# Utilising GPS wearable technology to monitor external work demands of seam bowlers between playing formats

**Jonathan Vickers**

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## DECLARATION

This Independent Project is the product of my own work and does not infringe the ethical principles set out in the University's Handbook for Research Ethics. Play agree that it may be made available for reference via any and all media by any by any and all means now known or developed in the future at the discretion of the University.

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# 1 ABSTRACT

It has been well established from previous time-motion analysis that seam bowlers have the greatest external work demands across all playing positions which has increased with the introduction of twenty over cricket (T20) to go alongside the traditional multi-day format (Petersen et al, 2010). Although it is established that the unique formats have different locomotion demands for all players including pace bowlers, it is not clear whether these differences affect run-up velocity (Maunder et al, 2017). Run-up velocity is seen as a key variable related to ball release speeds and better bowling performance whilst negative changes in run-up velocity throughout a match would be seen as an indicator of a pace bowlers' inability to sustain high intensity efforts (Duffield et al, 2009). Previous time-motion analysis has centred almost exclusively on total external workload demands in cricket, whilst not investigating individual bowling events which perhaps does not show how bowling is affected by the unique playing format (Bray, 2016). Recent developments in global positioning systems (GPS) technology have been shown to be valid and reliable in auto-detecting bowling events in live competition therefore increasing the ease from which meaningful measures of bowling intensity can be gathered (McNamara et al, 2018; Jowitt et al, 2020). Therefore, the primarily aims of the study were to quantify the differences in run-up velocity and locomotion demands between multi-day (MD) and T20 cricket. Secondary was to access the variability of locomotion and run-up velocity within each of the formats.

Five first class professional male pace bowlers (mean ± standard deviation) aged 27.33 ± 2.94 y, stature (183.20 ± 5.66 cm), and body mass (81.70 ± 3.26 kg) from a team playing in the top domestic league in English County Cricket wore GPS-accelerometery units during the 2022 playing season across 16 T20 fixtures and 16 days of MD cricket. Variables analysed were total distance (m), meterage (m/min), ball count, total duration (min), and maximal run up velocity ($m \cdot s^{-1}$). The main findings of the study showed daily fielding in MD to have significantly greater total distances, higher ball count, lower meterage, and a slower run-up velocity than T20 cricket ($p$ < 0.001). Variability findings found run-up velocity to be non-significantly changed from first to last over in T20 cricket (6.42 ± 0.41 and 6.42 ± 0.38 $m \cdot s^{-1}$, $p$ = 0.978) compared to MD where bowlers significantly increased their run-up velocity from first to last over (6.04 ± 0.43 and 6.23 ± 0.40 $m \cdot s^{-1}$, $p$ < 0.001).

This is an original study in its attempt to monitor and compare locomotive demands of pace bowling between and variability within playing formats from real world competition. The findings show that the increased total workload requirements in MD cricket will possibly make the bowler adopt a pacing strategy by having a slower run-up velocity to conserve energy throughout the fielding innings. This is different to T20 where the game is played at a higher

intensity and with faster run-up velocities where pacing to mitigate against fatigue is not required. As bowling at greater speeds is sought after for match success, practitioners and coaches should attempt to adequately prepare bowlers physically as well as tactically conserve pace bowler's energy to help maintain run-up velocities in MD closer to that seen in T20 cricket.

## 2 ACKNOWLEDGEMENTS

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# 5 INTRODUCTION

Cricket is a popular bat and ball team sport that has transformed over the centuries from its humble amateur routes in commonwealth nations to become a multi-million-dollar global sporting business. The sport of cricket is characterised by a fielding team and a batting team, where all players from each team are required to field and bat during their respective innings yet have specific roles within the team. Cricket positions are typically split between specialist batters and bowlers, with bowlers having further specialist roles based upon their adopted techniques, namely pace bowling or spin bowling. For the purposes of ease of understanding different terminology, during the following thesis, pace bowling will include all sub-categories of pace bowlers such as medium paced, medium-fast, fast-medium, and fast or express bowlers. The pace bowler differs from the spin, or slow bowlers by adopting a long run up where ball speeds typically range from 120 to 160 km/hr (Krishna & Malhotra, 2018; Feros, 2015). Although there are deviations in the balance of a team dependent upon multiple tactical factors, typically cricket teams will play up to five pace bowlers that will bowl several overs, characterised by six balls, before having to change the person that bowls the following over.

Cricket is unique to many other sports in that it has different playing formats whereby the rules drastically alter the duration of play, tactics, and physical demands of the sport. Most specifically the changes in format impact the amount of overs a pace bowler is allowed to bowl during a match. The traditional multiday format is played for up to five consecutive days (3 x 2-hour sessions) with each team getting two innings and has no limit on the number of overs a bowler can bowl. Dependent upon how the match unfolds during two fielding innings it is feasible that a bowler might be required to bowl between 25 and 50 overs or up to 300 balls which highlights the variability of the demands that are potentially placed on pace bowlers. The addition of one-day cricket emerged in the early to mid-1970's where each team is limited to 50-overs to bowl the opposing team out (typically four hours per innings) with each individual bowler capped at bowling 10-overs. Finally, the latest edition of the game, twenty-over cricket (T20) was introduced in the early 2000's where each team has 20-overs (typically 80 minutes per innings) and each individual bowler only has a maximum of four overs was introduced.

Pace bowlers have been identified in numerous studies as having the greatest physical demands amongst all playing positions regardless of playing format. Investigation into time-motion analysis show pace bowlers to cover greater total distances, high-speed running distances and have shorter rest periods between high intensity efforts compared to slow paced bowlers and batters. The reason for the greater external workload demand on pace bowlers is due to the elongated run-up they adopt from which to build greater horizontal linear velocity from which to impart kinetic energy onto the ball to produce greater ball release speeds. It is widely accepted that a mark of good pace bowling performance is having the ability to consistently reproduce a combination of explosive gross and fine motor skills to produce high ball speeds without detriment to accuracy. By generating greater ball speeds, it limits the batsman's decision-making times and therefore puts them at a greater likelihood of playing a poor shot or mistiming the ball and therefore increasing the probability of runs being restricted and or the likeliness of being dismissed. With elite international pace bowlers bowling circa 160 km/h, it is estimated that the batter has approximately 500 $ms^{-1}$ to perceive and react to the position of the ball (Muller, 2006). To support this further, Malhotra & Krishna (2017) found faster bowlers were more effective than slower bowlers at dismissing middle and lower order batters therefore highlighting that pace is effective against the less skilled batter.

The run-up distance adopted by a pace bowler is pre-determined by the individual with distances typically varying between 15-30m, followed by a series of largely consistent kinematic actions adopted by bowlers from which the run-up is transitioned into releasing the ball. These movements have been given various labels in the literature and from coaches and can be further divided into more sub-actions, but for simplicity and future reference in the following thesis will be called the pre-delivery stride, delivery stride, and the follow through (figure.1). The duration of activity during a bowling action from the beginning of the run-up till the end of the follow through after ball release is between 6-7 seconds with a typical peak running velocity between 5.3-6.3 $m \cdot s^{-1}$ (Ferdinands et al, 2010). A bowling delivery is typically followed by a period of 25-30 seconds of low activity where the ball is 'fielded' and returned to the bowler as he returns to his mark to commence the next delivery. Once the over is completed, which is typically a series of six deliveries unless 'no balls' are delivered whereby a further ball is required, the bowler will take part in fielding duties (3-4 minutes) in a designated position. Fielding for the pace bowler has been characterised as 'active recovery' where occasional random intermittent bouts of high intensity activity such as sprinting, diving, and throwing are interspersed with periods of standing and walking (Feros, 2015).

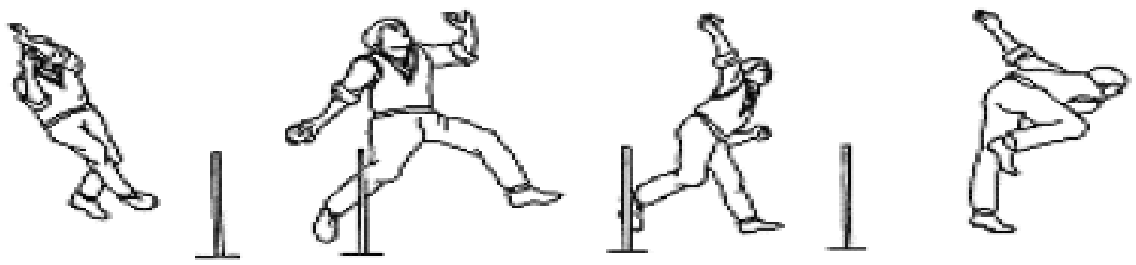

Figure 1 Bowling sequence from left right, pre-delivery stride, delivery stride (back and front-foot contact) and follow through (Ferdinands, 2008)

The external physical demand, or external load placed on pace bowlers has attempted to be quantified to allow coaches an insight in how best bowlers might be prepared in training to maximise performance and avoid overtraining and potential injury. Time-motion analysis (TMA) is the term used for quantifying player locomotion and external load which has become vastly more sophisticated over the years. TMA has developed from the early labour intensive-live-in-play pen and paper notation of player movements and durations using a stopwatch, to more recent wearable microtechnology in the form of global positioning system (GPS) units with internally housed accelerometers typically known as micro-electro-mechanical system (MEMS). The developments in wearable microtechnology have been used extensively in multiple sporting disciplines to more accurately quantify both gross and fine athletic movements for example the number and magnitude of collisions in rugby league and the detection and classification of different strokes in tennis (Hulin et al, 2017; Kos et al, 2016).

Pace bowling is a high intensity multi joint movement that integrates both gross and fine motor skills and has been extensively investigated in controlled conditioned laboratory conditions. Previous investigations have identified both kinetic and kinematic variables from force plate and 3D motion capture technology that relate to the ability to produce greater ball speeds. Although there is some variation amongst pace bowlers as to the technique they adopt (figure 2), namely, front-on, side-on or a mixed action that might explain kinetic differences between players (Portus et al, 2000). Studies have largely concluded that velocity related measures before and during the delivery stride are important determinants of ball speed. Specific examples include the horizontal velocity of centre of mass prior to the delivery stride, namely, back foot contact (BFC) and the negative change in horizontal velocity during the delivery stride from BFC to front foot contact (FFC). There are multiple additional kinetic and kinematic variables that have been shown to be important to explaining how pace bowlers produce quicker deliveries which will be explored in greater details in the following chapters. However, it is important to note that most previous investigations into bowling kinetics and kinematics have had to be performed under controlled conditions in biomechanics laboratories which is expensive, time consuming, and possibly lacking in ecological validity (Burnett et al, 1995; Duffield et al, 2009; Minett et al, 2012; Worthington et al, 2013). It is worth understanding, the central focus of a large proportion of the body of literature regarding pace bowling kinetics and kinematics has been investigating injury risk and mitigation (Portus et al, 2000; Glazier & Worthington, 2014; King et al, 2015; Shaefer et al, 2018). Although understandably research has focused on the area of injury risk, there is a gap in the literature focusing on pace bowling performance, particularly from live competition across formats.

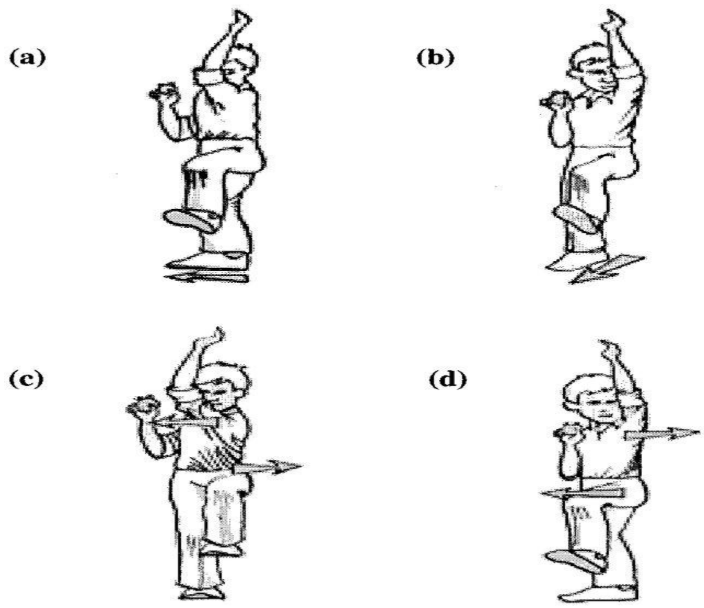


Figure 2 Fast bowling actions from the view of the batter. A = side-on, B = front-on, C = mixed with hips front-on, D = mixed with hips side-on (Portus et al, 2000)

The use of wearable GPS technology has therefore been highly sought after for attempting to quantify bowling kinematics in live competition. Unfortunately, although older models of GPS technology have been able to detect peak running velocities, distances, or duration at various velocity zones, it has not been valid in exclusively distinguishing bowling events or indeed acute changes in ball-by-ball bowling characteristics as would be possible in a laboratory. Both being unable to automatically detect bowling events or being sensitive enough to detect changes in the action are problematic for increasing the understanding of pace bowling performance in multiple levels whether that is comparison between playing formats or understanding bowling response throughout a spell, match, or series of matches.

Sophisticated MEMS devices have increased the utility and popularity of using GPS units to quantify training and playing due to algorithms built into the software that allow reliable automatic detection of bowling efforts within a fielding innings (Jowitt et al, 2020). Automatic detection of bowling events allows practitioners to identify changes accurately and more easily in metrics associated with higher ball velocities such as maximal run-up velocity. As mentioned previously, it is understood from previous time-motion analysis studies that there are clear differences in locomotive and time demands between the MD and T20 formats due to the constraints placed on each format. Yet no studies have investigated whether there are indeed differences in run-up velocities between the formats, or whether there are changes in run-up velocity within formats that could perhaps be causative of the different physiological demands. By investigating differences in run-up velocity between formats, and changes within-format, inferences can be made as to how intense bowling is depending on format. But also, practitioners will gain a greater insight into whether their bowlers are physically conditioned to adequately sustain high outputs throughout a fielding innings.

# 6 AIMS OF THE STUDY

- To quantify the differences in run up velocity and locomotion demands between playing formats
- To assess the variability of locomotion and run-up velocity within MD and T20 cricket formats, specifically changes from first to last over during a day of fielding

# 7 LITERATURE REVIEW

## 7.1 Methods of Quantifying External Training Load

Time-motional analysis (TMA) can be defined as objectively quantifying player locomotion to give practitioners valuable insight into the physiological demands of the activity or sport (Rudkin & O'Donoghue, 2007). Early instances of coaches attempting to quantify player movements was achieved by rudimentary methods such as pen and paper notation to more sophisticated use of post-match analysis using specialist computer software (Bray, 2017)

TMA has been used extensively across multiple sports to individualise physical preparation of athletes specific to their sport and positions, although cricket has traditionally not been as proactive as other team field sports in adopting modern developments in sport science (Rudkin & O'Donoghue 2007). Cricket has traditionally been viewed as a more leisurely sport compared to other competing team sports such as rugby union or soccer with a far greater emphasis being placed on skill level than understanding or acknowledgement of the physical side of high performance (Rudkin & O'Donoghue 2007; Bray, 2017).

Fletcher (1955) attempted to quantify energy demands from notational time-motion analysis from observing two college fielders for 30-minute periods. His findings indicated that fielders only undertook high-intensity activity for 1.55% of the time. Unsurprisingly due to impracticality and subjectivity of notational analysis of cricket there was no further published TMA data until the emergence of specialist software where post-match analysis could be undertaken. Rudkin & O'Donoghue (2007) investigated using real time video software over the first 10-over spells of morning, afternoon, and evening sessions in three first class county cricket matches. The investigation extrapolated data from prior speed trials in three different speeds of locomotion (walking, jogging, and running) from which estimations were made to calculate distances. The authors estimated that during 3 x 2-hour sessions, or a day of MD first class cricket that infielders covered approximately 15.5km with 1.6 ± 0.8% of the time spent at high intensity activity, thus finding similar findings to the early findings from Fletcher (1955).

Both the early findings of Fletcher (1955) and the subsequent follow up investigation from Rudkin and O'Donoghue (2007) conclusions agree with the largely historical bias that cricket is a physically non-demanding sport (Petersen et al, 2009). It must be noted however that these prior investigations were severely limited in their findings due to multiple factors including the validity of the methods, the small sample sizes, possible developments in playing tactics, and lack of specificity between playing positions or differentiation between playing formats.

Global positioning system (GPS) technology is a satellite-based navigation technology that has developed from its original purposes of military use to be increasingly used in sport to track the movements of athletes (Cummins et al, 2013). Prior to the 1980's non-military use of GPS technology was restricted, but since being made accessible to the mass market rapid developments in wearable GPS have allowed sports coaches and practitioners the ability to track player movement with greater ease and precision in comparison to notational and computer-based software (Bray, 2019).

GPS works by orbiting satellites synchronising GPS units with the atomic clock sending information to the precise time of the unit (Larsson, 2003). Units are then located by triangulation by calculating the exact distance to a minimum of four satellites with movement speed detected automatically by the Doppler shift calculated by the change in satellite signal frequency due to the movement of the unit (Larsson, 2003).

Since the availability of GPS usage to the general public, it has become common place for elite sporting organisations to utilise GPS technology in their practise for more simple quantification of real-time movement from both competition and training sessions (Cummins et al, 2013). Within cricket, the most comprehensive TMA of cricket movement variability comes from Carl Petersen and a selection of colleagues where movement patterns have been quantified both between positions and between formats (Petersen et al, 2009; Petersen et al, 2010). Initial TMA by Petersen et al (2009) investigated the positional movement demands of T20 cricket in Australian state-level cricketers ($n$ = 18, fast bowlers $n$ = 4) during four T20 fixtures using 5Hz GPS units (Catapult, Melbourne, Australia) further detail on validity and reliability of GPS units to be discussed in chapter 3. Players were categorised according to position (batsman, fast bowler, fielder, spin bowler or wicketkeeper) and a comprehensive movement analysis was broken down into total distance (km), walking distance (0-2 $m \cdot s^{-1}$), jogging distance (2-3.5 $m \cdot s^{-1}$), running (3.5-4 $m \cdot s^{-1}$), striding (4-5 $m \cdot s^{-1}$), sprinting (5+ $m \cdot s^{-1}$), number of sprints, maximum speed ($m \cdot s^{-1}$), number of high intensity efforts (greater than jogging, and finally recovery time between high intensity efforts (running, striding and sprinting). Importantly, for consistent game to game comparison each fielding innings was scaled to 80 minutes, the maximum time possible for a T20 innings. Although Bray (2017) cautions that this scaling might lack ecological validity because the distances risk being inflated if for example an innings ends before the twenty overs are bowled. The main findings from the study however confirmed that fast bowlers had the greatest workload compared to a general fielding position as categorised by total distance (8.4 ± 1.5km verses 8.1 ± 1.3km), sprint distance (0.7 ± 0.2km verses 0.6 ± 0.4km), number of sprints (42 ± 8 verses 31 ± 18, ES = 0.66; moderate), number of high intensity efforts (163 ± 44 verses 130 ± 57, ES = 0.60 moderate) and 13 seconds less recovery time between high intensity efforts (ES = 0.60).

In a follow up study Petersen et al (2010) attempted to make comparison between playing positions and match format on Australian Centre of Excellence male cricketers (*n* = 42, fast bowlers *n* = 18) during 24 tour fixtures and first-class opposition (7 x T20, 16 x OD, 1 x 3 day MD). The same 5Hz Catapult GPS units that had been used in previous inter-positional comparison in the T20 format were used. In terms of comparison of movement demands between formats, absolute values for fielding data were gathered as well as scaled values (1 hour) to allow for fair comparison between formats. Fast bowlers covered a total distance of 5.5 ± 0.4km (mean ± 90% CI) per hour in the T20 format equating to an additional 340 $m \cdot h^{-1}$ and 400 $m \cdot h^{-1}$ over OD and MD cricket respectfully. The study also identified when analysing total sprint distance per hour of play, T20 was 22% and 43% more intensive that OD and MD cricket respectfully with fast bowlers yet total sprint distance of T20 compared to a day of OD and MD (3 x 2hr sessions) was 39% and 80% lower. In terms of repeated activity (≥ 3 sprints with < 60 seconds recovery) fast bowlers met the criteria on 3.3 ± 1.5, 4.8 ± 1.4 and 5.5 ± 4.0 occasions for T20, OD and MD respectfully.

The final TMA related study by Petersen et al (2011) centred on a comparison between Australian state level domestic (fast bowlers: OD *n* = 8, MD *n* = 80) and test match players (fast bowlers: OD *n* = 21, MD *n* = 17) across two seasons. Data was again scaled to one-hour periods, same 5Hz Catapult units and adopting the same velocity bandings as in the previous two studies. Scaled distance showed that fast bowlers covered the same total distance and sprint distances in the domestic game (~4 $km \cdot h^{-1}$ and 0.3 $km \cdot h^{-1}$) respectfully.

In a more recent retrospective cohort study adapted from the pioneering study into T20 cricket by Petersen et al (2009), Sholto-Douglas et al (2020) analysed positional differences between players in the Australian Big Bash T20 competition (*n* = 14, fast bowlers *n* = 4) over 12 games. The study found that fast bowlers covered a total distance of 6.55 ± 0.53km and a total sprint distance of 0.04 ± 0.02km. These values are considerably decreased from those of the Petersen (2009) study in both total and sprint distance which might be down to methodological differences in data collection thus making direct comparison between playing eras difficult. Firstly, the units used ten years previously by Petersen were 5 Hz GPS units compared to the 10 Hz GPS units (Catapult, Melbourne, Australia) used by Sholto-Douglas et al (2020) which may have implications for the validity and reliability of the findings which will be discussed further in the following chapters. Additionally, the categorisation of speed zones or intensities were different to Petersen with the current study quantifying sprinting at > 7.2 $m \cdot s^{-1}$ compared to > 5 $m \cdot s^{-1}$. The recently highlighted study found with these velocity thresholds that fast bowlers performed 1.6 ± 1 sprinting efforts per match and 24.6 ± 7.1 striding efforts (5.8-7.2 $m \cdot s^{-1}$).

Perhaps the most comprehensive recent studies examining external work demands of pace bowlers across all formats has been conducted from retrospective longitudinal studies within international cricket across (Bliss et al, 2021; Bliss et al, 2022). Across five seasons (Bliss et al, 2021) quantified and compared absolute and relative match demands and variability between one-day international ($n$ = 160) and T20 international ($n$ = 44) matches from a single cohort of pace bowlers ($n$ = 13). The study found similarly to Petersen et al (2010) that relative to time, all physical variables other than distance covered at speed in 20-25 $km\text{-}h^{-1}$ was greater in T20 compared to OD cricket. The differences in the 20-25 $km\text{-}h^{-1}$ banding is likely attributed to bowling approximately three times as many overs in a match. The novelty in the study however was to quantify variability between international cricket match play which has only been attempted through a single case study previously (Petersen et al, 2009). The study found relative to minutes played, that particularly high intensity actions such as accelerations <4 $m \cdot s^{-1}$ (within-player ODI CV% 79.2%. T20 CV =77.2%) and decelerations <4 $m \cdot s^{-1}$ (within-player ODI CV% 75.5%. T20 CV =72.0%) and distance covered greater than 25 $km\text{-}h^{-1}$ (within-player ODI CV% 84.7%. T20 CV =38.8%) showed very high variability. The novel study suggested that such great variability in both formats is most likely due to changing fielding positions and the number of runs that are scored through boundaries or non-boundaries.

A similar methodology was applied by the same authors comparing match to match variability in test match cricket from a single cohort of bowlers ($n$ = 9). The study analysed 28 test matches with the primary aim to quantify the variability of absolute and relative fielding demands between matches (Bliss et al, 2022). The study found that across absolute and relative demands there was a high degree of variability (8-192%) due to fielding duration being highly variable (CV = 25%). Relative demands per hour were less variable than absolute (CV% 15-98) however the study showed how unpredictable fielding workload match to match is for pace bowlers. This highlights the importance of why practitioners will want to monitor matches as to adjust training workloads or recovery strategies.

Developments in GPS technology have seen the emergence of inertial sensors (accelerometers and gyroscopes) built into the wearable units (McNamara et al, 2015; Jowitt et al, 2020). Earlier GPS units that exclusively reported metrics such as total distance, sprint distances, accelerations and decelerations have given a good insight into player locomotion demands. There is, however, a clear limitation in building a greater understanding of total external workload demands of athletes when specific sporting actions are not identified and or quantified (McNamara et al, 2015). As previously shown, traditional GPS devices are shown to be less reliable and valid over shorter distances and greater movement velocities and are therefore likely to have a poor level of sensitivity to detect meaningful changes in pace bowling kinematics. In investigating international standard pace bowlers (*n* = 20), Worthington et al (2013) found mean maximal run up speed immediately prior to BFC to be 5.79 ± 0.58 $m \cdot s^{-1}$ with a top range of 6.76 $m \cdot s^{-1}$ and previous research has established both 5 and 10-Hz GPS units are limited in their validity with running speeds greater than 5.5 $m \cdot s^{-1}$ (Johnson et al, 2014). This therefore highlights the problems of relying on traditional GPS technology to show possible changes in run up velocity in fast bowling (Bray, 2017).

Tri-axial accelerometers (100-Hz) measure the frequency and magnitude of movements in three dimensions (anterior-posterior, mediolateral and longitudinal) and are thought to be superior compared to traditional GPS due to the greater sampling frequency (Boyd et al, 2011). One such early pioneering study using GPS housed inertial sensors was to quantify the number and intensity of collisions during a series of training sessions with elite rugby league players (Gabbett et al, 2010). Previous attempts to identify the number of collisions within the sport was labour-intensive whilst objective understanding of collision intensity from live training or match scenarios was previously not possible. Inertial measurement units (IMU) technology has proved useful in cricket whereby automatic detection of bowling deliveries through machine-based learning algorithms has been shown to be valid and reliable in training and competition (McNamara et al, 2018; Jowitt et al, 2020).

### 7.2 Validity and Reliability of Global Positioning Systems

There is a high volume of literature investigating the validity and reliability of GPS, with the gold standard of validity being GPS units measured against measured distances and speed timing gates or a speed gun (Cummins et al, 2013). As briefly mentioned in the previous chapter various cricket TMA studies utilising GPS technology have used different units, whether that is manufacturer or the sampling rate of the unit (Hz). Commercial GPS units typically sample at 1-, 5-, and 10-Hz with the sampling rate referring to the speed at which the unit collects locomotion information (Johnson et al, 2014). The following paragraphs will provide a brief literature review of GPS validity and reliability.

GPS units are manufactured and with various sampling rates (1, 5, and 10-Hz). Earlier 1-Hz units have been found to be less valid than GPS units sampling at higher frequencies (Cummins et al, 2013). In comparing 10-m sprint standing start with 1 and 5-Hz GPS units, standard error for measuring distance was found to be 32.4 and 30.9% respectfully, whilst for similar comparison a 10-Hz unit measured over 15-m had a far lower standard error of 10.9% (Jennings et al, 2010; Aughey, 2011).

Additionally, Johnson et al (2012) attempted to test validity and reliability of 5-Hz GPS units (Catapult MinimaxX, Catapult Innovations, Melbourne, Australia) during typical team sport movements with a simulated circuit ($n$ = 9) and a flying 50-m sprint ($n$ = 4). Validity was assessed by comparison of the unit results against measured distance (tape measure) and peak speed (radar gun). The 5-Hz units showed no significant differences between total GPS distance covered and measured distance and a low error of measurement ($p$ > 0.05, percentage typical error of measurement (%TEM = 2%). The 50-m sprint test found the units to be less reliable when measuring distance spent at high intensity running (14.00-19.99 $km \cdot hr^{-1}$) and very high intensity running (>20 $km \cdot h^{-1}$) with a standard error of 20.1 and 59.3% respectfully.

Following on from previous research Johnson et al (2013) conducted validity and inter-unit reliability on subjects wearing two 5- and 10-Hz units on different days performing the same simulated running circuit as in the previous study ($n$ = 8). Results showed no significant differences ($p$ < 0.05) between the measured distances (1320m) and the inter-unit reliability for either the 5-Hz (mean ± SD: unit 1 1268.8 ± 24.4; unit 2 1325 ± 26m; %TEM = 1.2) or the 10-Hz units (unit 1 1331.9; unit 2 1330 ± 23m; %TEM = 1.3). There was, however, greater variability in the measurements and increased error for both 5 and 10-Hz units at increased movement speeds (% TEM: 0-14%). In terms of differences between unit sampling rates, there were differences reaching significance for the 5-Hz units for distance covered (1287.2 ± 17. vs 1326 24.6 m; $p \leq 0.01$) and peak running speed 23.96 ± 1.62 vs 24.28 ± 1.54 $km.h^{-1}$; $p = \leq$ 0.05), respectfully. The conclusion of this study was that when analysing most simulated movement demands both 5 and 10-Hz units provided similar outcomes.

Summarising validity and reliability of GPS units it is important to be aware that comparison between studies when gauging accurate locomotion data will be looking at studies that aquired data on units with different sampling rates. Reliability and validity for total distances appears to be acceptable (<10% CV) in both training and competition). However, reliability at greater running velocities decreases and therefore practitioners should attempt to minimise between unit variability by ensuring each athlete uses the same unit in sessions during data collection.

## 7.3 Run-Up Velocity

The run up is deemed a key phase in the delivery of the ball for pace bowlers compared to slower pace or spin bowlers. The run-up is typically long enough to allow for a gradual linear or curvilinear acceleration to build momentum and impart greater kinetic energy onto the ball and deliver greater ball release speeds (Feros, 2015). Run-up distances are typically between 15-30m in length with the greatest running velocities occurring in the last 5m prior to ball release (Bartlett 1996; Johnson et al, 2014). Early research into kinematic factors influencing ball release velocities found that the run up contributed 19% of the final ball velocity (Davis & Blanksby, 1976a). However, there are contrasting findings within the literature that could be explained by many different factors, including the samples used and which kinetics and or kinematic variables were statistically analysed.

Glazier et al (2000) comprehensively investigated anthropometric and kinematic influences on ball release speeds on college pace bowlers ($n$ = 9; mean ± SD; age = 21.0 ± 0.9; mass = 77.2 ± 8.1kg; height = 183 ± 0.1m). The researchers set a pre-requisite for inclusion in the study that bowlers must have the ability to bowl either fast-medium (27.0-36.0 $m \cdot s^{-1}$) or fast (36.0-40.5 $m \cdot s^{-1}$) whilst the researchers also classified the bowlers according to action or technique, namely mixed or front-on. Focusing on the kinematics and specifically run up velocity pre-delivery stride, the mean run-up velocity of the group was 5.9 ± 0.7 $m \cdot s^{-1}$ and with a mean ball release speed of 31.5 ± 1.9 $m \cdot s^{-1}$). Pearson's product-moment correlation coefficients ($r$) showed run-up speed at pre-delivery stride to have a significant relationship with ball release speed ($r$ = 0.728, $P$ < 0.05). Interestingly, 8 out of the 9 bowlers were classified as mixed technique bowlers as categorised by Elliot et al (1992) as having a change in shoulder alignment angle during the delivery stride of 10° or more. Because out of the observed kinematic variables run-up speed was highly correlated with ball speed the researchers suggested that because all but one of the bowlers analysed adopted a mixed action whereby the bowler has a front on orientation at back foot contact that they will rely more heavily on a horizontal run up momentum to produce greater ball speeds (Glazier et al, 2000). Further support for bowling technique affecting run-up velocity comes from Burnett et al (1995) who although did not measure ball release speed, found that side on bowlers had slower run up velocities (5.0 $m \cdot s^{-1}$) than mixed (5.4 $m \cdot s^{-1}$) and front on bowlers (5.8 $m \cdot s^{-1}$). This is hypothesised to occur because higher running speeds make it more challenging to orientate the hips and shoulders during the gathering part of the action for the mixed or side-on orientated bowlers (Glazier & Wheat, 2014).

Additionally, Duffield et al (2009) found similar findings to those of Glazier et al (2000) regarding run up velocity and ball release speeds. The study investigated the physiological responses of first class domestic medium-fast pace bowlers (*n* = 6) mean ± SD age 23 ± 3y, stature 185.6 ± 6.8 cm, body mass 86.9 ± 11.3 kg. The purpose of the study was to investigate bowling relevant markers of performance such as ball and run up velocity and the relationship with internal physiological load measures such as blood lactate, heart rate, core temperature and session RPE over the course of 2 x 6-over spells of simulated bowling. The researchers found similar moderate to strong positive correlations to those found by Glazier et al (2000) between maximal run up speed in the final 5m prior to back foot contact (*r* = 0.70) whilst also finding that a greater run up length (17.7 ± 4.1m) was correlated with final 5m run up speed and peak and mean ball speeds (*r* = 0.70 and 0.72, respectfully). It should be noted however, that like Glazier at (2000) the sample sizes were small and apart from the bowlers being categorised based on their relative ball speed (medium-fast) they were not further categorised according to bowling action which might have different implications for the relevance of run up speed (Salter et al, 2007).

To potentially mitigate against the problem of conducting between-bowler analysis, whereby differences in bowling technique could lead to significant or non-significant erroneous findings between technical factors and ball release speed, Salter et al (2007) adopted both between and within-bowler analysis. Kinematic analysis of joint segments and horizontal centre of mass were analysed at back foot contact from 20 elite mixed action fast-medium bowled 20 balls under controlled conditions. Descriptive statistics found that horizontal centre of mass velocity at back foot contact had a strong positive correlation with ball speed (*r* = 0.737, *p* ≤ 0.001) in the within bowler analysis and a weak non-significant correlation in the between bowler analysis (*r* = 0.222, *p* = 0.360). The authors did however caution against making causal inferences regarding ball speed and individual kinematic markers as bowling is a complex integration of multiple kinetic and kinematic factors. Multiple stepwise linear regression modelling from within-bowler analysis revealed 87.5% of ball speed variation could be explained by four kinematic factors including centre of mass velocity at back foot contact, maximum angular velocity of the upper arm, vertical velocity of the non-bowling arm and stride length.

Additionally, research from Worthington et al (2013) supports the importance of greater run-up velocity for higher ball speeds. Investigating eleven kinematic parameters in elite fast bowlers (*n* = 20; mean ± SD: age 20.1 ± 2.6y; stature 188 ± 0.08 cm; body mass 81.5 ± 7.1 kg) performed six deliveries with the intention of delivering maximal ball speed. Stepwise linear regression identified that although many variables were analysed, only four technical variables significantly explained the variance in greater ball release speed (74%). The following variables that were found to contribute in order of significance were shoulder angle at ball release, run up speed, knee angle at ball release and shoulder angle at front foot contact. The authors however state that practitioners should not attribute too greater weighting on the order or significance of the individual technical variables from the multiple regression but look more holistically at the combination of factors that can aid in building a general framework to guide improving fast bowling performance (Worthington et al, 2013). Perhaps, this again highlights the importance of possibly analysing within as well as between-bowler variation to make more meaningful inferences into which variables are more important to a particular pace (Salter et al, 2007).

The general consensus within the research is largely in agreement that greater run up speeds facilitate a bowler's ability to be able to produce greater ball release speeds and possibly increase bowling performance (Ferdinands et al, 2010; Salter et al, 2007). Burden and Bartlett (1990) did however find conflicting results from their study investigating in competition bowling in elite fast and fast-medium bowlers ($n$ = 17) during the English County Championship. The investigation found a poor correlation between ball speed and run-up velocity ($r$ = 0.21) and therefore concluded that bowlers that were slower in their run up bowled fast deliveries. However, the investigation measured run up velocity at ball release rather than back foot contact or during the last 5 meters. This is potentially measuring a different variable as bowlers will generally decelerate their centre of mass aggressively to convert horizontal momentum into angular momentum between back foot contact and ball release (Glazier & Worthington, 2014). Additional caution should be made as to the validity of the methods used such as the authors stating that up to six deliveries were filmed and, in some instances, only one of the deliveries for a bowler was able to be digitised due to obstructions in the camera during live play. Although the aforementioned study did not find a relationship between ball speed and run-up velocity due to possible methodological issues, a possible explanation as to why some pace bowlers that adopt slower run-up velocities might produce greater ball velocities is due to different bowling techniques adopted. Feros (2015) commented that Australian fast bowler Jeff Thomson had a run-up velocity of 3.8 m. s $^{-1}$ yet could produce extremely high ball speeds of nearly 160 kph. Ferdinands et al (2010) showed that pace bowlers that adopt a mixed or side on bowling technique like Thomson will require a slower run-up to create more time to utilise the stretch shortening cycle of the trunk, pectoral and anterior shoulder musculature to generate a greater impulse. The emergence of tri-axial inertial sensors housed in GPS units, allow investigation into kinematic variables other than run-up velocity such as rotational and lateral accelerometery data (Cockley, 2020; Bailey et al, 2023. Baliey et al (2023) in a retrospective observational study in elite female pace bowlers from live in competition T20 cricket found alongside maximal run-up velocity, peak resultant acceleration (obtained from resultant of the peak x,y,z accelerometer outputs) was significantly correlated with ball release velocity (*p* = <0.001 and *p* = <0.013 respectfully). Although the study did not control for individual bowling biomechanics, it does evidence that factors other than just run-up velocity are important variables for generating high ball velocities which is an important consideration.

In summary greater run-up speeds have been shown to be one of the key factors associated with greater ball velocities or which is strongly associated with more successful bowling performance (Worthington et al, 2013; Krishna & Malhotra, 2017). Although other kinematic, kinematic, and anthropometric factors undoubtably are important in determining overall greater ball speeds. Run-up velocity is easily accessible through GPS technology and therefore is a practical measurement as a proxy for bowling intensity and possibly performance from real-life competition.

### 7.4 Bowling performance and fatigue

It is largely agreed across the literature that producing a high run up speed is conducive to producing high ball velocities for the individual bowler and therefore maximising a high level of performance. What remains less clear from previous studies is if and how run up speed is affected across spells, days, matches or indeed between playing formats. Within the last few decades and the increased popularity of shorter format cricket, elite players are playing a substantially greater number of matches, often across different tournaments across the globe (Maunder et al, 2017). This has increased the impetus to investigate pace bowling workload measurement most notably from an injury prevention perspective.

Anecdotally pace bowling is perceived to be a highly physically strenuous activity with most evidence being subjective reports of soreness, tiredness, and mental fatigue most cited amongst players (Maunder et al, 2017). In terms of quantifying fatigue or performance decreases in pace bowling, there have been multiple methodological approaches that have been undertaken in the literature to measure fatigue such as objective physiological measures, subjective measures, and performance related measures such as decreased accuracy, pace and or run up speed (Duffield et al, 2008; Cooke et al, 2019; Portus et al, 2000). Most studies that have attempted to investigate the mechanisms behind fatigue in pace bowling have looked at a combination of internal load measures such as heart rate, blood lactate, or evidence of muscle damage such as elevated levels of creatine kinase in conjunction with changes in kinetic and kinematic variables during prolonged bowling spells (Maunder et al, 2017). Although laboratory-based studies afford investigations at multiple levels they are limited in their ecological validity to accurately replicate the physiological external work demands of cricket as well as the psychological stress of live competition. The following paragraphs attempt to contextualise and understand the mechanisms of fatigue conducted from laboratory-based studies and live competition where extended spells of bowling have been conducted.

Relatively few studies have investigated physiological factors of fatigue in fast bowling, with most studies using a combination of heart rate and rate of perceived exertion (RPE). Early investigation by Burnett et al (1995) measured heart rate and blood lactate responses to 12-over spell in semi-elite fast bowlers ($n$ = 9) interspersed with fielding drills. The study found heart rate to range from 80.3 to 84.7% of maximum and a moderate increase in blood lactate from 4.6 ± 2.2 to 4.8 ± 3.1 from the 1st to the 12th over respectfully. Although there was a moderate increase in internal markers of fatigue there were not any significant changes in performance related variables. Notably, there was a non-significant marginal increase in run up velocity across the group from 5.5 $m \cdot s^{-1}$ to 5.7 $m \cdot s^{-1}$ ($p = 0.18$), stable ball release velocities, as well as non-significant changes in joint kinematics. The authors concluded that pace bowlers within the cohort were not affected by fatigue to leading to any performance detriments.

Similar conclusions were drawn in by Duffield et al (2008) when investigating 2 x 6 over spells in medium-fast-paced bowlers. The study analysed internal physiological (heart rate, blood lactate, pH and glucose) and psychological (RPE) load in addition to external markers of performance (ball speed, final 5-m run up speed, accuracy) and finally before and after spell vertical jump. The results were similar to those from Burnett et al (1995) whereby heart rate intermittently increased with a mean value of 162 ± 9 for the first 6-over spell and 162 ± 12 for the second therefore showing no significant differences ($p = 0.08$). Additionally, no differences were found for rises in core body temperature between spells ($p = 0.85$) or for blood capillary measures (pH, blood lactate or blood glucose ($p$ = 0.08 – 0.82). There were, however, large effects sizes for higher blood lactate and lower blood glucose for the beginning of the second spell of bowling ($d = 1.0$, $d = 1.2$) respectfully. In terms of internal perception of load, there were again no significant differences found in RPE or perceived muscle soreness between spells, although large effects sizes were observed ($d = 0.8$, $d = 1.4$) respectfully. Interestingly, it was observed however that bowlers that had longer, faster run-up speeds had increased values of blood lactate and higher perceived ratings of muscle soreness. It could therefore be posited that possible changes might occur during the following spells causing a possible decrement in performance, as might occur during live conditions during MD cricket where bowlers typically perform a far greater total number of overs over several spells. This point is particularly valid considering the small cohort of bowlers were identified as medium-fast bowlers, therefore it is logical to assume bowlers that are categorised as fast might experience a greater internal load.

Interestingly, the one study that investigated the physiological effects on bowlers over multiple days found a reduced level of bowling performance on the second day of simulated bowling conducted in more extreme heat and humidity conditions when investigating the effects of a cooling intervention against a non-cooling control group (Minett et al, 2012). A combination of performance (peak and mean ball speed, accuracy), physiological (heart rate, creatine kinase), and perceptual measures (RPE) were measured during day one (10-over spell) and day two (4-over spell). The control group that did not undergo a cooling procedure post day-one bowling appeared to have detrimental effects on day two from both a performance as well as physiological and subjective perception perspectives. Focusing on the physiological markers of performance, the control group had significantly greater creatine kinase concentrations pre-day two bowling indicating a better attenuation of possible muscle damage and soreness ($p$ = 0.04; $d$ = 0.56). This was additionally accompanied by a reduction in perceived muscle soreness prior to bowling on day 2 ($p$ = 0.03; $d$ = 2.05). Importantly, in the cohort of medium-fast bowlers, performance appeared to be negatively affected by the lack of a cooling intervention when going into the second day with large effect size for players undergoing the cooling intervention attenuating reductions in mean ball release speed during the second day (cooling $0.24 \pm 2.50$ km · $h^{-1}$ vs. control $-3.18 \pm 2.86$ km · $h^{-1}$ ; $p$ = 0.26; $d$ = 1.07). Additionally, mirroring similar findings in ball release speed, mean final 5-m run-up speed was reduced to a greater magnitude in the control group with large reductions in the control ($p$ = 0.04; $d$ = 1.05), compared to moderate reductions in the cooling group ($p$ = 0.19; $d$ = 0.77). Although the highlighted study investigates the effects of a cooling intervention during hot conditions, it supports that run-up speed is potentially affected during MD cricket under certain circumstances, although in the bowling cohort from the study it appears to be muscle damage that negatively effects bowling performance. This supports work by Noakes and Durandt (2000) who suggest that fatigue in pace bowling performance is not caused by 'classical models' of cardiovascular-anaerobic energy depletion model or energy supply depletion (Johnstone et al, 2014). Yet is more likely a result of acute changes in muscle action, recruitment and firing that are negatively affected by muscle damage due to the large, repeated bouts of eccentric muscle actions when bowling (Johnstone et al, 2014).

The theory that Noakes and Durandt (2000) postulated regarding changes at the muscle level being an acute factor in detrimental pace bowling performance have however not been substantiated in research. Tests of neuromuscular strength and or explosiveness are often used to infer levels of physical preparedness or changes following bouts of exercise or competition (Cooke et al, 2019). In a pioneering study being the first to investigate changes in neuromuscular fatigue in elite county cricketers across different formats. Cooke et al (2019) reported on countermovement jump variables at pre, immediately post, and 24hr+ after training

(10-overs+), multi-day and one-day competition. Interestingly, the results of the study found no significant differences in jump height across position or format ($p > 0.05$) from baseline to +24 hours, with seam bowlers increasing peak force from baseline to +0 hours in training and one-day competition. The hypothesis of the study was that different movement strategies would have been employed by the players to maintain a high output of jump height, although no differences were found in jump strategy measures. The authors suggested that specificity of fatigue meant that the countermovement jump might not be mechanically similar enough in nature to bowling to acutely detect neuromuscular fatigue compared to a faster stretch shortening cycle activity looking at reactive strength measures. They suggested this because positionally, wicket keepers had significant reductions in countermovement jump height, therefore suggesting fatigue is specific to the task. Additionally, the authors found that seam bowlers increased peak force post activity compared to non-seamers thus possibly showing a possible potentiation effect. Although it should be highlighted that jump height or peak power was not improved and therefore potentiation from one-day and training is still speculative. Important to understand however, is that the above study did not differentiate bowlers based upon level of fitness. It could therefore be hypothesised that lower level pace bowlers or those with poorer levels of physical fitness might not be able to maintain high neuromuscular outputs and fatigue even with non-specific tests such as a countermovement jump.

Feros (2015) investigated multiple physical, anthropometric, kinetic, and kinematic variables and their relationship with bowling performance measures in community standard pace bowlers ($n = 31$). The bowlers were asked to bowl 8-overs of which some were instructed to maximal intensity, match intensity and slower deliveries, as the investigators were analysing accuracy as well. In relation to endurance qualities associated with better repeated bowling performance, the participants were tested using a 20-m shuttle bleep test as well as a repeat-sprint ability test. Predicted $VO_{2max}$ from the bleep test was related to a lower percentage decrement in the repeat-sprint ability test ($r_s = -0.79$, $p < 0.01$). It has been shown the faster oxygen uptake kinetics are related strongly to repeated-sprint demands and therefore likely the ability to maintain explosive muscular contractions needed for fast bowling. This was evidenced in the current investigation with predicted $VO_{2max}$ being moderately linked with a faster power phase duration ($r_s = -0.42$, $p = 0.03$). The mean predicted $VO_{2max}$ for the group of community bowlers compared to elite pace bowlers in elite professional English cricket was modest at 49.7 compared 54.1 ($ml \cdot kg^{-1} \cdot min^{-1}$) respectfully (Johnstone & Ford, 2010). This highlights possibly that there is a baseline level of cardiovascular performance where elite pace bowlers should meet to avoid the onset of acute performance decrements in bowling.

## 7.5 Format related differences and bowling performance

Most of the extensive literature investigating format related differences is from time-motion analysis conducted by Petersen and colleagues (Bray, 2017). Whilst a few studies have also focused on internal measures of load, such as heart rate and session rate of perceived exertion (sRPE) from live competition between formats (Petersen et al, 2009; Cooke et al, 2019). There appears to be little in the way of research investigating the differences the formats may have on absolute bowling related measures of performance, such as ball velocity, run up speed or the ability to sustain performance throughout a match.

To the authors knowledge, only one study has investigated changes in bowling performance measures throughout the course of live competition. Cockley (2021) utilised GPS technology with in-housed inertial measurement units (IMU) to quantify bowling intensity via the PlayerLoad$^{TM}$ variable, run-up velocity and recorded bowling speed. PlayerLoad$^{TM}$ is a derived variable by the GPS manufacturer Catapult that represents high intensity acceleration movements and can be isolated to specific sporting movements such as bowling by a validated algorithm (Jowitt et al, 2020). The variable quantifies the high levels of rotation and angular velocity in all three axes which are found to be key variables in bowling speed (Glazier et al, 2014). The study investigated if bowling performance is affected across spells and overs of pace bowling in elite male crickets (*n* = 5). The author hypothesised that ball velocity would decrease over spells, and furthermore, that bowlers would compensate in their bowling mechanics to generate greater ball speeds which might be evident in PlayerLoad$^{TM}$ metrics. The study found that ball velocity increased throughout the overs of a spell, yet decreased from spell to spell, thus showing bowlers to be "warming up" throughout an over, yet gradually fatiguing throughout the day. Interestingly, however, run-up velocity did change from spell to spell, yet roll, the measurement of lateral flexion during bowling decreased spell to spell. The study concluded that elite bowlers might be able to mitigate changes in run up velocity, yet ball velocity and the ability to lateral flex the trunk explosively were tied to fatigue and reduction in bowling velocity. The study unfortunately has not included locomotion data from fielding in the matches thus limiting possible inferences as to whether it is the volume of fielding demands or perhaps the greater number of overs bowled, or perhaps a combination that might possibly be the cause for fatigue. Additionally, the research just investigated the effect of bowling during multiday matches, and therefore does not address how bowling could be affected in the shorter format of the games that have been shown to be more intensive in terms of the fielding demands (Petersen et al, 2011).

# 8 METHODS

## 8.1 Experimental Approach to the Problem

A single-cohort observational longitudinal repeated measures design was implemented during the 2022 cricket playing season. Five professional pace bowlers playing in first class English County Cricket were used to examine between format differences in maximal run-up velocity ($m \cdot s^{-1}$), total daily fielding duration (minutes), total daily fielding distance (m) and total daily fielding meterage (m/min). Additional comparison was made within-format to see differences between first and last over. Measurement of movement characteristics were acquired using portable MEMS devices comprising of GPS (10-Hz) and tri-axial accelerometer technology (100-Hz).

## 8.2 Participants

Five first class professional male pace bowlers (mean ±standard deviation) aged 27.33 ± 2.94 y, stature (183.20 ± 5.66 cm), and body mass (81.70 ± 3.26 kg) from a team playing in the top domestic league in English County Cricket were recruited for the study. The inclusion criteria needed to be met was that the player was deemed to be a pace bowler as decided by the fast-bowling coach and the player had to wear the GPS technology during at least one competitive fixture in both MD and T20 and bowl more than two overs in each format during the competition period.

## 8.3 Procedures

T20 data collection was taken from a combination of Vitality T20 blast competition, club friendly and second XI fixtures ($n$ = 16) in the 2022 playing season. Data was used for analysis if they bowler met the criteria of having bowled more than one over in the T20 fixture and had also bowled in the MD format. Data collection for the MD format was taken from a single day of fielding in a County Championship fixture ($n$ = 16) in the 2022 season to allow for more direct comparison to a fielding innings in the T20 format. Five bowlers met the criteria for inclusion in the data set having bowled significant overs in both playing formats. All matches were played on a professionally prepared first-class wicket across various grounds in the UK, meeting and conforming to requirements of Law 7 (The Pitch) and law 10 (Preparation and Maintenance of the Playing Area) of the Marylebone Cricket Club (MCC) Laws of Cricket (MCC. The Laws of Cricket).

Players wore the same individually assigned 10-Hz sampling GPS device (Vector S7, Catapult Sports, Melbourne, Australia; mass 53g; size 8.1 x 4.3 x 1.6 cm). Catapult S7 peak speed validity ($p$ <0.001) and reliability expressed as typical error of measurement (TEM%) 1.6% (Johnston et al, 2014). As previously highlighted in the literature review (section 7.1) GPS units were used over other methods due to their reliability in acquiring real-time locomotion data from match day files, as well as relevant kinematic data from individual bowling events for quick analysis (Jowitt et al, 2020). Units were switched on approximately 30 minutes prior to the beginning of each match as to establish a satellite lock (≥ 4 satellites for ≥ 15 minutes). Players were given the device sporadically before they went out to perform their individual warm up preparations, although any captured data prior to the onset of fielding was discarded from the data set. Players wore the device in a neoprene vest, with the unit housed between the scapulae at the base of the cervical spine and were instructed to keep the unit on for the duration of the fielding innings from then after it could be removed.

Bowling intensity or effort was measured by recording maximal run-up velocity for each individually detected bowling incident captured during the fielding innings. Maximal run-up velocity was analysed as a relevant kinematic variable compared other variables such as acceleration because the literature shows greater run-up speeds to be strongly related to ball speed whilst also being stable even if a bowler is disguising a slower ball (Ferdinands et al, 2010; Salter et al, 2007; Justham et al, 2008). Individual bowling actions are detected with the aid of machine-based learning algorithms detected by software housed within the device. Validation of the algorithm has been tested against ball by ball manual recording in both training and matches with the Optimeye S5 units (Catapult Sports, Melbourne, Australia) and has a Matthews Correlation Coefficient in training ($r$ = 0.911) and matches ($r$ = 0.968) respectfully (Jowitt et al, 2020). Locomotive demands were quantified using total distance covered during a day of a fielding innings for both formats, and meterage (m/min).

Data were downloaded from the post-match using Catapult console software (OpenField version 1.21.1, Catapult Sports, Melbourne, Australia). From which it was downloaded into a Microsoft excel spreadsheet. The spreadsheet was then organised into specific reference points to be filtered by athlete, date, format, over and specifically first and last over during the day of fielding. Locomotive demands for the individual bowler were given in absolute and relative terms indicative of fielding volume and intensity. Relative distance was calculated as total distance divided by the sum duration of the fielding innings (m/min).

### 8.4 Between-Format Differences

To calculate between-format differences, run-up velocity was averaged across the day of fielding in each respective match and separated by format to give an average match run-up velocity ($m \cdot s^{-1}$) for the individual bowler. Locomotion demands of total distance, relative distance, and total duration and ball count for each individual bowler and match were also separated by format.

### 8.5 Within-Format and Between-Format Variability

The same bowling and locomotion variables were analysed for within-format variability from each day of fielding in their respective formats from which between-format comparisons can be made. Run-up velocity was further analysed separately as a principal component of bowling performance with average run-up velocity of the first and last over in each respective format compared within each format. The averaging of the over is necessary rather than just individual ball by ball run-up velocity due to tactical changes in ball delivery that could acutely affect the run-up velocity (length, slow, bouncer etc). The minimum number of completed overs per match was set at two for both formats to be included in the data set.

### 8.6 Statistical Analysis

Data are reported as mean ± SD alongside maximal values to provide additional context to the data. Alpha level of <0.05 was set a priori. All statistical analyses were performed using SPSS (IBM SPSS Statistics 27) with dependent variables tested for normal distribution using the Kolmogorov-Smirnov test. A repeated measures factorial ANOVA was run using SPSS statistics to determine format related differences in dependent variables of average maximal run-up velocity, average total distance, and average relative distance.

Variability was analysed using a mixed effect linear model (SPSS) to estimate the between format and within format variability. Variability was expressed using the coefficient of variation (CV%); typical error expressed as a percentage of the mean (Hopkins et al, 2000). The smallest worthwhile change (SWC) was calculated from between-participant standard deviations (0.2*SD) for each dependent variable (Batterham & Hopkins, 2006; Hopkins, 2004). Cohen's *d* effects sizes were performed between formats for all dependent variables and categorised as 0.0-0.19 = trivial; 0.20-0.49 = small; 0.5-0.79 = moderate; 0.8-1.09 = large; > 1.10 = very large with 90% confidence intervals for clearly identified outcomes to be identified if effects are not substantial (Hopkins et al, 2009).

## 9 RESULTS

Descriptive statistics (mean ± SD) summarising average locomotion demands, duration, and ball count for MD and T20 format can be found in table 2. Additionally, within format coefficient of variation (± 90% CI) are reported in table 2. Format related differences in dependent variables of mean peak run up velocity, fielding duration, fielding total distance, fielding meterage, and ball count were first tested for normality to see if data was normally distributed prior to difference testing. Mean peak run up velocity (MD, $p$ = 0.066, T20 $p$ = 0.043), total duration (MD, $p$ = 0.002; T20, $p < 0.001$), ball count (MD, $p$ = 0.087; T20, $p$ = 0.001) were not normally distributed therefore Mann Whitney U tests were run. Total distance (MD, $p$ = 0.189; T20, $p$ = 0.421) and meterage (MD, $p$ = 0.097; T20, $p$ = 0.050) were found to be normally distributed therefore independent samples t-tests were run. Mann Whitney U tests found mean peak run up velocity was significantly greater in the T20 format compared to the MD format ($p$ = 0.005), whereas total duration and total ball count was significantly greater in the MD format compared to T20 ($p < 0.001$; $p < 0.001$). Independent samples t-test found that total distance was significantly greater in MD than T20 ($t(80) = 7.68$, $p < 0.001$), however it was found that T20 was more intensive with a significantly greater meterage than MD ($t(80) = -6.736$, $p < 0.001$).

Table 1 Individual participant matchday values (mean ± SD)

| | Matchday files | Total balls | Total overs | First overs analysed | Last overs analysed |
|---|---|---|---|---|---|
| **T20** | | | | | |
| Participant 1 | 9 | 223 | 35 | 9 | 9 |
| Participant 2 | 11 | 257 | 43 | 11 | 11 |
| Participant 3 | 3 | 50 | 7 | 2 | 3 |
| Participant 4 | 13 | 230 | 35 | 13 | 13 |
| Participant 5 | 6 | 110 | 16 | 6 | 6 |
| **Mean** | 8.4 | 174 | 27.2 | 8.2 | 8.4 |
| **SD** | 3.97 | 89.30 | 15.04 | 4.32 | 3.97 |
| **MD** | | | | | |
| Participant 1 | 16 | 907 | 151 | 35 | 35 |
| Participant 2 | 9 | 528 | 90 | 9 | 9 |
| Participant 3 | 3 | 90 | 15 | 3 | 3 |
| Participant 4 | 3 | 115 | 19 | 3 | 3 |
| Participant 5 | 12 | 684 | 114 | 12 | 12 |
| **Mean** | 8.6 | 464.8 | 77.8 | 12.4 | 12.4 |
| **SD** | 5.68 | 357.22 | 59.62 | 13.22 | 13.22 |

Table 2 Descriptive Data (mean ± standard deviation and variability statistics for T20 vs MD

| | T20 (max value) | MD (max value) | T20 Between-player CV% ± 90% CI) | MD Between-player CV% ± 90% CI) | T20 SWC | MD SWC |
|---|---|---|---|---|---|---|
| Duration (min) | 82.52 ± 13.13 (124.93) | 254.37 ± 124.24 (408.50) | 14.67 (86.11, 92.93) | 48.84 (221.27, 287.46) | 2.63 | 24.85 |
| Total Distance (m) | 5102.82 ± 447.08 (6073.43) | 10700.40 ± 4704.16 (18488.02) | 8.76 (4986.72, 5218.91) | 43.96 (9447.20, 11953.60) | 89.42 | 940.83 |
| Meterage ($m\cdot min^{-1}$) | 57.89 ± 8.45 (71.01) | 45.03 ± 8.84 (62.25) | 14.59 (55.70, 60.08) | 19.63 (42.68, 47.39) | 1.69 | 1.77 |
| Ball Count (n) | 20.33 ± 5.40 (27.0) | 56.33 ± 23.20 (104.0) | 26.55 (18.93, 21.74) | 41.19 (50.14, 62.51) | 1.08 | 4.64 |
| Run Up Velocity ($m\cdot s^{-1}$) | 6.46 ± 0.36 (7.01) | 6.20 ± 0.38 (6.78) | 5.64 (6.37, 6.56) | 6.00 (6.10, 6.30) | 0.07 | 0.08 |

CV%, coefficient of variation; CI, confidence interval; SWC, smallest worthwhile change

A repeated measures ANOVA was performed to compare the effects of playing format on average run-up velocity between format and within format differences between the first and last over in competitive playing fixtures. There was a statistically significant difference in run-up (mean of first and last over) velocity between the playing formats with MD run-up velocity being slower than T20 (mean ± SD) 6.14 ± 0.42 and 6.42 ± 0.39 $m\cdot s^{-1}$ respectfully ($F(1,247) = 208.769$, $p < 0.001$. There was also significant difference in run-up velocity with first over run-up velocity being slower than last over 6.24 ± 0.45 $m\cdot s^{-1}$ and 6.33 ± 0.40 $m\cdot s^{-1}$ ($F(1,247) = 47.582$, $p < 0.001$. There was a significant interaction between format and first and last over ($F(1,247) = 65.811$, $p < 0.001$. Post-hoc paired samples T-test were run and found that bowlers in the MD format significantly increased run-up velocity between the first and last over (6.04 ± 0.43 and 6.23 ± 0.40 $m\cdot s^{-1}$, $t(254) = -0.28$, $p < 0.001$) respectfully. There was, however, no significant change in run-up velocity within the T20 format between first and last over (6.42 ± 0.25 and 6.42 ± 0.38 m·s$^{-1}$, t(247) = -10.58, *p* = 0.978).

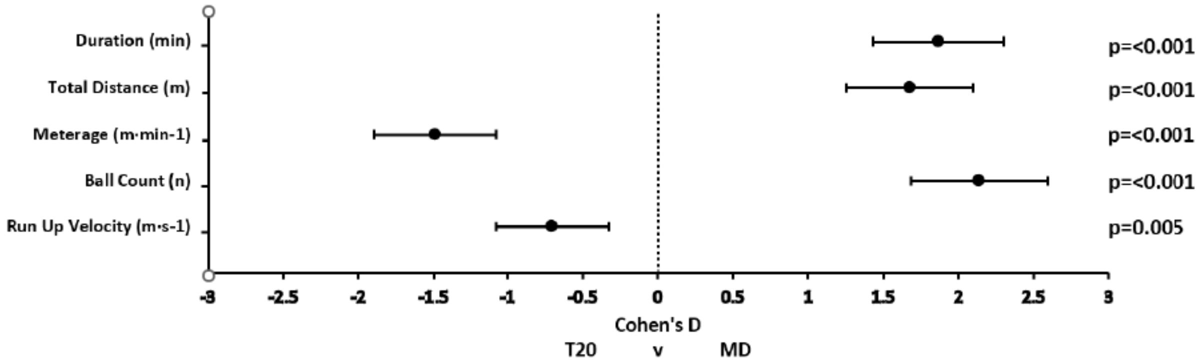


Figure 2 Comparison of daily fielding and bowling demands of T20 vs MD formats. Effects sizes ± 90% CI. P values = pairwise comparisons.

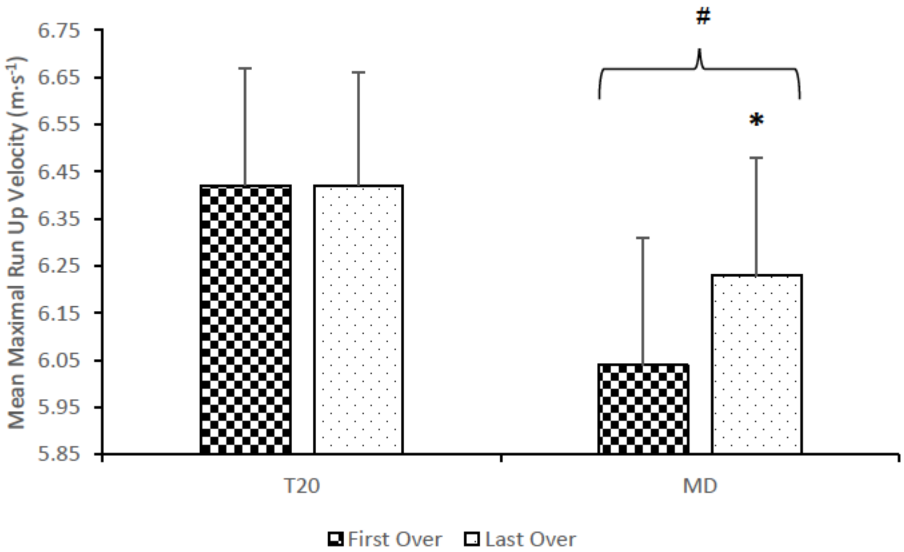


Figure 3 First and last over comparison of maximal run up velocity within and between formats; * Represents significant difference between first and last over; # represents significant difference between formats

## 10 Discussion

The study was the first to analyse run-up velocity differences between playing formats in elite cricketers from live competition. The primary aim of the study was to quantify the differences in run-up velocity as a proxy for bowling intensity between T20 and MD cricket. The secondary aim was to analyse the variability of run-up velocity, specifically changes from the first to last over, whilst also comparing locomotion demands between formats. The results showed that T20 cricket elicited a greater maximum run-up velocity on average than MD cricket which agreed with the hypothesis of the author based on previous data from controlled conditioned studies analysing different lengths of bowling spells (Maunder et al, 2017). The results also showed that during MD cricket, there was greater variability in run-up velocity between overs. The variability highlighted a significant increase in run-up velocity in MD cricket compared to T20 which remained unchanged. This is in contrast to the hypothesis that run-up velocity would decrease gradually throughout the day of bowling in the MD format due to fatigue related to the greater volumes of work required. Finally, our results agreed with previous research, showing locomotion demands to be significantly different between playing formats (Petersen et al, 2009; Petersen et al, 2011). The results showed T20 to be played at a greater intensity than MD as characterised by a significantly higher meterage compared to MD where greater volumes of total distance occurred. From a reliability perspective, the study showed run-up velocity to be a highly reliable and stable measure of bowling intensity regardless of format with low coefficient of variation (CV) values of 5.64 and 6% for T20 and MD respectfully. This is largely in agreement with previous controlled conditioned studies showing run-up velocity to be relatively reliable (Milne et al, 2022). Variability in locomotion demands showed MD to be more variable day to day than T20 for measuring total distance (CV% = 43.96% and 8.76%) and meterage (CV% = 19.63% and 14.59%) respectfully. Previous research investigating locomotion data in test match cricket over a 4-year period (Bliss et al, 2022) found during 28 test matches total distance variability and total distance relative to the hour had a CV% of 26.4 and 16.7% respectfully. Although out study showed greater levels of variability in total distances than test match cricket, it should be noted that during the Bliss et al (2022) study they compared match to match data from combined fielding innings rather than a single day of MD cricket compared to the next. This therefore likely would show lower variability in total distance where the majority of MD matches will include 2 fielding innings. Specifically looking at variability in total distance and relative distance for T20, our results were found to be similar to international T20 cricket. Bliss et al (2021) analysed 44 T20 matches over a 5-year period where total distance variability and meters per minute had a CV% of 10.7 and 7.9% respectfully compared to 8.76 and 14.59% in our own study.

As previously stated, the primary aim of the study is novel in its approach in attempting to quantify bowling intensity via run-up velocity between formats during live competition. Although there are no directly comparable research studies to draw exact conclusions, previous literature from lab-based controlled-conditioned studies as well as time-motion analysis from live competition can identify potential areas of agreement or disagreement in our findings.

## 10.1 Differences in run-up velocity between playing formats

Direct comparison between formats related to possible differences in physical performance markers of bowling performance, namely speed or run-up velocity is challenging due to a lack of published comparable data (McNamara et al, 2018). Indeed, the majority of the body of research investigating changes in bowling intensity or performance has centred around measuring fatigue across varying lengths of bowling spells in controlled-conditioned studies (Maunder et al, 2017). Comparison between these studies and our own is challenging due to multiple methodological differences with the most obvious being the ability to replicate the duration of simulated fielding and bowling spells during a typical day of MD cricket (Cockley, 2021). It is feasible to compare controlled-conditioned studies replicating fielding demands from T20 and OD cricket to data from MD live competition, however, to the knowledge of the author no studies have utilised the same cohort of pace bowlers therefore rendering direct comparison between formats less valid. These methodological problems highlight the strength and uniqueness of our study whereby the same cohort of fast bowlers played across both formats allowing for a valid comparison in bowling intensity.

To the authors knowledge only one published study shares a similar methodological approach to our own study. Justham et al (2008) investigated differences in ball release speed and pitching line and length using Hawk-Eye™ video-based ball tracking technology across one-day (OD), T20 and MD international cricket matches from the same bowlers. Although, our own study investigated run-up velocity as a proxy for bowling intensity compared to ball release speed, it has been shown by multiple studies that ball release speed is positively correlated with run-up velocity (Duffield et al, 2009; Worthington et al, 2013). The study found that fast bowlers bowled quicker deliveries on average during MD matches (85.92 ± 7.92 mph) compared to OD (83.69 ± 4.49) and T20 matches (81.31 ± 1.09 mph) respectfully. Based on the premise of ball release velocity being a proxy measure of bowling intensity, this would contrast to the findings from our study where run-up velocity was significantly slower in MD compared to T20. The findings from Justham et al (2008) were in contrast to the authors hypothesis where they predicted bowlers would bowl more aggressively in the shorter formats due to a lower level of fatigue. It is worth noting however, that even though fast bowlers in T20 matches consistently bowl between 80 and 94 mph with consistent line and length, colloquially called a ‘stock ball’. Fast-bowlers will occasionally bowl deliberately slower deliveries between 60 and 75 mph in an attempt to mislead the batsman into mistiming a shot (Justam et al, 2008). This is important to understand when comparing ball release velocity with run-up velocity as a proxy measures for bowling intensity as highly skilled elite bowlers will be better able to disguise slower deliveries whilst maintaining run-up speed (Malhotra & Krishna, 2017). It could therefore be argued that analysing changes in average ball release velocities, particularly in T20 cricket, could be a poor measure of bowling intensity as it pertains to indicating fatigue. It is also worth highlighting that although a similar methodological approach was used between the aforementioned study and our own, Justham et al (2018) study only investigated a single fast and a single medium pace bowler and therefore could be considered to be underpowered in comparison to our own study where five bowlers participated across both formats.

## 10.2 Within format differences in run-up velocity

To the authors knowledge the most comparable study to that of our own when investigating variability within playing formats was conducted by Cockley (2021) who investigated changes in bowling performance and intra-player variability in bowling performance throughout overs and spells during live competition in MD cricket. The study analysed multiple measures of bowling intensity such as ball velocity alongside GPS derived measures of bowling intensity such as run-up velocity, PlayerLoad™, roll and yaw. Cockley (2021) found that last 5m run-up velocity did not significantly decrease across overs ($p = 0.25$) or spells ($p = 0.51$). The non-significant results showed a decrease in run-up velocity between bowling spells (0.19 km/h) and a small over to over increase in run-up velocity within a spell (0.05 km/h). Cockley (2021) did however find significant negative differences in ball velocity across spells with an average decrease of 0.45 km/h each spell which was consistent for four of the bowlers with one remaining stable throughout. The decrease in ball velocity across spells was consistent with the findings of run-up velocity showing an over to over within-spell increase in ball velocity (0.33 km/h). These findings according to the author indicated a possible potentiation affect for within-spell bowling with cumulative fatigue from the previous spells and fielding demands negatively affected both run-up and ball velocity in the subsequent spells. It is worth noting however that the study did not define a minimum number of overs that might constitute a spell, which is potentially problematic when making inferences on spell to spell reductions in intensity. Our study showed that by comparison there was a significant difference between first and last over during a day of MD cricket with bowlers significantly increasing run-up velocity by 0.68 km/h ($p < 0.001$). This strongly contradicts findings to that of Cockley (2021) where bowlers in our study were not negatively affected by previous overs and fielding demands and may actually have had a potentiation effect. However, it is important to understand that our study did not compare within and between bowling spells, therefore possible changes in run-up velocity throughout a day of play might not be conclusive. It is possible that bowlers might have had prior knowledge of the length of their spell and therefore gave more effort in their last over which may give a false impression of cumulative fatigue which perhaps may have been negated by grouping overs into spells.

Although lacking possibly ecological validity to our own study. Controlled-conditioned studies have investigated possible changes in bowling intensity and accuracy from a single spell (4-12 overs or just two spells (2 x 6 overs) with most finding non-significant changes in bowling performance measures (Maunder et al, 2017). Of the few studies that did show significant changes in bowling performance were studies that investigated spells that were longer than 10 overs in duration and or also investigations into spells of bowling on consecutive days (Tailep et al, 2003; Minett et al, 2012). This is important when drawing comparisons with MD cricket in our own study where players would perform longer spells as well as bowl on consecutive days. Tailep et al (2003) investigated ball velocity across 12-overs of maximal intensity bowling with four minutes of simulated fielding between overs. The results from the study found that ball speed significantly decreased ($p < 0.05$) from the first over (32.9 ± 2.1 $m \cdot s^{-1}$) to the last (32.1 ± 1.8 $m \cdot s^{-1}$). It was found however, that the decrement in ball velocity only significantly occurred between the overs of 7 and 12 which would tend to be the upper most limits of a bowling spell duration during competition (Maunder et al, 2017). Although the study did not measure run-up velocity as in our study, ball velocity has a strong relationship with run-up velocity therefore could be used as a proxy for fatigue (Bailey et al, 2023). The results of our study possibly contrast with the findings of Tailep et al (2003) and Minett et al (2012) where bowling intensity, as measured by run-up velocity increased from first to last over. This could be explained by Tailep et al (2003) instructing the players to explicitly bowl a maximal intensity ball in each effort. The same instruction might not necessarily be beneficial to optimal bowling during competition against live batsman (Malhotra & Krishna, 2017).

Minett et al (2012) found a decrease in final 5m run-up velocity on the second day of consecutive bowling in high temperatures. The design investigated bowling performance from a four-over spell after a cooling intervention post bowling a 10-over spell the previous day. The study found no changes in the four-over spell in the experimental group that underwent the cooling intervention. However, a control group had a significantly decreased run-up velocity between session 1 and session 2 (20.9 ± 1.8 km/h and 19.6 ± 1.5 km/h) respectfully (Minett et al, 2012). The experimental group also had positive effects on bowling accuracy, subjective RPE and creatine kinase 24-hours compared to the control group. Although, our study did not investigate changes in run-up velocity on consecutive days of MD cricket. During a single day of our study, pace bowlers bowled up to 17 overs therefore its findings are relevant and comparable to our own. Although our study found run-up velocity to be increased throughout a day of MD cricket, it is important to understand that comparison between days might have shown different results. Delayed onset muscle soreness (DOMS) from a previous day's play might elicit negative effects to run-up velocity due to muscular damage caused by multiple eccentric muscle actions. Minett et al (2012) however did demonstrate that perceptual and internal markers of muscle damage can be mitigated with appropriate cooling and or recovery measures.

The results from our study found no significant differences in run-up velocity between first and last over in the T20 format. Comparison between controlled-conditioned studies investigating bowling intensity and T20 live competition are more applicable due to a larger body of research investigating shorter bowling durations in controlled-conditions (Maunder et al, 2017). Milne et al (2020) developed a novel T20 fast bowling simulation which was found to be valid in comparison with most reported match demands. The study investigated multiple measures of bowling performance, such as accuracy and run-up velocity and found run-up velocity was insignificantly changed from first to last over (5.45 ± 0.51 and 5.60 ± 0.65) respectfully (Milne et al 2020). These findings agree with our own where no significant changes occurred from first to last over in run-up velocity. Although many studies have not directly investigated performance and physiological responses to specific T20 cricket demands such as the Milne et al (2020) study. Multiple studies investigating spells between 6 and 12-over spells in a single session of controlled-conditions bowling have found no significant changes in performance outcomes such as run-up or ball velocity (Burnett et al, 1995; Portus et al, 2000; Duffield et al, 2009; Crewe et al, 2013). Research has suggested that sub-elite and elite pace bowlers do not have an acute negative effect on their bowling performance. This could be due in part to a relatively small to moderate contribution from the anaerobic energy pathway with a stable mean blood lactate levels reported at 4.8 mmol. $L^{-1}$ and 5.0 ± 1.5 mmol. $L^{-1}$ (Burnett et al, 1995; Duffield et al, 2009; Johnstone et al, 2014). Even though T20 cricket is played at a higher intensity than MD cricket with shorter work to rest ratios, rest intervals appear to be sufficient to suggest that the classic cardiovascular-anaerobic energy supply models are unlikely to explain performance decrements (Petersen et al, 2009; Noakes & Durant, 2000).

## 10.3 Practical Applications

The study is one of very few to investigate possible changes in bowling performance from GPS technology during live competition between and within different playing formats. It has highlighted an under researched body of research into pace bowling demands that could assist practitioners to make better and more informed decisions from a physical preparation and tactical perspective to maximise performance and mitigate against possible injury risk and fatigue.

### Injury risk mitigation and bowling load

Pace bowlers have been shown to have the greatest injury risk out of all playing positions with an injury prevalence of 20% compared to batsman which sustain injury 7.4% of the time

(Orchard et al, 2016). By quantifying bowling demands such as run-up velocity, practitioners can have a greater knowledge of the physical cost of bowling for each format. The study showed that pace bowling in T20 cricket is of greater intensity than MD cricket with bowlers having significantly faster run-up speeds. Greater run-up speeds have been suggested to be a possible contributing factor to an increased risk of injury due to the greater horizontal and vertical ground reaction forces and loading rates upon front foot contact (King et al, 2016). During the English county season, T20 cricket is played in block format for approximately six weeks after an initial period of six weeks of MD cricket after pre-season (ESPNCricketInfo.com). Coaches should be aware that not only is T20 bowling at greater intensity than MD, but also played at a high frequency with up to six matches being played in eleven days, with occasion matches played on consecutive days (ESPNCricketInfo.com). This is potentially an important factor for format specific bowling load monitoring to avoid potential spikes in workload that might contribute to increased risk of injury (Feros et al, 2021; Hulin et al, 2017). With the knowledge coaches have of the high frequency of matches in T20 cricket, and consecutive days of fielding in MD, it is important that coaches have reliable measures of how bowlers are performing match to match to potentially manage the workload of their bowlers. The study showed between bowler run-up velocity regardless of format to be a stable and reliable measure of intensity with a low coefficient of variation value of 5.64 and 6% for T20 and MD respectfully. Because run-up velocity has been shown to be highly stable, match to match changes in run-up velocity can be more accurately detected. Smallest worthwhile change values in run-up velocity of 0.07 and 0.08 $m \cdot s^{-1}$ for T20 and MD were found which show a practical bandwidth from which practitioners could make justified inferences regarding changes in performance. This could be important for retrospectively identifying bowlers that are not able to maintain run-up velocity during bouts of high frequency and are possibly fatigued and predisposed to injury.

Specifically, regarding bowling loads and how these could be more accurately quantified, it has been shown in previous biomechanical research that bowling with shortened run-ups which in turn decrease the run-up velocity reduces the loading rates through the lumbar spine upon ground contact (Grieg & Childs, 2020). Practitioners could therefore consider applying a greater weighting on T20 bowling compared to MD in their bowling load monitoring system. GPS technology allows practitioners to be more precise with prescribing appropriate bowling loads during training sessions rather than just being reliant on ball count. This might also be of particular use when an athlete is returning from injury and is prescribed bowling at progressively higher intensities.

**Physiological preparation**

The study showed that elite pace bowling intensity did not diminish throughout either playing format, it was shown to significantly increase throughout a day of MD cricket despite potentially bowling up to 17 overs in a day and covering up to 18km of total distance. This suggests that the pace bowlers had an adequately developed aerobic system to buffer the lactate accumulation from high intensity action to mitigate against muscular fatigue (Duffield et al, 2009). Although physiological testing data was not gathered from the cohort of pace bowlers in the study, it has been shown that elite pace bowlers tend to have moderately well-developed aerobic systems similar to other team sports such as rugby union and soccer with predicted VO2 maxes ranging between 50.6 – 62.7 $ml.kg^{-1}\cdot min^{-1}$ (Johnstone et al, 2014). As previously highlighted, the high reliability of run-up velocity as a measure of bowling intensity gives reliable measures of smallest worthwhile change between matches which could show how well athletes are able to tolerate congested fixtures of T20 or bowling consecutively in MD cricket. Research has regularly suggested that pace bowlers do not experience an acute reduction in run-up velocity during bowling spells or matches, however, it is suggested that better recovery from exercise induced muscle damage (EIMD) could play a factor in the ability to maintain high levels of performance between matches (Minett et al 2012; Maunder et al, 2017). Furthermore, it has been suggested that improved aerobic fitness may improve parasympathetic activity facilitating improved recovery from EIMD (Joyce & Lewingdon, 2014; Novack et al., 2018). It is therefore suggested that practitioners focus on developing a moderately well-developed aerobic system to limit acute fatigue from metabolic by-products as a result of the lactic contribution whilst also aiding the ability to chronically recover from EIMD (Kiely, 2020; Noakes & Durant, 2000).

**Tactical**

As run-up velocity in T20 cricket remained unchanged and at a greater average speed than MD cricket, it can be presumed that bowlers are performing at maximal effort from first over to last compared to MD cricket where a pacing strategy is most likely being implemented. Although there are many possible explanations why MD bowling is bowled at a lower intensity than T20. Perhaps, the knowledge that there are hypothetically no limits on the number of overs that could be bowled during a single spell or day could contribute to a bowler consciously or unconsciously adopting a pacing strategy to conserve energy. The study did show that bowlers increased run-up velocity from first to last over which could indicate that bowlers are not confident in their ability to maintain a maximal effort from the start as they do during four overs of T20 cricket. It could be suggested therefore that to maintain a more consistent high level of bowling intensity throughout a day, spell length and fielding position could be managed tactically to reproduce maximal efforts. This in turn may decrease the gap in bowling intensities between both formats and possibly maximise bowling performance in the MD format.

Additionally, providing regular feedback on run-up velocity could potentially provide valuable information as to optimal spell length or total number of overs that a bowler should bowl during MD cricket which in turn could aid more specific conditioning programmes to bowler.

# 11 LIMITATIONS

Although the study was novel in its approach to quantifying possible differences in run-up velocity between and within format bowling in live competition, there were limitations to the study. In the MD format, number of overs, duration, or fielding demands was not standardised to be included in the data set. Additionally, although the study is grounded on the basis that run-up velocity is a proxy for bowling intensity which might increase understanding of the physiological demands. No measures of internal load were taken which might build a more comprehensive understanding of differences between and within format bowling.

# 12 FUTURE RESEARCH

Use of microtechnology to monitor external work demands of pace bowling is still very much in its infancy. The thesis is novel in its approach to attempt to quantify between and within format changes in bowling intensity using run-up velocity during live-competition. It is clear that understanding training load is vitally important in cricket to minimise risk of injury and maximise performance especially with an ever increasingly dense playing schedule. Future research therefore should look to investigate further external load variables which are accessible in newer GPS models such as run-up distance, roll, yaw and player load from live-competition (Jowitt et al,2020; Cockley et al, 2021; Bray et al, 2016). By investigating a greater number of variables relevant to ball velocity, potential changes in bowling strategy or technique might be understood which may have implications on more accurate athlete monitoring (McNamara et al, 2018).

An additional potential area of future research should be to understand how a bowler's level of physical preparation may influence their ability to withstand fatigue during longer spells of bowling. The current study showed the cohort of pace bowlers to not decrease bowling intensity in T20 with an increase throughout MD cricket. By conducting similar studies with pace bowlers across different playing or fitness levels practitioners could have a greater knowledge of how to physically prepare bowlers to maximise performance relevant to the specific playing format (Feros, 2016).

# 13 CONCLUSION

The main findings of the study found significant differences in run-up velocity which was significantly faster in T20 than in MD cricket. Additionally, as expected, a single day of T20 cricket elicited less total distance but played at a higher intensity as measured by meters per minute. Secondarily, it was found that there was greater variability in run-up velocity in MD cricket where bowlers significantly increased their run-up velocity from first to their last over. This was in contrast to T20 bowling where a higher average run-up speed was maintained from first to last over.

With the restrictions on the number of overs bowled in a T20 innings for both the individual and the team, players are aware that an innings will last on average around an hour and a half and therefore would be unlikely to be adopting a pacing strategy. This is in contrast to what is occurring in MD cricket where a day of fielding could be up to 6 hours in duration without restrictions on the number of overs that an individual can bowl. Due to the lower average run-up velocities in MD cricket compared to T20, and that the speeds increased from first to last over this suggest that bowlers are running in at sub-maximal speeds to conserve energy early on in the day. Coaches should be aware that this might be sub-optimal for bowling quicker deliveries and increasing the possibility of taking wickets or reducing run scoring opportunities. By looking at changes in run-up speeds throughout MD games, coaches and captains could utilise this knowledge to perhaps tactically alter the length of bowling spells or where pace bowlers stand in the field as to encourage pace bowlers to perform closer to their maximal efforts as seen in the shorter format. Additionally, performance coaches might build a better understanding of what levels of physical conditioning might be required of pace bowlers to perform at or near their optimal consistently during the longer format.

The study provides an important contribution to an under-researched area of literature investigating real-world data of what elite pace bowlers experience in the short and long formats of the game. Previous studies where bowling has been conducted in simulated conditions possibly lack ecological validity due to the absence of real match-play variables such as the crowd, weather conditions, previous days play, and the pressure of being in a competitive scenario with live opposition. Sophisticated advances in GPS wearable technology allow the further understanding of external load monitoring across different playing formats and provide valuable insight as to how technical and performance staff might prepare and tactically manage players to maximise performance and mitigate against fatigue and injury.

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# 14 APPENDICES

**Estimates**

Measure: MEASURE_1

| format | Mean | Std. Error | 95% Confidence Interval Lower Bound | 95% Confidence Interval Upper Bound |
|---|---|---|---|---|
| 1 | 6.139 | .025 | 6.090 | 6.187 |
| 2 | 6.424 | .024 | 6.377 | 6.470 |

**Pairwise Comparisons**

Measure: MEASURE_1

| (I) format | (J) format | Mean Difference (I-J) | Std. Error | Sig.[b] | 95% Confidence Interval for Difference[b] Lower Bound | 95% Confidence Interval for Difference[b] Upper Bound |
|---|---|---|---|---|---|---|
| 1 | 2 | -.285* | .020 | <.001 | -.324 | -.246 |
| 2 | 1 | .285* | .020 | <.001 | .246 | .324 |

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

**Multivariate Tests**

| | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Pillai's trace | .458 | 208.769[a] | 1.000 | 247.000 | <.001 |
| Wilks' lambda | .542 | 208.769[a] | 1.000 | 247.000 | <.001 |
| Hotelling's trace | .845 | 208.769[a] | 1.000 | 247.000 | <.001 |
| Roy's largest root | .845 | 208.769[a] | 1.000 | 247.000 | <.001 |

Each F tests the multivariate effect of format. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

**4. time * format**

Measure: MEASURE_1

| | | | | 95% Confidence Interval | |
|---|---|---|---|---|---|
| time | format | Mean | Std. Error | Lower Bound | Upper Bound |
| 1 | 1 | 6.044 | .027 | 5.991 | 6.098 |
| | 2 | 6.426 | .026 | 6.375 | 6.478 |
| 2 | 1 | 6.233 | .025 | 6.183 | 6.283 |
| | 2 | 6.421 | .025 | 6.372 | 6.469 |

## T-Test

**Notes**

| | | |
|---|---|---|
| Output Created | | 14-JUL-2022 12:48:56 |
| Comments | | |
| Input | Active Dataset | DataSet1 |
| | Filter | <none> |
| | Weight | <none> |
| | Split File | <none> |
| | N of Rows in Working Data File | 264 |
| Missing Value Handling | Definition of Missing | User defined missing values are treated as missing. |
| | Cases Used | Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis. |

| | | |
|---|---|---|
| Syntax | | T-TEST PAIRS=T20First MDFirst WITH T20Last MDLast (PAIRED) /ES DISPLAY(TRUE) STANDARDIZER(SD) /CRITERIA=CI(.9500) /MISSING=ANALYSIS. |
| Resources | Processor Time | 00:00:00.00 |
| | Elapsed Time | 00:00:00.01 |

**Paired Samples Statistics**

| | | Mean | N | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| Pair 1 | First over of T20 cricket | 6.4229 | 255 | .40521 | .02538 |
| | Last over of T20 cricket | 6.4234 | 255 | .38243 | .02395 |
| Pair 2 | First over of MD cricket | 6.0443 | 248 | .42531 | .02701 |
| | Last over of MD cricket | 6.2329 | 248 | .39853 | .02531 |

**Paired Samples Correlations**

| | | N | Correlation | Significance | |
|---|---|---|---|---|---|
| | | | | One-Sided p | Two-Sided p |
| Pair 1 | First over of T20 cricket & Last over of T20 cricket | 255 | .743 | <.001 | <.001 |
| Pair 2 | First over of MD cricket & Last over of MD cricket | 248 | .770 | <.001 | <.001 |

**Paired Samples Test**

| | | Paired Differences | | | |
|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference Lower |
| Pair 1 | First over of T20 cricket - Last over of T20 cricket | -.00049 | .28295 | .01772 | -.03539 |
| Pair 2 | First over of MD cricket - Last over of MD cricket | -.18852 | .28049 | .01781 | -.22360 |

**Paired Samples Test**

| | | Paired Differences: 95% Confidence Interval of the Difference: Upper | t | df | Significance: One-Sided p |
|---|---|---|---|---|---|
| Pair 1 | First over of T20 cricket - Last over of T20 cricket | .03440 | -.028 | 254 | .489 |
| Pair 2 | First over of MD cricket - Last over of MD cricket | -.15344 | -10.584 | 247 | <.001 |

**Paired Samples Test**

| | | Significance: Two-Sided p |
|---|---|---|
| Pair 1 | First over of T20 cricket - Last over of T20 cricket | .978 |
| Pair 2 | First over of MD cricket - Last over of MD cricket | <.001 |

**Paired Samples Effect Sizes**

| | | | Standardizer[a] | Point Estimate | 95% Confidence Interval: Lower |
|---|---|---|---|---|---|
| Pair 1 | First over of T20 cricket - Last over of T20 cricket | Cohen's d | .28295 | -.002 | -.124 |
| | | Hedges' correction | .28379 | -.002 | -.124 |
| Pair 2 | First over of MD cricket - Last over of MD cricket | Cohen's d | .28049 | -.672 | -.809 |
| | | Hedges' correction | .28135 | -.670 | -.807 |

**Paired Samples Effect Sizes**

| | | | 95% Confidence Interval[a] |
|---|---|---|---|
| | | | Upper |
| Pair 1 | First over of T20 cricket - Last over of T20 cricket | Cohen's d | .121 |
| | | Hedges' correction | .121 |
| Pair 2 | First over of MD cricket - Last over of MD cricket | Cohen's d | -.534 |
| | | Hedges' correction | -.532 |

a. The denominator used in estimating the effect sizes. Cohen's d uses the sample standard deviation of the mean difference. Hedges' correction uses the sample standard deviation of the mean difference, plus a correction factor.