

LOAD MANAGEMENT AS AN INJURY PREVENTION AND PERFORMANCE ENHANCEMENT APPROACH IN SHOULDER INJURY

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BACKGROUND

Baseball introduced load management in sport as an injury reduction strategy

Fifty years ago Dr Frank Jobe described the surgical procedure for reconstructing the ulnar collateral ligament of baseball pitchers, a procedure for which Dr James Andrews documented the outcomes of more than 2,000 cases from his experience less than 40 years later. Dr Andrews always preferred prevention to cure, and his experience and guidance was formative in the creation of the USA Baseball Medical and Safety Advisory Committee whose mission in part was to reduce these surgeries and other injuries in baseball players. In 2006 baseball implemented rule changes to limit the number of pitches thrown, and a raft of subsequent research has demonstrated a strong association with these changes and youth injury rates. Strict pitch count rules

remain a mainstay of youth baseball to this day.

Load management was integral to the “Moneyball” approach of performance enhancement

One of the seminal moments came during the 2003 National League championship series in the 7th and deciding game, the same year Michael Lewis’ book “Moneyball” was released. Contemporary wisdom at that time was that the Red Sox star pitcher Pedro Martinez began to tire at 100 pitches, becoming less effective against the opposition. After throwing 115 pitches and allowing a run to score from back-to-back hits, he was visited on the mound by his manager Grady Little who decided to let his gut feeling and the player’s reported well-being dictate his ultimately ill-fated decision to leave him in the game - a decision which

cost the game, Little his job, and extended the Red Sox’s drought of championships to 86 years.

Little was asked in a recent documentary if he considered the pitch count when he made his decision to stick with Martinez:

“No, I’m looking at what he’s got...I knew about where he was, but I knew what he was showing on the mound, too. A lot of my own gut feel.”

In the same documentary the Hall of Fame pitcher Pedro Martinez reflected:

“He plain and simple just asked me, ‘Do you think you have enough bullets to get Matsui?...You don’t ask a wounded warrior. Of course, I’m going to say yes.’”



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Illustration

While commonplace at the time, this would be considered an unusual managerial strategy in the modern game where data on every pitch is available to a team of analysts to ensure performance outcomes are optimized.

Perhaps baseball and “Moneyball” were not the genesis of using data to inform decisions in all sports, but tacitly or otherwise it’s commonplace now to consider some sort of load management approach for performance and injury prevention to some extent across many, if not all, professional sports. In this article we will present a brief summary of examples of actual training and performance load monitoring practices from high-level sports which place large demands on the shoulder, and are documented to have high shoulder injury burden in an effort to break down some silos and learn from each other.

BASEBALL

Magnitude of the (throwing) load in baseball

At the highest level of the game, professional baseball players have a 162-game regular season schedule, in addition to pre- and post-season games. Translating to playing about 27 games every month for 6 months of the

year in the regular season, sophisticated load monitoring approaches are seen as crucial for optimizing performance and mitigating player injury risk. Within a baseball team, pitching and position players have different throwing workload demands which vary their monitoring strategies. While broadly, the players can be split between pitching and position players, there is a further subdivision of those pitchers who start the game, and those “relief” pitchers whose job is to complete the remainder once a starter has been removed from a game. A typical game has about 150 total pitches in the scheduled 9 innings for 1 team, but in the modern game it’s rarely more than 100 for any given pitcher. In the last 30 years “starting” pitchers have seen a reduction from an average of about 95 pitches per game to about 85. A starting pitcher might typically have an official game with the entailed high volume of maximum effort throwing once every 5 days, typically with some throwing load every day in addition to other gym and preparation work, while the loads placed on relief pitchers are more variable depending on game situations as they arise. Position players don’t have the same maximum effort throwing volume

requirements, but the rigors of daily games and position players possibly playing every day, also place significant throwing demands on these players. Accordingly, teams at the elite college and professional levels leverage a wealth of data to understand and manage player workload, moving far beyond simple pitch counts to embrace a holistic, athlete-centered strategy.

The Dual Lens: External and Internal Loads

Professional baseball organizations differentiate between external and internal loads to gain a better understanding of a player’s true workload.

- **External Loads** represent the physical demands placed on the athlete during training and competition. For pitchers, this primarily involves pitch count, with a more nuanced approach considering the combined total of pitches thrown across back-to-back appearances, including those during bullpen warm-ups. For position players, external load is mostly running, and is tracked by distance covered daily, with a focus on high-effort runs versus general running. Technologies like Statcast are utilized to measure daily distance covered and

track high-effort sprint speeds.

- **Internal Loads** reflect the athlete's physiological and psychological response to these external demands. This can include subjective measures like perceived exertion, where players rate their effort levels. While players can sometimes be "off" with this measure, consistent use can improve their accuracy. Physiological responses are monitored through metrics such as heart rate variability (HRV), though this information is often private to players using wearable technology.

Pitcher-Specific Monitoring: Beyond the Mound

For pitchers, load management is a multifaceted endeavor that goes beyond just counting pitches.

- **Pitch Count Progression:** While there's no universal strategy, pitch loads are progressed individually based on prior years' workload and player comfort. A history of injury warrants a more conservative progression. The unique demands on relief pitchers, who have fewer recovery days and frequently warm up without entering a game ("dry humped"), necessitate a more careful look at their pitch counts. The total number of pitches off the mound, including bullpen warm-ups, can significantly exceed game pitches.
- **Velocity Monitoring:** Velocity is typically only addressed if it drops below a pitcher's norm. A decrease prompts a thorough investigation into external and internal workloads, recovery

strategies, weight training programs, arm care, diet, sleep, and even blood work. General throwing mechanics are assessed daily. Interestingly, velocity is not heavily weighted during bullpen sessions, where most pitchers throw at 80-85% of their game velocity for comfort. However, some "unicorns" may throw bullpens at 50% effort.

- **Strength and Range of Motion (ROM):** Regular strength measures are taken, often every two weeks, using tools like a Force Frame to capture isometric strength data. Both raw and relative strength data are analyzed. Additionally, shoulder, elbow, thoracic spine, and hip ROM are measured, usually at the same frequency. Countermovement jump (CMJ) data is also collected, and players with a history of specific injury may have additional targeted monitoring. These measures are historical key metrics for injury reduction and readiness identification.
- **Throwing Between Outings:** Surprisingly, tracking the number of throws and velocity between games (practice and "side" sessions) has not shown a significant impact on injury or lost time, perhaps indicating that the higher effort throws (>90%) are more relevant.

Position Player Load Management: Running and Recovery

Position players, despite baseball not being considered a "heavy running sport," have their running loads closely monitored due to the demanding schedule.

- **Distance and High-Effort Runs:** Load is tracked by daily distance covered, with running efforts categorized into "high effort" and general running. This data, often provided by analytics teams, guides load management and return-to-sport protocols.
- **Workload Ratios:** While workload ratios can be used, they present statistical and logistic challenges in baseball due to the unpredictable nature of game action. Spikes in workload are closely monitored. Identifying strain values for in-game running is helpful, as players may need additional sprinting to maintain lower body resiliency if they experience several games without high-effort runs.

Recovery: The Unsung Hero

Regardless of position, recovery is highlighted as a critical piece of the workload management process and the most difficult aspect of maintaining player health.

- **Common Modalities:** Various recovery strategies are employed which will depend on the individual team and player typically - discussion of which is beyond the scope of this article, but the reader is directed to previous targeted topic issues in the journal which address this in some detail.
- **Key Variables:** Sleep, nutrition, and hydration are considered the most important variables for optimizing recovery. The complexities of the baseball schedule, such as frequent travel across time zones, can disrupt circadian



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rhythms and hinder recovery. Strategies like proper fueling, limiting electronic device use, and some supplements can be encouraged to foster better sleep. Hydration is monitored through weight and urine analysis, especially in hot and humid weather.

- **Individualized Approach:** Recognizing that each player responds differently to various loads, active recovery days are planned to optimize overall recovery.

Data Integration and Communication: The Art of Load Management

With the abundance of data, the challenge lies not in obtaining it, but in effectively combining it into interpretable and actionable plans for athletes, coaches, and medical staff.

- **Data Pipelines and Team Input:** Specific data pipelines are created, using a holistic, athlete-centered approach to determine what, how, and when data are collected and disseminated. This process involves complete team input, including athletic trainers, strength and conditioning staff, biomechanists, sports scientists, data scientists, coaches, and athlete team leaders. This collaboration balances obtaining “right” data with quality and combating collection fatigue.
- **Descriptive and Prediction Models:** Load monitoring data is aggregated into descriptive and predictive models. New players are compared to normative values, while established players receive individualized normative values and “n of 1” models to provide unique outputs.
- **Communication Strategies:** A base communication template is provided for new athletes and staff, with specific outputs tailored to different knowledge groups (athlete, coach, performance, medical). This tailoring becomes more individualized after six months within the organization.
- **Early Warning Systems and Interventions:** Early warning systems, categorized as yellow and red flags, guide interventions. Yellow flags lead to minor, day-to-day adjustments by individual staff, while red flags necessitate staff-wide input to identify root causes and develop short- and medium-term action plans. The final say on interventions can rest with either

the coach or medical staff, depending on the warning.

In essence, professional baseball teams employ a sophisticated, data-driven, and highly collaborative approach to load monitoring. By meticulously tracking both external and internal loads, focusing on individualized needs, prioritizing recovery, and fostering clear communication, they aim to optimize player performance and safeguard athlete health throughout the rigorous season.

VOLLEYBALL

In volleyball, load monitoring and injury prevention efforts have traditionally focused on jump-related metrics. Jump count, external load measured via accelerometry, and subjective symptom reporting,

particularly for conditions such as patellar tendinopathy, are now well-established. In contrast, our understanding and monitoring of shoulder-specific load, despite its clear clinical and performance relevance, remains significantly underdeveloped.

A core challenge is the absence of a validated, sport-specific tool to objectively quantify arm swing actions. Unlike jump load, which can be easily tracked using commercially available inertial sensors, no equivalent solution exists for measuring shoulder load in volleyball. Devices have been established for use in baseball, but attempts to validate these devices in a volleyball cohort have yielded poor results. As a result, practitioners are often limited in their ability to manage shoulder stress with the same sophistication afforded to lower



Illustration

limb monitoring. In some cases, jump count is used as a proxy for swing count, based on the assumption that a relatively consistent proportion of jumps involve an overhead swing. While clearly imprecise, this method can serve as a moderately effective surrogate when direct measurement is unavailable.

This limitation is compounded by the technical constraints of the movement itself. Arm swing patterns tend to be deeply ingrained, and efforts to modify these mechanics are rarely successful, particularly once athletes are further along their developmental pathway. However, this difficulty in altering technique is made more challenging by the fact that we lack detailed kinetic and kinematic analyses of attacking arm swings across different playing positions and competitive levels. Without this foundational understanding, we are unable to identify which specific mechanical features may contribute to increased shoulder stress or risk of injury. As a result, interventions often shift away from technical refinement and toward strategies that manage cumulative load and support tissue capacity, despite the possibility that underlying movement patterns themselves may be contributing factors.

One area of progress has been the development of progressive return-to-sport loading protocols, particularly following off-seasons or injury-related absences. These include structured throwing programs with weighted balls and standing hitting protocols designed to gradually reintroduce high-speed overhead actions. Player-specific overhead attack and serve counts should be established to assist with the return-to-sport process, similar to the use of training and match jump loads in the lower extremities. Additionally, internal response to loading can be quickly performed pre- or post-session, looking for short-term changes and subsequent recovery of shoulder strength and range of motion. While still based on general principles rather than precise loading data, these protocols reflect an effort to bridge the gap between theory and practice in the absence of direct measurement tools.

Looking ahead, AI-driven video analysis solutions may offer a breakthrough in shoulder load monitoring. These systems could passively track arm swing volume, velocity, and force output by synchronizing player and ball tracking. This would offer practitioners contextual load data alongside



Illustration

performance-linked metrics, allowing for more precise alignment between shoulder loading strategies and both performance goals and injury risk. Although still in development, these technologies represent a promising step toward addressing one of the sport's most persistent monitoring challenges.

Despite progress in some areas, key knowledge gaps continue to constrain our ability to advance shoulder load management in volleyball. Most notably, we lack a comprehensive understanding of the biomechanical differences in attacking arm swings across positions and levels of play, as well as a current analysis of the physiological demands of the sport. Without these foundations, we cannot fully interpret performance data, prescribe individualized training loads, or design optimal recovery strategies. Closing these gaps represents a critical opportunity for the next wave of applied sport science to shape more precise, evidence-informed approaches to both injury prevention and performance optimization in volleyball.

SWIMMING

Data on swimming performance outcome is abundant, with the times swum at

competitions readily available on different online platforms. However, data from the training and the training load is lacking. Historically, coaches and swimmers have focused on volume as the main parameter of interest and sometimes at the different intensities with which this volume has been achieved. The volume and intensity is prescribed by the training program as set by the coach and not measured often. This is still commonplace in the sport of swimming. Rarely, coaches have added information on subjective scales, such as the session RPE, to their monitoring package.

The reason for the lack of data is straightforward. Swimming takes place in an aquatic environment, which makes the use of technology problematic. Sensors have to be waterproof and deal with the special requirements that water imposes. For example, most heart rate sensors targeting the measurement of the electric signal of the heart, have to deal with short-circuit between the electrodes. Similarly, heart rate monitors using PPG (photoplethysmogram) suffer from the refraction of light of small layers of water between the sensor and the skin. Furthermore, several performance determining factors (such as drag, the rate of energy liberation via metabolism, gross



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for each stroke and each lap that swimmers make. A quick calculation, assuming a season that lasts 48 weeks with 10 training sessions per week of around 5 kilometres in a 50 metre pool and around 30 strokes per lap, means that we are challenged by around 1.5 million strokes per swimmer per year with data points over multiple channels. The sport of swimming now finds itself at a crossroads, where suddenly an incredible amount of data has become available. To prevent drowning in data, we have to streamline the information to a situation that is useful for practitioners within the sport.

As can be gleaned from the estimation of data points, most swimmers take an incredible number of strokes per year. Not surprisingly, swimmers are prone to shoulder injury. Most of the current algorithms that are used by the devices focus on load monitoring and performance improvement. The next step would be to discover relationships between different aspects of load, health and injury prevalence. Several researchers have proposed to present the data in the form of a dashboard, where the different parameters can be observed at a glance with an overview for the group and the individual swimmer.

The additional information appears to be invaluable. Research into swimmers shoulder suggests that distance swum is not the primary issue but swimming intensity (e.g. speed, acceleration, resistance with paddles or drag suits) and changes in intensity potentially play a greater role in the onset of symptoms. The current practice of load monitoring recording the training program set by coaches is clearly insufficient to capture the detail required for monitoring the intensity aspect of an individual's training. This has limited the ability of health professionals such as physiotherapists to gain insight into the cause of symptoms and to provide advice around preventative measures. With the more detailed information on swimming loads provided by the new sensor technology, the role of the support team in swimming can develop from a reactive to a more proactive one.

HANDBALL

Pulling together all of the information from the scientific literature and our years of experience regarding the care and attention paid to shoulder load in handball wasn't a

terribly difficult exercise, to be frank, and we can perhaps best summarise it for you with this message one of us received recently from a handball player:

"I just had a private practice session with one of our coaches because he wanted me to improve my diagonal jump throw. So, for about 1.5 hours, I did around 200 throws into the same corner and about 50 breakthroughs. I woke up this morning and can barely lift my arm over my head. What do you think is wrong? We have a practice later tonight and a game tomorrow— is there anything I can do to fix it?"

This exchange typifies what we've experienced in terms of the perceived importance of monitoring shoulder load in handball from both players and coaching staff alike.

In elite handball, current load management practices are still in their infancy compared with other sports. Still, most high level clubs now use some form of player position tracking systems that monitor general locomotor activity—such as distance covered, sprinting, and accelerations. However, there is a notable absence of technology or systematic monitoring focused on shoulder-specific loads, despite the high volume of passing and throwing actions that place repeated stress on this joint (i.e., players are likely to pass way more often than they jump and throw over a training session or a match). Strength training, particularly upper-body work done in the gym, tends to be better structured and individualized, offering some degree of load classification. On-court activity, in contrast, is largely dictated by tactical priorities and match preparation, leaving little room for targeted shoulder load regulation. Despite the increasing professionalism in the sport, there is still no operational framework in place for managing the specific load imposed on the shoulder, which remains a major oversight to me.

So what to do then?

Even though there are limitations—both in terms of research and technology—when it comes to monitoring shoulder load in handball, there are still practical steps we can take while waiting for the sport to catch up. And to be frank, it often isn't rocket

efficiency, propelling efficiency and power output) are difficult to measure directly in general. Similarly video footage has to be captured underwater and often other swimmers are in the way. Fortunately, technological advancements in the last decades have led to more readily available sensors in water and the use of AI leads to faster analyses of video. Only recently, different devices have surfaced that are commercially available and allow for mass usage. These devices typically combine a physiological indicator, the heart rate, with one or more biomechanical parameters, such as stroke type, time per lap, stroke rate and stroke count.

There is a variety in the location of the body on which the devices should be worn. Different devices have to be worn on the head, the back, the sacrum, the wrists or the hands. The outcome parameters are slightly different per location. The devices worn on the hand often provide an indication of the forces that are generated by the body moving through the water. Therefore, for the research on shoulder injury, these devices are likely to make the most impact.

The aforementioned devices measure continuously throughout a training session, from which information is now available

science, as highlighted in the quote at the start of this section.

It has been shown that a rapid increase in handball training load doubles the risk of shoulder problems in youth players. Several studies also indicate that training programs aimed at strengthening the shoulder can reduce the risk of injury. These programs may act as a protective buffer against sudden increases in shoulder load. For example, Møller et al. found that players who rapidly increased their training load had a higher risk of injury, but those with greater shoulder rotational strength were more tolerant of these increases. However, and most importantly, they also demonstrated that beyond a certain threshold of workload increase, there was no difference in injury risk between stronger and weaker players. In simple terms, if the increase in workload is too steep, it doesn't matter how strong you are, how well your scapula moves, or what your strength ratios are—workload will override them all.

While differences in throwing workload will always exist at the coach, club, or player level, there are some common patterns and scenarios where rapid increases in throwing volume tend to occur—and these should be addressed.

Returning from season breaks

Like trading stocks, handball is a winter sport with a typical break during the summer. What makes handball unique is that players rely on resin for grip, so nearly all high-speed throwing happens on the court. During the off-season, throwing volume drops—often to zero—especially among youth players. Then, once pre-season starts, they jump straight back into intense throwing, which can lead to injury.

A simple way to reduce this risk is by introducing a shoulder-strengthening program with a throwing progression. A recent study shows that players who follow such programs over the summer cut their injury risk in half and avoid the early-season injury spike (see Figure 1).

Returning from injury

This situation is similar to coming back after the off-season but with a few added risks—especially after long-term lower limb injuries. You can't throw hard or perform jump throws without a solid base, particularly a fully functioning knee. Most advanced throws in handball rely heavily

on lower-body strength and coordination. That's why shoulder load tolerance can't be properly rebuilt until the final phase of lower limb rehab—something often overlooked. Rushing this part increases the risk of shoulder issues during return to play.

Jumping into throwing

Other common load spikes happen when players jump into new throwing programs—whether it's adding weighted balls or simply increasing the number of throws. These programs can boost performance, but only if the load is built up gradually.

Another typical example is high-volume throwing sessions, often during goalkeeper-focused practices. These involve lots of repetitive, high-speed throws—especially in the same movement pattern—which can quickly overload the shoulder if not monitored.

Practical Approaches to Throwing Load Management in Handball

Even though detailed data on throwing load in handball is limited—and tracking it isn't always feasible due to technology, time, or resource constraints—there are still important and effective steps we can take. The basic principles described above, such as managing return from breaks, gradual throwing progression, and recognizing high-risk scenarios, offer practical ways to apply throwing load knowledge.

RUGBY LEAGUE

Although the media would have us believe that “Load Management” involves sitting players out, resting players, or otherwise reducing training loads, this rarely occurs in rugby league. There will be occasions where injured players will have their training loads “managed” during rehabilitation,

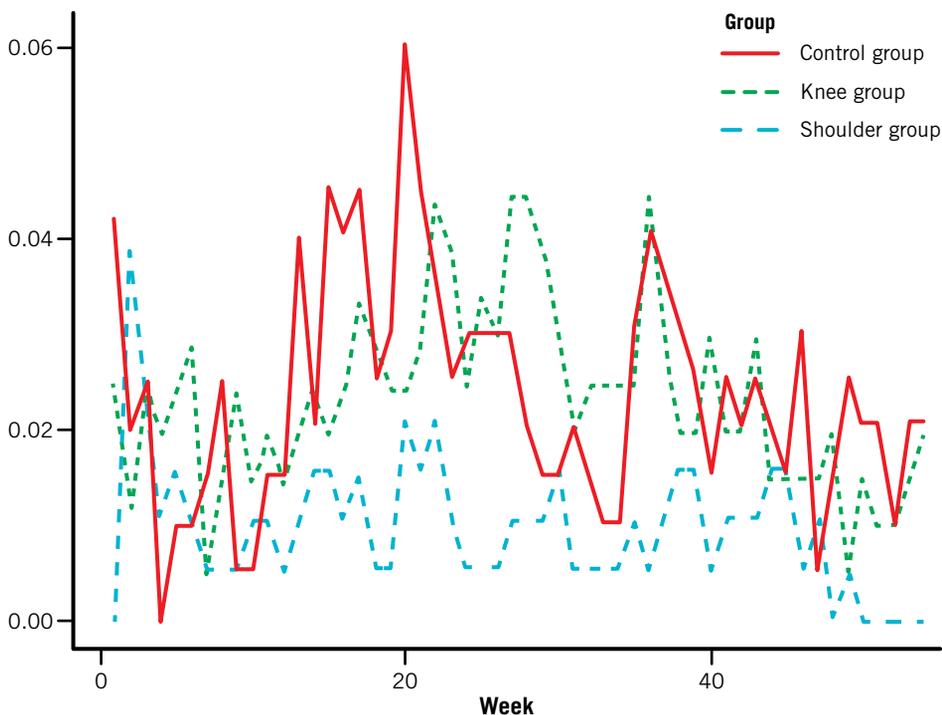


Figure 1: Weekly prevalence of substantial shoulder problems for the duration of the study intervention. Eighteen Swedish handball-profiled secondary schools (clusters) with players aged 15–19 years, 54% males were randomised into either the Shoulder Group or Knee Group (interventions) or a Control Group. Players in the Shoulder Group were instructed to perform the Shoulder Control programme, and players in the Knee Group to perform the Knee Control programme, three times per week during May 2018 to May 2019. Control Group players continued their usual training. The weekly prevalence of any and substantial shoulder or knee problems is defined as the number of players who reported any and substantial shoulder or knee problems, with the Oslo Sports Trauma Research Center Overuse Injury Questionnaire respectively in each group, divided by the total number of player reports in the group for each week. (From: Asker, M., Hägglund, M., Waldén, M. et al. The Effect of Shoulder and Knee Exercise Programmes on the Risk of Shoulder and Knee Injuries in Adolescent Elite Handball Players: A Three-Armed Cluster Randomised Controlled Trial. *Sports Med - Open* 8, 91 (2022). <https://doi.org/10.1186/s40798-022-00478-z>).

but healthy players will be required to participate in all training sessions, including contact, strength, and field sessions.

Load management is the use of well-established training principles to achieve performance outcomes. Although overuse injuries are uncommon in rugby league, collision injuries, particularly those to the upper body and limbs, occur frequently. There are four key areas where football department staff play a role in reducing the risk of these injuries: (1) a heavy emphasis on strength and power training (improving local tissue capacity), (2) coaching on correct and effective tackling technique, (3) regular exposure to wrestling, grappling and collision activities (improving sport-specific capacity, and (4) the systematic progression and scheduling of training loads related to these activities.

1. Strength and Power Programs

Around 2011, the National Rugby League in Australia (NRL) experienced a spike in pectoral tears, with some sports medicine practitioners speculating that the heavy emphasis on strength training might be the cause of these injuries. However, the vast majority of studies show that strength training is a safe activity, and there is currently no evidence that strength training contributes to pectoral tears. Conversely, there is evidence that players with better developed upper-body strength have a lower risk of collision injuries. There are no randomised-controlled trials specifically addressing if one form of strength and power training is better than another for reducing collision injury risk. However, clearly no coach is advocating for less strength training in their programs!

2. Coaching on Correct Tackling Technique

In the last ~20 years, rugby league tackling technique has changed considerably. Previously, the “textbook” tackling technique involved contact with the shoulder, “under the ball”, and the defenders’ centre of mass forward of their feet. In the modern game, NRL players are coached to control the ball. As a result, tackles are more commonly made with the chest, “over the ball”, with the defender in a more upright position (centre of mass over their feet). The tackle often includes up to 3 defenders, requiring synchronization of movements among these players. Incorrect tackling technique can increase the risk of shoulder, pectoral,

and bicep injuries – hence, skill coaches are critical to injury prevention efforts.

3. Contact Conditioning

Exposure to wrestling, grappling, and blunt force trauma is critical for rugby league players. This collision exposure has been likened to high running loads for a marathon runner – the musculoskeletal system needs to be adequately prepared in order to tolerate these loads. Along with skill activities performed in the field (that often include tackles and collisions), players will also undergo technical and “full noise” contact sessions up to 4 times per week. The intensity of collisions can be quantified using inertial measurement units (i.e. accelerometers and gyroscopes), although more commonly, high performance staff will arbitrarily assign an intensity rating (i.e. light, moderate, heavy) to these activities. Rugby league (along with many other collision sports) now have return-to-contact protocols for players requiring reintegration into full contact following injury.

4. Scheduling and Progression of Training Loads

National Rugby League players will have at least 8 weeks away from structured training activities during the off-season. While encouraged to continue some normal training activities during this time to prevent deconditioning, they are under no obligation to do so. Furthermore, while it is relatively easy to continue strength

and conditioning activities, it is harder to replicate the intensity of collisions that occur in match-play. Consequently, exposure to collisions upon return to training requires a systematic and progressive approach. Studies have shown that the incidence of collision injuries in preseason (9.3 injuries per 10,000 collision) is greater than in-season (4.2 injuries per 10,000 collisions), suggesting that (1) the ability of players to withstand collisions detrains over the off-season and (2) a periodized return-to-contact program is required upon returning to pre-season training. High performance managers also play a key role in ensuring adequate recovery between sessions on the same day, and across days.

REFLECTIONS

The authors’ combined experience documented here highlight a spectrum of approaches to load management across different sports where upper limb injury is a primary concern. In baseball, the emphasis is on detailed data collection, from pitch counts to biomechanical metrics, with a focus on creating actionable plans tailored to individual pitchers. This contrasts with volleyball, where shoulder load monitoring is less developed, primarily due to the absence of validated tools to quantify arm swing actions. Authors suggest that AI-driven video analysis may bridge this gap. Swimming faces a different challenge: while performance data is abundant, training load data is scarce due to the aquatic



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environment's technological limitations. Recent advancements, however, are beginning to provide more comprehensive data, which authors believe will shift the focus from reactive to proactive injury prevention. In handball, the monitoring of shoulder load is described as being in its infancy, with a lack of technology and systematic monitoring. Rugby, on the other hand, emphasizes strength and power training, correct tackling technique, and gradual exposure to contact to manage and reduce the risk of collision injuries, including those to the upper limb.

These varied experiences suggest a need for cross-sport learning and innovation in load management. For instance, the data-driven approach in baseball, with its focus on individualizing interventions based on comprehensive data, could inform strategies in other sports. Similarly, the emphasis on technique and gradual exposure in rugby could be adapted to sports like volleyball and handball to mitigate upper limb injury risk. To validate and improve load management approaches, future research should focus on developing sport-specific tools and technologies, like the AI-driven video analysis proposed for volleyball and the wearable sensors for swimming. Additionally, longitudinal studies are needed to establish clear links between specific load parameters and injury risk, and to evaluate the effectiveness of different management strategies.

The ultimate success of any load monitoring approach hinges on its validation in terms of reducing injury risk and enhancing performance. This validation process is complex, requiring rigorous scientific methodology to establish cause-and-effect relationships between monitored loads, injury incidence, and performance outcomes. Studies must account for numerous confounding factors, including individual athlete variability, training history, and other extrinsic factors that may influence injury or performance. Furthermore, a critical aspect of validation involves determining the accuracy of the monitoring tools and methods used. This ensures that they accurately detect harmful load levels (low, high, inappropriate type, etc) without producing excessive false positives, which could lead to unnecessary restrictions on training and hinder performance.

Moreover, conflicts may arise between injury prevention and performance

enhancement goals. For example, high training loads are nearly always necessary to maximize performance gains, but its thought that inappropriately high loads could also increase the risk of injury. Effectively navigating this balance requires a nuanced understanding of the dose-response relationship between load, injury, and performance in each specific sport and individual athlete. Other barriers to optimal load management include the lack of standardized definitions and metrics for quantifying load, the difficulty in accurately measuring internal load (i.e., the physiological stress imposed on the athlete), and the ethical considerations surrounding data collection and athlete monitoring.

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