Running Title: Workload monitoring in throwing sports

Monitoring workload in throwing-dominant sports: A systematic review

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Key Points

Optimal techniques for monitoring workload in throwing-dominant sports have been less researched than in running-based team sports.

Workload monitoring can be used effectively to detect and identify injury risks and thresholds in some throwing-dominant sports. However, a number of key limitations impair current research. These limitations include: the lack of reliability of self-reported load data, inability of current techniques to monitor all of the training completed by athletes and the majority of published workload-injury data being based around game loads, with training loads often neglected.

The use of more than one workload-monitoring technique potentially provides coaches with an understanding of the factors influencing performance and contributing to injury and may also facilitate further individualisation of the training process.

Abstract

Background. The ability to monitor training load accurately in professional sports is proving vital for athlete preparedness and injury prevention. While numerous monitoring techniques have been developed to assess the running demands of many team sports, these methods are not well suited to throwing-dominant sports that are infrequently linked to high running volumes. Therefore, other techniques are required to monitor the differing demands of these sports to ensure athletes are adequately prepared for competition.

Objective. To investigate the different methodologies used to quantitatively monitor training load in throwing-dominant sports.

Methods. A systematic review of the methods used to monitor training load in throwing-dominant sports was conducted using variations of terms that described different load-monitoring techniques and different sports. Studies included in this review were published prior to June 2015 and were identified through a systematic search of four electronic databases including Academic Search Complete, CINAHL, Medline and SPORTDiscus. Only full-length peer-reviewed articles investigating workload monitoring in throwing-dominant sports were selected for review.

Results. A total of 8098 studies were initially retrieved from the four databases and 7334 results were removed as they were either duplicates, review articles, non-peer-reviewed articles, conference abstracts or articles written in languages other than English. After screening the titles and abstracts of the remaining papers, 28 full-text papers were reviewed, resulting in the identification of 20 articles meeting the inclusion criteria for monitoring workloads in throwing-dominant sports. Reference lists of selected articles were then scanned to identify other potential articles, which yielded one additional article. Ten articles investigated workload monitoring in cricket, while baseball provided eight results, and handball, softball and water polo each contributed one article. Results demonstrated varying techniques used to monitor workload and purposes for monitoring workload, encompassing the relationship between workload and injury, individual responses to workloads, the effect of workload on subsequent performance and the future directions of workload-monitoring techniques.

Conclusion. This systematic review highlighted a number of simple and effective workload-monitoring techniques implemented across a variety of throwing-dominant sports. The current literature placed an emphasis on the relationship between workload and injury. However, due to differences in chronological and training age, inconsistent injury definitions and time frames used for monitoring, injury thresholds remain unclear in throwing-dominant sports. Furthermore, although research has examined total workload, the intensity of workload is often neglected. Additional research on the reliability of self-reported workload data is also required to validate existing relationships between workload and injury. Considering the existing disparity within the literature, it is likely that throwing-dominant sports would benefit from the development of an automated monitoring tool to objectively assess throwing-related workloads in conjunction with well-established internal measures of load in athletes.

1. Introduction

Documentation of training and competition workloads is increasingly important in team sports, with much interest on the influence of training volume, intensity, and frequency on injury [1, 2]. While positive dose-response [3-5] relationships to load have been reported, negative responses have also been highlighted, with the greatest incidence of injuries occurring when workloads are highest [6, 7]. The importance of monitoring workload in athletes has stemmed from research supporting a positive relationship between workload and injury. Although it is hypothesised that restricting workloads may minimise the likelihood of athlete injury [6], reducing workloads in competition and training may also be detrimental to an athlete's conditioning and performance in team sports [6]. A recent review highlighted that both under- and over-training can increase the risk of injury. While conflicting relationships exist between workload and injury, excessive and rapid increases in workload result in sharp increases in injury risk [8].

Given an individual's response to a specific workload can be highly variable [3], understanding how each athlete responds to the demands of training and competition is paramount. Traditionally, elite and sub-elite teams have relied on video time-motion analyses to monitor player workloads and to quantify the individual contributions to each specific game. This particular method of workload analysis is both labour-intensive and prone to human error. Also it cannot be performed in real-time and is typically restricted to a single player within a given time [9]. Although a number of new technologies exist within different sports (Prozone®, Pitch Fx®) that have the ability to monitor player workloads during games, these technologies are not typically used to monitor performance during training or practice. To address the many issues associated with video time-motion analyses, global positioning systems (GPS) have more recently been used to measure external workloads in team sport athletes [10,11] in both training and game situations. GPS technology that samples at a frequency of 10 Hz has acceptance as a valid and reliable measure of velocity, distance, and acceleration [12]. As such, this technology allows coaches and sports scientists to quantify the activity profiles and demands of training and competition in a wide variety of sports. With the addition of inertial measurement sensors (i.e. accelerometers, gyroscopes, and magnetometers), these microtechnology units are increasingly used as a reliable and accurate method of monitoring athlete workloads [13].

The relationship between running volumes and subsequent injury risk has been broadly researched in team sports [1], with research highlighting links between weekly training loads [14] and 3-weekly sprint distances [15] and injury risk in Australian Football players. Similarly, rugby league players who perform a higher volume of very-high speed running have been shown to have an increased risk of subsequent injury [1]. Notably, an understanding of these relationships has allowed running load thresholds to be established to decrease injury risk and protect those athletes who are involved in running-dominant team sports [1, 15].

Although multiple techniques for monitoring training load have been suggested [16, 17], their invasive nature (e.g. blood sampling [18]), makes their recurring use problematic with elite athletes [19]. Therefore, the use of the session-rating of perceived exertion (RPE) method has emerged to monitor training loads in team sports [2, 6, 15, 16]. Other monitoring techniques include: self-reported measures of mood states [20-22] and wellness [23] and have been reported to be sensitive to subtle changes in training load. Collectively, these studies [20-23] support the inclusion of wellness questionnaires as a technique to monitor workload in team sport athletes Using a subjective (session-RPE x training duration) method to monitor training load, Australian Football research indicated that injury risk was significantly higher for players who exerted larger “1- and 2-weekly loads” or large volumes of arbitrary units (AU) (>1,250 AU), prior to their current week’s increments in workload (odds ratio: 2.58) [2]. Multiple studies have monitored training loads using the session-RPE method in rugby league [1, 6, 24] with conflicting results reported. However a recent review of literature [8] has highlighted a critical variable in workload monitoring, the acute: chronic workload ratio. The findings [8] highlight the importance of monitoring acute and chronic training loads and their ability to identify and understand injury thresholds and injury risk in team sport athletes.

Despite the wealth of research documenting workload and its relationship with injury in many running-dominant team sports, evidence investigating workload monitoring techniques in throwing-dominant sports is far less substantive. Furthermore, considering a large number of sports include physically-demanding activities involving few locomotor demands (e.g. bowling, pitching, throwing), it is likely that research which has focussed on characterising the locomotive, kinematic demands of team sports [13] as a measure of total workload, may not provide an accurate representation of the physical demands of throwing-dominant sports. Given that throwing sports are largely under-represented in the monitoring and managing of athlete workloads it was the purpose of this systematic review to investigate the literature surrounding the methodologies most commonly implemented to monitor workload in throwing-dominant sports. Specific sports explored (baseball, cricket, handball, javelin, shot put, softball and water polo) were chosen in order to investigate player workloads predominantly involving physically-demanding throwing activities with fewer locomotor demands than other team sports. This review shifts the focus from running-based team sports to throwing-dominant sports and will provide coaches, sport scientists, and strength and conditioning staff with a perspective on the evidence relating to workload monitoring techniques in throwing-dominant sports.

2. Methods

2.1 Literature Search Strategy

This review investigated different methodologies used to quantify and monitor training load in throwing-dominant sports. Articles for this review were systematically identified through the search of electronic academic databases that included Academic Search Complete, CINAHL, Medline, and SPORTDiscus. These databases were searched using the combinations of the following key words: (i) ‘baseball’; ‘cricket’; ‘softball’; ‘handball; ‘water polo’; ‘javelin’; ‘shot put’ (ii) ‘work load’; ‘workload’; ‘training load’; ‘pitch’; ‘bowl’; ‘throw’. Terms were connected with ‘OR’ within each of the two combination groups and these two search categories were combined using ‘AND’.

2.2 Selection Criteria

The process used for selecting articles is outlined in Figure 1. Duplicate articles were eliminated from the initial search results and the titles and abstracts of remaining articles were then independently reviewed by three assessors (GMB, TJG and MHC) for relevance to the review. For the purpose of the review, articles included were required to describe methods to monitor workload in throwing-dominant sports. As such, articles that only provided a technical description of throwing, pitching or bowling movements were excluded. Publications were also excluded from this research if they were review articles, not a full-length paper, non-peer reviewed or studies that described or reported general training or game-related demands of sports (i.e. did not separate throwing-related demands from running-related demands, for example). In situations where one or more of the three independent reviewers disagreed regarding the suitability of a paper for inclusion, the merits of the paper were discussed until a consensus was reached. The selected articles included papers published prior to June 2015 that were written in English and included the search terms in the title or abstract. The full-text of the manuscripts was assessed for inclusion using the same criteria, once articles were selected. Reference lists of selected articles were then scanned to detect any potentially relevant articles not identified by the original search. Secondary-sourced articles were then subjected to the same screening procedures.

Insert Figure 1 about here

2.3 Quality of Research

The quality of reporting in the included research studies was assessed based on a modified version of currently established scales used in sport science, healthcare and rehabilitation (i.e. Cochrane, Coleman, Delphi and Physiotherapy Evidence Database (PEDro)) to evaluate research conducted in athletic-based training environments [25]. The current scale (Table 1) was adapted and modified from a recent review [26], where study quality was appraised based on ten items that were each scored on a scale that ranged from zero (no), to one (maybe) or two (yes). As no intervention studies were included in this review, the score attributed to the "intervention" criterion was replaced with a criterion that assessed the overall thoroughness with which the data collection procedures were reported in each paper. Considering observational study designs are most commonly used in applied sport science, the "control group" criterion was removed from the scale, leaving 9 criteria yielding a maximum of 18 points. For those studies that did not involve cohorts being allocated to different groups (e.g. injured versus uninjured), the criterion related to the reporting of subject assignment was omitted from the quality of assessment and these papers were scored out of 16. To ensure that the quality assessment was equitable for all of the included studies, the scores were summed and expressed as a percentage that ranged from zero to 100%.

Insert Table 1 about here

3. Results

A total of 8,098 studies were initially retrieved from the four databases, of which 2,291 were duplicates, 94 were non-English papers, 88 were conference abstracts, 4,799 were not full-length articles and 62 were review articles. Non-peer reviewed articles that included magazine articles, newspaper articles and opinion pieces were also excluded. The titles and abstracts of the remaining 764 unique research articles were screened, resulting in 736 being excluded and 28 progressing to full-text review. After full-text review, a further 8 papers were omitted and one was included in the review after the references of selected articles were scanned (Figure 1). Therefore, 21 articles remained for inclusion in this review.

Ten articles investigated workload monitoring in cricket (Table 2); reporting on the relationship between workload and injury (n=8), fatigue responses (n=1) and the use of microtechnology to detect fast bowling events (n=1). Eight addressed workload in baseball (Table 3) investigating the relationship between workload and injury (n=6), the impact of pitch count on performance (n=1) and, fastball velocity trends (n=1). The final three articles (Table 4) investigated workload in water polo (n=1), handball (n=1) and softball (n=1).

Furthermore, five of the 21 articles selected sought to characterise the use of different methods to monitor workload, while 16 articles assessed workload to establish its relationship to injury. Fifteen articles assessed workload using objective measures, and three articles used self-reported methods to monitor workload. Three articles included a combination of objective and subjective methods to monitor workload.

Insert Tables 2 to 4 about here.

Assessment of the reporting quality of the selected articles provided a mean quality rating of 92.6 ± 7.7% (see Tables 2-4). Eight of the 21 studies assigned subjects appropriately into comparative groups by similar baseline measures, comparing injured and non-injured groups. Each of these studies stated the inclusion criteria and dependent variables examined in their respective research. The least reported criterion was "subject assignment" and the best reported criterion were "inclusion criteria stated" and "dependent variables defined".

4. Discussion

The aim of this systematic review was to investigate the methods used to monitor workload in throwing-dominant sports. From the studies included in this review, it was apparent that workload monitoring techniques are not advanced in throwing-dominant sports, although simple monitoring methods have been shown to have the capacity to identify injury risks and injury thresholds in instances within these sports. A clear need exists for more reliable and less labour intensive workload monitoring techniques to provide further understanding of the physical and technical demands experienced by athletes in throwing-dominant sports.

A large number of studies included in this review monitored workload and its relationship with injury in cricket (67%) [27-33] or pain [36-40] and injury in baseball (86%) [41]. Research has highlighted that cricket fast bowlers and baseball pitchers are the positional groups most prone to injury in their respective sports. While the location of injury and pain differed between sports, this can be attributed to differences in pitching and fast bowling technique. Fast bowlers are more likely to sustain injuries to the lower back and lower limb [31], due to the fast bowling action involving a run-up. Baseball pitchers are more susceptible to elbow and shoulder pain [38, 39] and injury [40] due to the accumulation of microtrauma from the repetitive pitching motion [48]. Notwithstanding the different injury types between cricket fast bowlers and baseball pitchers, the results of this review demonstrated similar relationships between high workloads and the likelihood of injury or pain in these sports.

4.1 Reporting Quality

On the basis of this review, it is evident that research that has focussed on quantifying workload in throwing-dominant sports has typically adhered to a high standard of reporting. The study quality was most commonly affected by items three (rigor of data collection), five (assessments practical) and six (training duration practical) in Table 1. Improving the descriptions around accuracy, reliability and relevance of specific workload monitoring techniques in throwing-dominant sports may improve the quality of future research.

4.2 Workload Monitoring in Cricket

4.2.1 Workload and Injury in Cricket

Of the 21 studies included in this review, eight (38%) monitored workload in cricket fast bowlers to establish the relationship between workload and injury risk. The majority (75%) of studies examining workload in cricket were limited to subjective monitoring techniques [27-33]. Dennis et al [27] monitored workload using log books, completed by participants, detailing the number of bowling deliveries completed each day over a 6 month period. Although this study [27] provided evidence to support optimal rest days between bowling in junior cricketers, the small sample size provided insufficient power to detect small differences in bowling workload between the injured and uninjured bowlers. Furthermore, this study [27] was based on self-reported load data and the reliability of the log books completed by the bowlers was not reported.

More objective reports of the number of deliveries bowled per week [28] and the number of sessions bowled per week [29] have also been used to monitor the relationship between load and injury risk in cricket fast bowlers. During one study [28] bowling workloads were evaluated by filming each participant’s training session. Match workloads were recorded from scorecards and participants were asked to keep a personal record of deliveries completed at any session where filming was not possible [28]. While video-based methods have been shown to be an accurate method to monitor bowling workloads in professional matches, it can be an expensive and time consuming technique to implement, especially at lower levels of competition where resources are often limited. Based on this, Dennis et al. [29] employed research assistants to attend, observe and monitor bowling workload during all training sessions completed by participants. While these studies provided innovative results for fast bowling workload and injury, total throwing workload was not assessed. Therefore, the findings of these studies [27, 28] may be limited to the sub-group of fast bowlers in a cricket team and, hence, may not provide an accurate indication of the workload-injury risk faced by other players in the team.

In an attempt to monitor throwing workload in all cricketers, the relationship between total throwing workload and injury risk in elite cricketers supported by the objective data available from video-footage of matches and training was investigated [30]. Despite the novel approach of the research, this study [30] did not account for bowling workload or any throwing workload completed during players’ participation in sub-elite competition or practice matches. Consistent with previous research [28], the use of video recording to monitor workload is not ideal due to the labour-intensive nature of the technique.

Although relationships between fast bowling workloads and injury are well established [27-29, 31] , currently, interest lies in the investigation of the delayed effect of high bowling workloads on injury.

Comparisons have been made between the number of overs bowled by players during a match with the player's injury risk subsequent to the match [31]. Bowling injury and workload data were extracted from a pre-existing database and findings suggested that elite bowlers who bowled more than 30-50 overs had an increased injury risk in the next 21-28 days [31]. Similarly, when pre-existing load data was considered, bowlers who bowled more than 50 match overs in a 5-day period had a greater incidence of injury over the next month than players bowling less than 50 overs (relative risk = 1.54) [32]. While high acute match workloads and high previous season workloads have also been identified as risk factors for developing tendon injuries in cricket, workloads that induce a protective and beneficial response have been further investigated [33]. Collectively, these studies provide evidence that workloads can be both beneficial and detrimental to elite fast bowlers. However, the results of these studies should be interpreted with a degree of caution as the training workloads of other competitions not involving Australian teams and the workloads of other training sessions (e.g. strength and conditioning sessions) were not included.

While balls and overs completed are the most common methods used to monitor workload in cricket, Hulin et al. [34] was the first to combine workload using both external (balls bowled) and internal (session-RPE x training duration) monitoring techniques. This study [34] compared acute (1-week data) and chronic (4-week average rolling data) workloads and associated injury risk in elite fast bowlers. An acute:chronic workload ratio was also assessed by dividing the acute by the chronic workload. An acute:chronic workload ratio >1.5 for both internal and external workload was associated with an increased risk of injury in the subsequent week [34]. Furthermore, an acute:chronic workload ratio greater than 2.0 (i.e. acute workload was double that of the chronic workload) had a relative risk of injury of 4.5 and 3.3 compared with those shown to have an acute:chronic workload ratio between 0.5 and 0.99 for internal and external workloads, respectively [34]. In summary, while the majority of research has investigated the influence of workload on injury, further studies considering other methods to monitor load in cricket are warranted.

4.2.2 Other Workload Monitoring Techniques Used in Cricket

McNamara et al. [35] conducted the only study using methods other than balls bowled to monitor load in cricketers. The researchers investigated key fatigue and workload variables of elite youth fast bowlers and non-fast bowlers during a 7-week physical preparation period and a 10-day intensified competition period [35]. Using GPS, the researchers established that fast bowlers performed greater external workload during competition than other playing positions, covering greater total, low- and high-speed distances [35]. Higher cortisol and lower testosterone concentrations were also reported in the preparation and competition phases for fast bowlers [35]. Additionally, perceptual well-being was poorer during the competition phase for fast bowlers compared to non-fast bowlers [35]. This study [34] shows that monitoring techniques other than balls bowled can provide information on the individual responses to workloads and also distinguish between positional groups.

4.3 Workload Monitoring in Baseball

4.3.1 Workload, Injury and Pain in Baseball

Of the eight studies examining workload in baseball, four used injury [36, 37, 40, 41] and two used pain [38, 39] as their outcome measure. Consistent with the findings in cricket players [28], Lyman et al. [39] reported a positive relationship between pitching load and arm pain. Coaches were required to complete a pitch count book for each pitcher during games, and pitchers were contacted for a postgame interview via telephone to collect details on each game and any pitching-related pain complaints [39]. In a subsequent study, [38] similar relationships were found between pitch counts, pitch types and arm pain. Using similar workload monitoring methodology as Lyman et al. [39] a significant association was reported between the number of pitches thrown in a game and during the season and the rate of elbow and shoulder pain [39]. One study compared youth pitchers who had required surgery for a pitching-related injury with uninjured pitchers [41]. A telephone survey was conducted containing questions on injury history, playing history and potential risk factors less than one year following the pitching-related injury [41].The group who required surgery pitched more months per year, games per year, innings per game, pitches per game, pitches per year and warm-up pitches than the uninjured group. Despite demonstrating an increased risk of injury or pain in response to a high pitching load, there are a number of potential limitations of these studies that should be considered. First, they were reliant on self-reported recall of pitching practice, which may have led to biases in the data. For example, it is possible that the injured group of players may have reported higher workloads as they may have been primed to believe that higher workloads lead to greater injury or pain risk. Second, the specific methodologies of these studies made it impossible to examine the effect of pitching intensity on pain and injury risk. Third, these studies [38, 37, 41] lacked any description of any procedures implemented to determine the validity of the surveys used to collect the aggregated self-reported data for their research.

Twenty-three baseball pitchers were monitored during a spring game period to investigate the association between maximum pitch velocity (defined as the fastest ball thrown for a strike during one game) and subsequent elbow injuries in professional baseball pitchers. Pitch velocity was recorded using a standardised radar gun and workload information for the following three seasons were determined using a baseball statistical website [40]. Although the injured group (n=9) had a higher mean pitch velocity (89.2 ± 5.4 *vs.* 85.2 ± 3.2 mph), the small sample size may have contributed to the lack of between-group differences [40]. Nevertheless, the three pitchers with the highest maximum pitch velocity sustained the injuries requiring elbow surgery [40].

A recent investigation focussed on the relationship between cumulative workload metrics and injury risk [37]. Cumulative metrics included: games pitched in a season, total innings pitched during a season, pitches thrown in one season, average number of innings pitched per appearance and average number of pitches thrown per appearance. All pitcher statistics were obtained from a baseball statistical website and results demonstrated that none of the cumulative work metrics investigated were significant predictors of injury in the following season [37]. This study [37] had limitations that warrant consideration when interpreting the results. First, an injury was defined as a pitcher missing 15 games or more; therefore potentially under-reporting injury rates. Second, none of the metrics (e.g. games pitched, pitches thrown) analysed in this research accounted for pitching intensity.

Additionally, between-game cumulative work that would have contributed to total workload throughout the season was not reported.

Further research using pitcher data from a baseball statistical website [36], extended upon previous findings to examine the relationship between the number of innings pitched and future injury in elite baseball pitchers <25 years of age. The number of innings pitched during a single season and the difference between the number of innings pitched over consecutive seasons were compared to predict future injury. Despite this study suggesting limitations to the number of innings that a younger elite pitcher can pitch may not be an effective means of protecting players, the number of pitches thrown during a game or innings were not accounted for. While innovative and beneficial in providing basic workload-injury data, the extensive research in baseball has not yet included the between-game cumulative work. Considering the significant impact of extra throwing practice and off-field practice on cumulative load, it is important to accurately examine these variables. Further research is warranted to investigate techniques to monitor both game and training workloads in baseball.

4.3.2 Workload and Performance in Baseball

Bradbury and Forman [42] quantified the relationship between the number of pitches thrown and pitcher performance and found the number of pitches thrown was negatively associated with future performance. Results indicated that each pitch thrown in the preceding game increased the estimated run average by 0.007 runs in the following game [42]; suggesting that higher pitching loads can hinder immediate future performance. Velocity trends as a measure of workload in elite baseball pitchers have been monitored [43]. The researchers found the fast ball velocity increased linearly over an 8-game period [43]. However, it is likely that the sole use of pitch velocity as a workload monitoring tool would be insufficient as it fails to take into account any other load completed by individual players. In addition, this study was only conducted over an 8-game period; consequently different trends may emerge towards the latter end of the season as cumulative fatigue develops.

4.4 Workload Monitoring in Handball, Softball and Water Polo

Handball, softball and water polo accounted for 14% (3 of the 21) of the articles selected within this review. Bresciani et al. monitored biological and psychological measures through an entire handball season [44]. Training load was calculated across the season using four monitoring tools that included the session-RPE (training intensity x training duration), blood analyses (e.g. blood C-reactive protein concentration; oxidised glutathione (GSSG) concentration; reduced/oxidised glutathione ratio (GSH/GSSG)), a stress questionnaire (Profile of Mood States (POMS) Questionnaire) and the Recovery-Stress Questionnaire (REST-Q Sport). Handball players developed small increases in inflammatory and oxidative states during periods of high training load [44]. Positive correlations were reported between biological and psychological markers and training load [44]. This study effectively implemented a number of techniques to monitor workload across a season of handball.

A prospective monitoring of 12 softball pitchers over a competitive season assessed the relationship between pitch count and upper extremity injury [45]. Team coaches collected pitch counts during each game for the pitcher; however, no attempt was made to account for pitches or throws completed outside game situations. An injury was defined as any shoulder or elbow muscle, joint, tendon, ligament, bone or nerve complaint reported by a player during the season [45]. Although trends were evident, the small sample size and low incidence of injury limited the ability to perform statistical analyses on the relationship between pitch count and injury. Furthermore, game load is not representative of total weekly load therefore, further research is required to assess the effect of throws and pitches completed during training situations on total weekly workload and injury.

Only one study has investigated workloads in water polo players [46]. In this study, the validity of the session-RPE method was evaluated and compared with the Edwards heart-rate-zone method in 13 players. Strong correlations ($r=0.88$; $p<0.001$) were reported between the Edwards heart-rate-zone and session-RPE methods [46]. This was one of only two studies selected for review that validated a workload monitoring tool in their respective sport.

4.5 Future Directions of Workload Monitoring

Workload monitoring is often subjective and as such is reliant on players' capacity to accurately recall and report their individual training and competitive workload. However, there are potential inaccuracies associated with athletes self-reporting during training and game situations. This has led to the development and validation of specific microtechnology algorithms for the automated detection of bowling counts and events in cricket fast bowlers. Through the use of an accelerometer, gyroscope and magnetometers (Catapult Innovations, Melbourne, Australia), researchers cross-validated the direct bowling counts and microtechnology outputs using notational analysis, using a bowling detection algorithm embedded in the software [47] . No significant differences were reported between direct measures of bowling with true positive and negative events recorded by the algorithm [47]. Sensitivity of the unit during training (99.0%) and competition (99.5%) were both acceptable [47]. Although further development is required, the use of microtechnology to automatically detect and monitor load is the next logical step in the advancement of monitoring techniques used in throwing-dominant sports.

Finally, an absence of research surrounding workload monitoring in individual throwing-dominant sports has become apparent. Although it is possible that some case studies may have been excluded during the selection phase of this review, to our knowledge there has been no research to investigate workload monitoring techniques in individual throwing-dominant sports. Considering this gap in the literature, future research should focus on effective methodologies for monitoring throwing load in individual sports.

5. Conclusion

This review provides a comprehensive profile of workload monitoring techniques used in throwing-dominant sports. While the monitoring of throwing loads is likely to be implemented in high performance sporting environments, as this study only included peer-reviewed literature, it is possible that some innovative throwing monitoring approaches have been excluded. However, from the studies identified the most commonly-used workload monitoring techniques lacked reliability and validity and were not capable of monitoring all aspects of training completed by the athletes. Currently, without greater consistency in design and more reports of reliability and validity, confidence in these instruments to improve our understanding of the relationships between total workload, performance and injury remains limited. While the results highlight a large variety of workload monitoring techniques examined in throwing-dominant sports, there is currently no gold standard workload measure. The use of objective microtechnology should be further explored to establish its reliability and validity for monitoring throwing load in all throwing-dominant sports. The use of an automated load monitoring system has the ability to provide coaches and researchers with a tool to further understand and report accurate and cumulative individual workloads for athletes involved in these sports. In conclusion, we have found inconsistencies in the reporting of terminology, monitoring methods, units of measure, periods of measure and populations being studied within throwing-dominant sports.

Compliance with Ethical Standards

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Conflicts of Interest

Georgia Black, Tim Gabbett, Michael Cole and Geraldine Naughton declare they have no conflict of interest relevant to the context of this review.

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Table 1. Study quality scoring system [26]

No.	Item	Score
1	Inclusion criteria stated	0-2
2	Subjects assigned appropriately (random/equal baseline)	0-2
3	Intervention described	0-2
4	Dependent variables defined	0-2
5	Assessments practical	0-2
6	Training duration practical (acute versus long term)	0-2
7	Statistics appropriate (variability, repeated measures)	0-2
8	Results detailed (mean, standard deviation, percent change, effect size)	0-2
9	Conclusions insightful (clear concise, future directions)	0-2
	Total	0-18

Table 2. Summary of results from studies investigating workload in cricket**.**

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Dennis et al. [29]	90 elite adult cricket fast bowlers	Balls bowled/session Balls bowled/week Balls bowled/month	Workload was quantified by examining scorecards and conducting surveillance at training sessions. Risk ratios were used to identify the relationship between bowling workload and injury.	Bowlers who completed, on average, <123 or >188 deliveries/week had an increased risk of injury compared to those who bowled between 123 and 188 deliveries/week.	100%
Dennis et al. [28]	12 elite adult cricket fast bowlers	Balls bowled/session Balls bowled/week Balls bowled/month Balls bowled/season	Workload was quantified by examining scorecards and conducting surveillance at training sessions. Risk ratios were used to identify the relationship between bowling workload and injury.	Players who bowled ≥5 sessions in a week were 4.5 times more likely to be injured. Injured bowlers bowled significantly more deliveries/week. Injured bowlers had a spike in deliveries/session in the 8-21 days prior to injury as compared to the average number of deliveries/session ($p<0.02$). Bowlers who bowled >522 balls in a 30-day period were at an increased risk of injury ($p<0.01$).	100%
Dennis et al. [27]	44 elite junior cricket fast bowlers	Daily diary to assess: Balls bowled/match innings Training sessions/week Balls bowled/training session	Prospective cohort study. Bowlers completed a daily diary over one season to record bowling workloads and self-reported injuries. Bowling workload prior to injury was compared to workload across a whole season for uninjured bowlers.	Injured bowlers had been bowling significantly more frequently than uninjured bowlers. Increased risk of injury was associated with bowling ≥2.5 days/week or ≥50 deliveries/day.	94%

Table 2 continued. Summary of results from studies investigating workload in cricket**.**

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Hulin et al. [34] *	28 elite adult cricket fast bowlers	Balls bowled/week (external workload) RPE multiplied by training duration in minutes (internal workload) Training stress balance	Workload data was accessed from Cricket Australia from 2006-2012. Data were categorised into weekly blocks. One week data, together with four-week average rolling data were calculated for external and internal loads. Training stress balance was calculated by dividing the acute by the chronic workload and expressed as a percentage. The likelihood of sustaining an injury was determined for the current week and subsequent week.	A negative training stress balance was associated with an increased risk of injury in the subsequent week for internal and external workload. Compared with a training stress balance between 50 and 99%, the relative risk of injury associated with a training stress balance greater than 200% was 4.5 times and 3.3 times for internal and external workload, respectively.	100%
McNamara et al. [35]	26 elite youth cricketers. Classified as fast (n=9) or non-fast (n=17) bowlers	Movement analysed using GPS units (MinimaxX, Catapult Innovations, Melbourne, Australia). CMJ relative power and flight time. Perceptual well-being Cortisol and testosterone concentration.	Workloads and markers of neuromuscular, endocrine and perceptual fatigue were compared in male fast and non-fast bowlers in response to a 7-week physical preparation period and a 10-day intensive period of competition. GPS units were worn during all training and competitive sessions. CMJs were completed pre-training and pre-match, perceptual fatigue scores were completed daily, salivary analyses were completed weekly during the preparation phase and daily during competition.	Fast bowlers covered greater total, low and high speed distances during competition. Cortisol concentrations were higher in the preparation and competition phases, and testosterone concentrations were lower in the competition phase for fast bowlers. Perceptual well-being was poorer during competition for fast bowlers compared to non-fast bowlers. No differences were reported in neuromuscular function between groups.	100%

Table 2 continued. Summary of results from studies investigating workload in cricket.

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
McNamara et al. [47] *	12 highly-skilled fast bowlers	Comparison of MinimaxX S4 unit (Catapult Innovations, Melbourne, Australia) and manually recorded balls bowled. True-positive, true-negative, false-positive, false-negative.	Bowlers performed a series of bowling, throwing and fielding activities during training and competition. Sensitivities and specificities of the bowling-detection algorithm were determined by comparing the device outputs with manually-recorded bowling counts.	No significant differences were reported between direct measures of bowling and the true positive and negative events recorded by the MinimaxX unit. Sensitivities during training (99.0%) and competition (99.5%) were acceptable. Specificities during training were also high (98.1%), but lower during competition (74.0%).	100%
Orchard et al. [31] *	198 elite adult cricket fast bowlers	Overs bowled/match	Prospective cohort study following bowlers to compare overs bowled in a match and injury risk subsequent to the match.	Players who bowled >50 overs had an increased injury risk in the next 21 days of 3.37 injuries per 1000 overs bowled. Bowling >30 overs in the second innings increased injury risk per over bowled in the next 28-days (RR 2.42).	100%
Orchard et al. [32] *	235 elite adult cricket fast bowlers	Overs bowled/match	Prospective cohort study using bowling workload data extracted from Cricket Australia databases. Bowling workloads monitored during time periods from 5 to 26 days were examined to highlight an increased injury rate during the month subsequent to the workload	Players who bowled >50 match overs in a 5-day period had an increase in injury rate over the next month compared to those who bowled <50 overs (RR 1.54).	100%

Table 2 continued. Summary of results from studies investigating workload in cricket**.**

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Orchard et al. [33] *	235 elite adult cricket fast bowlers	Acute match overs ≥50 Career overs ≥1200 Overs in previous season ≥400 Overs in previous 3 months ≥150 Career overs ≥3000	Prospective cohort study investigating the relationship between injury risk and workload status. All game workload data were extracted from official scorecards.	High acute match workload and high previous season workload were risk factors for developing tendon injuries. High medium-term workload (3-month workload ≥150 overs) was protective. Low (<1200 overs) and also very high (≥3000) career workloads were protective for tendon injuries compared with medium-high career workloads (1200-3000 overs).	100%
Saw et al. [30] *	28 elite adult cricketers	Throws/day Throws/week	Prospective cohort study monitoring daily throwing workload over one cricket season. All throws completed during the 1st and 2nd XI training and matches were video recorded or manually recorded by direct observation and were used to determine workload. Risk ratios were calculated to describe the association between throwing workload and injury	Injured players threw 40 more throws/week and 12.5 throws/day. Players were at an increased risk of injury if they completed 40 throws per day.	88%

RPE – rating of perceived exertion. CMJ – countermovement jump. GPS – global positioning system. RR – relative risk
*denotes papers that were scored out of 16

Table 3. Summary of results from studies investigating workload in baseball**.**

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Bradbury & Forman [42] *	1058 elite baseball pitchers	Pitches/game	Pitching workload data was obtained from a baseball statistics website. Data from pitchers who started games after <15 days rest were analysed. Multiple regression analyses were used to assess the immediate and cumulative effect of pitches thrown and the days of rest on performance.	Pitches thrown were negatively correlated with future performance. Estimates indicate each pitch thrown in the preceding game increased ERA by 0.007 in the following game. Increased number of rest days was not associated with performance.	94%
Bushnell et al. [38]	23 elite baseball pitchers	Pitch velocity using a radar gun.	Prospective cohort study. Pitch velocity was recorded; the ball speed was recorded for the fastest pitch thrown for a strike during the game (maximum pitch velocity). Pitchers followed over three seasons and the association between maximum pitch velocity and elbow injury was analysed.	9 players had elbow injuries during the study. The injured players had a higher average pitch velocity (89.22 ± 5.36 vs 85.22 ± 3.24 mph). There was a statistically significant relationship between pitch velocity and elbow injury. The three pitchers with the highest maximum pitch velocity had injuries requiring elbow surgery.	83%
Crotin et al. [41] *	12 elite baseball pitchers	Pitch velocity Pitch type	Baseball pitchers monitored over an 8 game period. Ball velocity was recorded for each pitch using a radar gun. Pitch types were manually recorded. Pitcher data were grouped and the mean fast ball velocity was computed for each game. Regression analyses were performed to compare pitching velocity and the game number.	The FBV increased linearly over the 8-game period. The mean FBVs increased 0.56 mph over the 8 games.	81%

Table 3 continued. Summary of results from studies investigating workload in baseball**.**

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Karakolis et al. [37] *	3760 elite baseball pitcher seasons[a]	Games pitched/season Total innings pitched/season Pitches thrown/season Average number of innings pitched/appearance Average number of pitches thrown/appearance	Pitcher statistics were obtained from a baseball statistics website. Work metrics were analysed to determine if there was a correlation between cumulative work and injury in the following season.	Based on the regression analyses performed, none of the cumulative work metrics investigated were significant predictors of injury in the following season.	100%
Karakolis et al. [36] *	761 elite baseball pitcher seasons[a]	Number of innings pitched in a season. Difference in total innings pitched between consecutive seasons.	Pitching workload data were obtained from a baseball statistics website. Regression analyses were performed to determine whether the number of innings pitched during a single season or the difference in innings pitched over consecutive seasons were correlated with future injury (measure of time spent on disabled list).	No significant correlations were found between innings pitched and future injury. No significant differences were found when pitchers were split into groups based on consecutive innings pitched difference cut-offs.	88%
Lyman et al. [41] *	298 youth baseball pitchers	Pitches/game Pitches in a season Innings pitched Games pitched Pitch types	Prospective cohort study in which coaches completed a pitch count book following each game. Participants were contacted by phone after each game to identify arm complaints.	Risk factors for elbow pain included throwing <300 or >600 pitches during a season. Risk factors for shoulder pain included throwing >75 pitches per game, and throwing <300 pitches in a season.	81%

Table 3 continued. Summary of results from studies investigating workload in baseball

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Lyman et al. [40] *	172 youth baseball pitchers	Pitches/game Cumulative season pitches Pitch type	Prospective cohort study using a pitch count log of pitches thrown per pitcher during the season. Phone interviews were completed post-game to identify arm complaints.	There was a significant association between the rate of elbow and shoulder pain and the number of pitches thrown in a game and during the season. The curveball was associated with a 52% increased risk of shoulder pain and the slider was associated with an 86% increased risk of elbow pain.	81%
Olsen et al. [39]	150 adolescent baseball pitchers. Further grouped into pitchers who had shoulder or elbow surgery (n=95) and pitchers who had never had a significant pitching injury (n=45).	Months/year competitive pitching Pitch velocity Number of: pitching appearances/year innings/appearance pitches/appearance pitches/year warm-up pitches	Pitchers responded to a survey and results were compared between pitchers who had shoulder or elbow surgery and pitchers who had never had a significant pitching injury. Multivariable logistic regression models were developed to identify the risk factors for injury	The injured group pitched more months/year, games/year, innings/game, pitches/game, pitches/year and warm-up pitches. High pitch velocity was also associated with increased risk of injury.	83%

[a] Baseball pitcher seasons – number of individual seasons pitched and analysed. ERA – estimated run average. FBV – fast ball velocity
*denotes papers that were scored out of 16

Table 4. Summary of results from studies investigating workload in handball, water polo and softball**.**

Study	Sample	Load monitoring techniques	Method	Findings	Quality score
Bresciani et al. [44]*	14 elite handball players	Session RPE multiplied by training duration Haematological analyses POMS Questionnaire and REST-Q Sport	Players were monitored over a 40-week season. Session-RPE was collected following each session and match. Blood samples were collected and the POMS completed on five occasions throughout the season.	Blood C-reactive protein and oxidised glutathione concentrations increased during high load periods. Reduced/oxidised glutathione ratio decreased during periods of high load. No changes were observed in total mood based on the POMS test. Following high training load, injury, being in shape and physical recovery (REST-Q) correlated with workload.	94%
Lupo et al. [46] *	13 elite youth water polo players	Heart rate Session RPE multiplied by training duration	Players monitored during 8 sessions. The Edwards summated heart-rate-zone method was used and session-RPE rating (CR-10 scale) was obtained following each sessions. Correlations between the two measures were completed.	Strong and significant ($p<0.001$) correlations between the Edwards heart-rate-zone and session-RPE methods were reported.	94%
Shanley et al. [45]	12 youth amateur softball players	Pitch count/game Pitches/season Total games pitched	Prospective cohort study in which each coach collected pitch counts for individual players following each game	No significant differences between injured and non-injured groups.	83%

RPE – rating of perceived exertion. POMS – profile of mood states. REST-Q – recovery-stress questionnaire. CR – category ratio
*denotes papers that were scored out of 16

FIGURE LEGENDS

Figure 1. Flowchart of the selection process for inclusion of articles in the systematic review