speed may look like and how this could influence their shot selection versus fast ball speeds in games. Third, targeted strength and power training of the qualities identified above may drive an increase in maximum bat speed capacity, allowing batters experiencing the same technical limitations to generate faster bat speeds when facing faster ball speeds. This would lead to potentially higher ball exit velocities and greater shot distances for Fast deliveries, advantageous for maximizing run scoring during matches. Fourth, batters who display small reductions in maximum bat speed across slow and fast deliveries may have higher elite batting ceilings of performance.

Practical Applications

Absolute upper body pulling strength, dominant rotational power, and absolute total body isometric strength are important qualities to consider for professional female cricket environments training power hitting. Practitioners seeking to develop evidence-based programs may include these research findings in their strength and conditioning program design to better orient their support of female athletes. The assessment of these qualities allows the description of the physical capacities related to the power hitting profile of both individual athletes and teams. When assessed repeatedly over time, the changes observed may provide insight into the effectiveness of programs seeking to enhance bat speed and power hitting performance.

Conclusions

Multiple strength and power capacities exhibited associations with bat speed overall, and to specific shot types in professional female cricketers. These associations explain a significant portion of the total variance in bat speed and demonstrate that physical capacities play a key role in power hitting. Future research should explore these associations with larger sample sizes, as well as how bat speed may be enhanced by training, and assessing these qualities and bat speed over time to establish evidence-based methods.

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