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An Investigation into the Relationship between Training Load and Injury and Illness in Competitive Swimming

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A thesis submitted to the University of Limerick in fulfilment of the requirement for the degree of Doctor of Philosophy

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i.Abstract

Title: An Investigation into the Relationship between Training Load and Injury and Illness in Competitive Swimming.

Introduction: In competitive swimming, optimal performance relies heavily on maximising specific capacities to succeed in competition. The training demands for this optimisation require overreaching interspersed with recovery. Elite coaches rely on their previous experience, coupled with wider sports science support to plan, organise and periodise training cycles. However, despite these practices, competitive swimmers often train and compete with persistent health problems. Training load monitoring and injury/illness surveillance practices are a necessary process in counteracting training load-related errors and designing and implementing injury/illness prevention strategies.

Aims: (1) To explore best practice in monitoring training load and injury and illness surveillance in competitive swimming environments and (2) To investigate the relationships between training load and injury and illness in competitive swimmers.

Methods: Five studies were conducted in this programme of research. Firstly, a systematic review explored the prevalence of training load monitoring practices within competitive swimming research. The review also investigated the relationship between training load and pain, injury, and illness within competitive swimming research *(Chapter two).* Secondly, an online survey was used to determine the current applied training load monitoring and injury surveillance practices within competitive swimming environments *(Chapters three and four).* Subsequently, an integrated training load monitoring and injury/illness surveillance system for use within competitive swimming environments was designed, implemented, and reported, while a qualitative end-user evaluation process was additionally executed *(Chapter five).* Finally, a prospective, longitudinal data collection was conducted using the integrated training load and injury/illness surveillance system. The resulting data were analysed to explore the relationship between training load and aggregates of training load and injury and illness in competitive swimmers *(Chapter six).*

Results: The systematic review identified no clear evidence of an association between training load and pain, while there may be some evidence to suggest a relationship between training load and injury and illness. An international survey of training load monitoring practices found that 83.9% of those surveyed employed some element of training load monitoring. Both internal and external training load monitoring were used in 80.8% of those cases, with swim volume (mileage) (96.2%) and session rate of perceived exertion (sRPE) (92.3%) most frequently used. Thematic analysis highlighted that "stakeholder engagement", "resource constraints" or "functionality and usability of the systems" were shared barriers to the training load monitoring process. An international survey of injury surveillance practices found that 68.1% of practitioners participated in injury surveillance. A recognised definition for injury was used in 86.6% of those cases. Injury surveillance was identified as very effective at identifying injury trends by 66.6% of those surveyed, while previous injury history and training load data were perceived to be influential in preventing injury. Athlete adherence to training load monitoring was impacted by "*process constraints*" and "*data access and control*". Practitioners highlighted *communication and cooperation amongst stakeholders*, *layering context to the data*, *maintaining data integrity* and the *coach's influence in the monitoring process* as being important to the monitoring/surveillance process. Prospective training load and injury/illness monitoring highlighted that the average weekly volume was 33.5 ± 12.9 km. The weekly total training load (AU) averaged 3,838 ± 1,616.1 AU, with 85% of that load coming from swimming. A total of 60 medical attention illnesses and 58 medical attention injuries were recorded during the observation period. Statistical analyses found no association between Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU) and 4-week Rolling Total Training Load (AU) and ACWR and medical attention injury and illness. This occurred irrespective of a 0-day or 7-day lag time.

Conclusions: The findings of this programme of research do not support an association between training load and medical attention injury and illness in the studied cohort of athletes. Monitoring training load and injury/illness surveillance have their own unique challenges which must be navigated during the design and implementation stages. Periodic end-user evaluations are necessary to meet the demands of dynamic sporting environments. The sRPE method of monitoring training load should be employed in practical environments to guide coaches' periodisation plans and to compare the coaches' planned training volume and intensity against what the athlete is subjectively experiencing. sRPE is also beneficial as it can transcend all aspects of a modern-day swim programme. Dryland activities, competition and swim training load can be quantified utilising the same method, allowing for an accurate measure of total training load.

ii.Authors Declaration

I hereby declare that the work in this thesis is my own work, and was completed with the counsel of my supervisors, Dr. Tom Comyns (Department of Physical Education and Sports Sciences, University of Limerick), Dr. Karen McCreesh (School of Allied Health, University of Limerick), Dr. Mark Lyons (Department of Physical Education and Sports Sciences, University of Limerick), Dr. Cormac Powell (High Performance Unit, Sport Ireland). This work has not been submitted for any academic award at this, or any other, third level institution.

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Dr Mark Lyons

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Dr Karen McCreesh

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Dr Cormac Powell

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I am indebted to SJ, Kathryn and Julianne for all their time and effort in designing and implementing the injury/illness data collection system. You have guided a crucial aspect of this research and without your input, organisation, and direction, the data collection process would not have been as efficient and enjoyable. As practitioners, I have learned significantly from you all and have loved working with three outstanding people.

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Interestingly, ULBohs get a mention in a swimming research project. I would like to thank the Dream Team and players who have become a large part of my life (again!) this past year. You have been a welcome support and distraction when needed and provided plenty of laughs and liquid inspiration. I am looking forward to next season already.

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vii.Abbreviations

Term	Explanation
ACWR	Acute:Chronic Workload Ratio
AU	Arbitrary Unit
Borg CR 10 Scale	Borg Category 10 Scale
CHERRIES	Checklist for Reporting Results of Internet Surveys
CI	Confidence Intervals
CMJ	Countermovement Jump
CPD	Continued Professional Development
DASH	Disabilities of the Arm, Shoulder and Hand Questionnaire
EWMA	Exponentially Weighted Moving Average
FINA	Fédération Internationale de Natation
GDPR	General Data Protection Regulation is a Regulation
HR	Heart Rate
IOC	International Olympic Committee
JBI	Joanna Briggs Institute
MA	Medical Attention
MDC	Medical Data Collector
MDT	Multidisciplinary Team
MeSH	Medical Subject Headings
NCD	National Centre Dublin
NCL	National Centre Limerick
NGB	National Governing Body
NPRS	Numerical Pain Rating Scale
OR	Odds Ratio
OSIICS	Orchard Sports Injury and Illness Classification System
OSTRC	Oslo Sports Trauma Research Centre Questionnaire
POMS	Profile of Mood States
PRISMA-P	Preferred Reporting Items for Systematic review and Meta-Analysis Protocols
PSS	Penn Shoulder Score
RPE	Rate of Perceived Exertion
S&C	Strength and Conditioning
SIP	Shoulder Interfering Pain

sRPE	Session Rate of Perceived Exertion
sRPE-TL	sRPE multiplied by session duration in minutes
StDev	Standard Deviation
TL	Training Load
TRIMP	Training Impulse
TRIPP	Translating Research into Injury Prevention Practice
UKSCA	United Kingdom Strength and Conditioning Association
URTI	Upper Respiratory Tract Infection
URTPI	Upper Respiratory Tract Pulmonary Infection
VAS	Visual Analogue Scale

viii.Glossary of Terms

Term	Explanation
4-week Rolling Pool Volume (km)	Accumulated distance swam for 4 weeks. Sum of the weekly volume for the current week and the previous three weeks.
4-week Rolling Total Training Load (AU)	Accumulated TL (AU) for 4 weeks. Sum of the weekly total (AU) for the current week and the previous three weeks.
Acute Load	Training load that is applied over a shorter period of time (e.g., days) (Hulin *et al.,* 2014).
Acute: Chronic Workload Ratio (ACWR)	The ratio of the acute TL (past 7 days) in relation to the chronic TL (past 28 days). $EWMA_{this\ week} = Load_{this\ week} * \lambda_a + ((1 - \lambda_a) * EWMA_{last\ week})$ Where λ_a is a value between 0 and 1 that represents the degree of decay, with higher values discounting older observations at a faster rate. The λ_a is given by: $\lambda_a = 2/(N+1)$ Where *N* is the chosen time decay constant, typically 7 and 28 days for acute ('fatigue') and chronic ('fitness') loads, respectively.
Chronic Load	Training load that is applied over a longer period of time (e.g., weeks or months) (Hulin *et al.,* 2014).
Competition	The period during which the athletes participate in an event against athletes from another team/ league/ nation that are timed (swimming and open water swimming) (Mountjoy *et al.*, 2016).
Competitive Swimming	Primary purpose of the sport is competitive performance not participation.
Direct Contact	Contact that leads directly to the health problem in an immediate and proximal manner. Can be contact with another person, object or animal (diving block, lane marker, water surface from heights) (Bahr *et al.*, 2020).
Exacerbation	An injury/illness where the index injury/illness has not completely healed or recovered (Hamilton *et al.*, 2011).

External Training Load	Objectively measured work performed by the athlete during training and/or competition, independent of internal workloads (Bourdon *et al.*, 2017).
Fatigue	Fatigue can be defined as muscular when an athlete is unable to maintain the required muscle contraction or performed workload. It can also encompass extreme tiredness after exertion. It can be subcategorised as peripheral or central in the nervous system (Phillips 2015).
Illness	A complaint or disorder, experienced by an athlete, not related to injury. Illnesses include health related problems in physical (e.g. influenza), mental (e.g. depression) or social well-being, removal or loss of vital elements (air, water, warmth) (Bahr *et al.*, 2020).
Incidence	The number of new occurrences of an injury/ illness in relation to the athletes at risk in a given time period (Mountjoy *et al.*, 2016).
Index Injury or Illness	The first recorded injury/illness (Hamilton *et al.*, 2011).
Indirect Contact	Contact where force is not directly applied to the injured area but contributes to the casual chain leading to the health problem. Can be indirect contact through another person, object or animal (diving block, lane marker, water surface from heights) (Bahr *et al.*, 2020).
Injury (IOC Bahr *et al.*, 2020)	Tissue damage or other derangement of normal physical function, resulting from rapid or competitive transfer of kinetic energy (Bahr *et al.*, 2020).
Injury (FINA Mountjoy *et al.*, 2016)	A physical complaint or observable damage to body tissue produced by the transfer of energy experienced or sustained by an athlete during participation in training or competing in an aquatic discipline, regardless of whether it received medical attention or its consequences with respect to impairments in competition or training.
Injury (IOC Soligard *et al.*, 2017)	New, pre-existing, or recurring (athletes having returned to full participation after a previous condition) musculoskeletal complaints, concussions, or other medical conditions (injuries) or illnesses incurred in competition or training receiving medical attention, regardless of the consequences with respect to absence from competition or training.
Injury Surveillance	The method of habitually collecting data relating to the occurrence of an injury and the risk factors associated with it.

Internal Training Load	The physiological and/or psychological stress imposed on the athlete during training and/or competition (Bourdon *et al.,* 2017).
Lag period	The period between the dose (training load) and response (onset of injury) (Drew and Finch, 2016).
Maladaptation	A negative change in the biological system in response to external loading and/or inadequate recovery (Soligard *et al.,* 2016).
Medical Attention	A physical complaint where a qualified clinician has assessed the athlete's physical complaint or medical condition. A qualified clinician is anyone who is involved in the health care of athletes, reviews medical or physiological information, and/or implements an action plan to improve the athlete's health, where health is considered in a broad sense but must be more than performance enhancement (Mountjoy *et al.,* 2016).
Medical Condition/Health-Related Incident	"Any physical or psychological complaint or disorder experienced by an athlete irrespective of the need for medical attention or time loss from training or competing in an aquatic discipline (Mountjoy *et al.,* 2016).
Non- Contact	No direct or indirect contact from an external source was related to the health problem (Bahr *et al.,* 2020).
Non-Time Loss	Any physical complaint as a result of competition or training but without time-loss (Langhout *et al.,* 2019).
Prevalence	The proportion of athletes affected by a specific condition at a defined time (point prevalence) or time period (eg, 12-month prevalence, life-time prevalence), and is calculated by dividing the number of athletes with an injury or illness (regardless of the onset time) by the total number of athletes (Mountjoy *et al.*, 2016).
Recurrent Injury or Illness	A subsequent injury/illness that is the same *location or system* as the index injury/illness and has the same *type or diagnosis* as the index (Hamilton *et al.,* 2011).
Reinjury/Repeated Illness	An injury/illness where the index injury/illness has completely healed or recovered (Hamilton *et al.*, 2011).
Severity	Mild 0-7 days missed, moderate 8-28 days missed, severe >29 days missed (Mountjoy *et al.*, 2016).
Subsequent Injury or Illness	Any injury/illness occurring after the index injury/illness (Hamilton *et al.,* 2011).

Subsequent Local Injury or Illness	A subsequent injury/illness that is the same *location or system* as the index injury/illness but has a different *type or diagnosis* as the index (Hamilton *et al.*, 2011).
Subsequent New Injury or Illness	A subsequent injury/illness that is not to the same *location or system* as the index injury/illness (Hamilton *et al.*, 2011).
Time Loss	A health problem which leads to the athlete being unable to take full part in FINA activities. If the athlete misses the rest of the training or competition session but returns for the next training/competition, this should be recorded as a time-loss incident (Mountjoy *et al.*, 2016).
Training	Training is defined as “physical activities that are aimed at maintaining or improving athletic skills or physical condition (Mountjoy *et al.*, 2016).
Training load	The cumulative amount of stress placed on an individual from a single or multiple training sessions (structured or unstructured) and matches over a period of time (Soligard *et al.*, 2016).
Training Monotony	A measure of day-to-day training variability (Comyns and Flanagan 2013).
Training Strain	A value that represents the overall stress that the athlete was exposed to (Comyns and Flanagan 2013).
Weekly Gym Training Load (AU)	Gym TL for one week. Session RPE * Duration (minutes) = sRPE-TL. All dryland session sRPE-TL from Monday to Sunday summed together to generate weekly gym (AU).
Weekly Pool Training Load (AU)	Pool TL for one week. Session RPE * Duration (minutes) = sRPE-TL. All pool session sRPE-TL from Monday to Sunday summed together to generate weekly pool (AU).
Weekly Pool Volume (km)	Distance swam per week in kilometres. All session volumes (km) from Monday to Sunday are summed together to generate weekly volume.
Weekly Total Load Training (AU)	All TL for the week. Weekly pool (AU) and weekly gym (AU) are summed together.

ix.Units of Measurement

Term	Explanation
%	Percentage
cm	Centimetres
m	Metres
Kg	Kilograms
Min	Minutes
Km	Kilometres
Hr	Hours
AU	Arbitrary Units
AE	Athlete Exposure
Yrs	Years
Wk	Week
$mmo \cdot L^{-1}$	Millimoles per Litre

x.List of Publications

Journal Publications

Barry, L., Lyons, M., McCreesh, K., Powell, C., and Comyns, T. (2021) 'The relationship between training load and pain, injury and illness in competitive swimming: a systematic review', *Physical Therapy in Sport*, 48, 154–168, available: https://doi.org/10.1016/j.ptsp.2021.01.002.

Barry, L., Lyons, M., McCreesh, K., Powell, C., and Comyns, T. (2022) 'International survey of training load monitoring practices in competitive swimming: how, what and why not?', *Physical Therapy in Sport*, 53, 51–59, available: https://doi.org/10.1016/j.ptsp.2021.11.005.

Barry, L., Lyons, M., McCreesh, K., Powell, C., and Comyns, T. (2022) 'International survey of injury surveillance practices in competitive swimming', *Physical Therapy in Sport*, 57, 1–10, available: https://doi.org/10.1016/j.ptsp.2022.07.001.

Barry, L., Lyons, M., McCreesh, K., Powell, C., and Comyns, T. (2023) 'The design and evaluation of an integrated training load and injury/illness surveillance system in competitive swimming', *Physical Therapy in Sport*, 60, 54–62, available: https://doi.org/10.1016/j.ptsp.2023.01.007.

Conference Publications

Barry, LA., Lyons, M., McCreesh, K., Powell, C., Comyns, T. (2021). *International survey of training load monitoring practices in competitive swimming: How, what and why not?* [Online Poster]. BASES 2021 Conference, 16th -18th November.

Barry, LA., Lyons, M., McCreesh, K., Powell, C., Comyns, T. (2022). *Epidemiology of injury in Ireland's performance level swimmers; The race to the Tokyo Games.* [Poster]. 2022 ACSM Annual Meeting & World Congresses, 31st May-4th June, San Diego, California, USA.

Barry, LA., Lyons, M., McCreesh, K., Powell, C., Comyns, T. (2022). *Training load and injury/illness surveillance in competitive swimmers; a case study example.* [Poster]. 2022 All Ireland Postgrad Conference in Sport Science, Physical Activity and Physical Education, 9th September 2022, DCU, Dublin.

Chapter 1 Introduction

1.1 Background

The Fédération Internationale de Natation (FINA) was established in 1908 and has global management over the development of aquatic disciplines including swimming, water polo, diving, artistic swimming and open water swimming ('About FINA' 2021). In 2022, FINA was rebranded as World Aquatics, however for consistency, throughout this thesis World Aquatics will be referred to as FINA. Swimming has a long history as an Olympic sport, dating back to the 1896 Games in Athens (Hill *et al.*, 2021), and has four distinct strokes; front crawl (metonymically referred to as freestyle), backstroke, breaststroke and butterfly. Within global competitions, swimming takes place in either a 25-meter pool (short course) or 50-meter pool (long course); however, only the 50-meter format is used at the Olympic Games. At the most recent 2020 Tokyo Olympic Games, a total of 35 swimming finals were held (the highest in Olympic history), with 21 countries represented on the medal table (*FINA Annual Review* 2021). This highlights the global impact of the sport of swimming and the level of competitiveness at the upper echelons of the sport. To perform at the elite level, exceptional physical demands are placed on the athlete. Elements of power, speed and endurance are all required to reach optimal performance (Pyne and Sharp 2014). Swimming performance, at the fundamental level, is related to the optimal balance between a swimmers' propulsive force capabilities and their ability to overcome drag or water resistance (Pendergast *et al.,* 2005). More holistically, elite performance requires that the training demands be periodised throughout training cycles and ultimately optimised during peak competition periods (Hellard *et al.,* 2019).

Monitoring training load is a critical aspect of planning and periodising training demands (Foster *et al.,* 2001). To improve insight into the training load of an athlete, key metrics need to be monitored and understood. Training load can be divided into external and internal load (Bourdon *et al.*, 2017). External training load refers to the work completed by the athlete (Halson 2014) and is frequently used because of its ease of quantification (Paquette *et al.*, 2020). External training load is measured independently of the internal training load (Halson 2014) and may include metrics such as distance, speed and time. Internal training load is the measurement of the athletes' relative biological (physiological and psychological) stress and may include measures such as heart rate, rate of perceived exertion (RPE) and oxygen consumption (Bourdon *et al.,* 2017). Typically, internal training load has been seen as more challenging to monitor (Paquette *et al.,* 2020), however, best practice advocates for an integrated approach where both internal and external training loads are monitored to provide optimal insight into the athlete's load related stress (Bourdon *et al.,* 2017). The session rate of perceived exertion method (sRPE) is one such method of monitoring internal training load that has been widely used in team sports (Gabbett 2016) because of its ease of use and interpretation (Fusco *et al.,* 2020). The amalgamation of internal and external training can be calculated to monitor the total training load (sRPE-TL) of a session by multiplying the athlete's sRPE (internal load) by the session duration in minutes (external load). Since its conception, the application of sRPE-TL to quantify training load has been used in a large number of studies (Askow *et al.,* 2021). A systematic review completed in 2016 investigated the relationship between training load, injury, illness and soreness (Drew and Finch 2016). The review included 35 papers from a range of sports. The findings showed that sRPE-TL was the most frequently (n=25) used method of monitoring training load within team sports. The sport of swimming was represented in only one (Hellard *et al.,* 2015) of the 35 papers. Furthermore, Hellard *et al.,* (2015) did not utilise the sRPE method, leaving the relationship between training load, injury, illness, and soreness in swimming unclear.

The relationship between sRPE based training load and injury and illness has been investigated using both absolute and relative measures. Absolute measures encompass the sum of all or one category of training load and presented over a set duration e.g. weekly pool load, total weekly load (Drew and Finch 2016). Relative load expresses the change in training load (percentage, ratio) in proportion to another (Drew and Finch 2016), e.g., acute to chronic workload ratio (ACWR). sRPE has been seen as the most commonly used measure of training load in the literature (Eckard *et al.,* 2018), with both absolute and relative loads being linked with injury and illness (Drew and Finch 2016). Acute increases in absolute load have been associated with increased risk of injury with absolute changes in week to week training load (1069AU) increasing the risk of injury by 60% in the subsequent week in a Rugby Union population (Cross *et al.,* 2016). Similarly, accumulated loads over a number of weeks has also been shown to increase injury risk in professional soccer players (Jaspers *et al.,* 2018). Previous research has noted that the use of a exponentially weighted moving average (EWMA) ACWR is the more sensitive measure of relative training load when compared with the more traditional rolling average (Griffin *et al.,* 2020a). Research has shown that ACWR has been related to an increased risk of injury (Griffin 2021). However, the majority of the research examining the relationship between EWMA ACWR, and injury has also been conducted in team or field-based sports with a noticeable gap with regards endurance sports or competitive swimming.

Competitive swimmers typically train with large training demands including high training distances and session frequencies (Pollock *et al.*, 2019), potentially resulting in fatigue related illness (Johnson 2003), repetitive strain and micro-trauma (Gaunt and Maffulli 2012). Individual athlete characteristics such as age have been highlighted as moderators for both injury and illness risk in aquatic sports (Prien *et al.*, 2017). This elevated risk of injury and illness (Pollock *et al.,* 2019) heightens the need for individualised training load management alongside adequate recovery strategies (Collette *et al.*, 2018).

The injury profile of competitive swimmers has been well established, with the most recent review of epidemiology of swimming injuries published in 2021 (Trinidad *et al.,* 2021). This review highlighted the main location of injuries in swimmers are shoulder, back and knee with muscle overuse and tendon injuries being the most common. Injury incidence rates of 2.6-3.0 injuries per 1000 hours of exposure or 3.2-6.1 per 100 registered athletes have been reported (Trinidad *et al.,* 2021). However, the review concluded that there is no consensus on reporting injury rates in swimming studies. They summarised that the incidence rate was highly variable which is often due to methodological inconsistencies between study design and reporting (Trinidad *et al.,* 2021). The authors concluded that future studies should follow consensus guideline recommendations in terms of data collection and injury surveillance in swimming. Additionally, they recommended that swimming literature should focus more broadly on all injuries as opposed to a narrow focus on shoulder injuries which has been significantly more researched than less prevalent injuries.

A competitive swimmer's illness profile is also critically important but has been less well established than their injury profile. Swimmers have been shown to train and compete with persistent health problems (Prien *et al.,* 2017) which has been shown to negatively impact performance (Pyne 2005). Studies have highlighted that significant immune deficiencies are not commonplace in competitive swimmers (Hellard *et al.,* 2015). However, minor deteriorations in health related to intensive periods of training can lead to minor illness such as upper respiratory tract infections (URTI) (Hellard *et al.,* 2015). It has been found that URTI are not more common in swimmers than the general population, but the infection has a greater impact on training and symptoms can be exacerbated by chlorine inhalation (Johnson 2003). After a two-year observational study, Hellard *et al.,* (2011) also concluded that URTI infections were the most common condition in elite international and national swimmers. The intensive training periods and winter months were deemed the highest risk for infection, with national swimmers at a higher risk of illness when compared to their international peers (Hellard *et al.,* 2011). Despite a relationship between URTI and training load, swimming level and seasons being established within this study, further research is needed to provide conclusive evidence into the associations with all pathologies affecting competitive swimmers.

FINA published an injury and illness surveillance consensus statement in 2016 to provide direction on injury and illness surveillance methods (Mountjoy *et al.,* 2016). The consensus statement outlined specific definitions of injury and illness, with improved clarity on classification systems and exposure reporting. The statement concluded that consensus guidelines should direct future prospective in-competition and out-of-competition injury and illness surveillance. It also recommended that future research should assess or monitor potential risk factors in parallel with injury and illness surveillance. This practice would inform future preventative intervention strategies (Mountjoy *et al.*, 2016). More recently, the International Olympic Committee (IOC) also published a consensus statement for recording and reporting of injury and illness surveillance data (Bahr *et al.*, 2020). The aim was to provide practical guidance on sports generic data collection and reporting protocols, with the ultimate goal of the consensus statement to be used in tandem with sport specific statements to encourage greater consistency in injury and illness surveillance projects (Bahr *et al.,* 2020). The IOC consensus statement also echoed the recommendations by FINA on supplementing injury and illness surveillance data with additional relevant metrics (demographics, health data, performance and training level) which may inform related risk factors and allow better comparison of findings (Bahr *et al.,* 2020). According to Trinidad *et al.,* (2021), since the consensus statement publication in 2016, the implementation of the methodological recommendations for data collection has not been observed.

Since 2016, two in-season prospective surveillance studies have been published (Matsuura *et al.,* 2019; Boltz *et al.,* 2021). Both studies, while robust in design, have significant limitations in the reporting of the results. Matsuura *et al.,* (2019) calculated incidence rates as the number of events per competing athlete and per 100 athletes by body part over the course of the whole study period. Boltz *et al.,* (2021) did not calculate incidence rates but instead opted for the rate per 1000 athlete exposures (AE). An AE in this case was one athlete participating in one exposure event; however, the authors acknowledge estimating AE based on roster size rendering it less accurate (Boltz *et al.*, 2021). In both studies, the surveillance procedures were robust, but the data presented lacked practical application based on their exposure or incidence rate reporting. Both studies provide recommendations, which include more detailed athlete exposure data (type or intensity of training, distance swam, and cardiovascular/exertional indices) in parallel with their surveillance procedures (Matsuura *et al.,* 2019; Boltz *et al.*, 2021). The use of a common training load metric such as swim volume (km) or sRPE-TL in parallel with injury/illness surveillance could be a potential solution to improving the incidence rate or exposure reporting in competitive swimming.

Load management is a risk factor that is considered to be a major element in the incidence of injury (Soligard *et al.*, 2016) and is potentially a factor in the incidence of illness (Schwellnus *et al.,* 2016). However, training load prescription in swimming has historically been planned through a coach's experience and intuition (Wallace *et al.*, 2008) and is heavily reliant on monitoring the volume of training in either meters, kilometres, minutes or hours (Feijen, Tate, Kuppens, Barry, *et al.* 2020). Research has shown a swimmer's compliance to adhering to the prescribed training distance is considered good; however, they are less effective in adhering to planned intensity (Stewart and Hopkins 1997). Heart rate is a measure of internal training load frequently employed in swimming (Feijen, Tate, Kuppens, Barry, *et al.* 2020), but it has several limitations including logistical issues within an aquatic environment, accuracy in evaluating high-intensity interval training and use in the dryland environment (Wallace *et al.,* 2008). This highlights a need for training load monitoring in competitive swimming to prescribe and monitor both volume and intensity in a practical way. sRPE has been found to be ecologically valid in a swimming environment and can provide a practical, non-invasive method for quantifying internal training load in swimming (Wallace *et al.,* 2009). To date, the use of sRPE, sRPE-TL or its aggregates in swimming research seems to be limited. Collette *et al.,* (2018) explored the use of training load, derived through sRPE and its influence on the recovery-stress state of highly trained swimmers. This study recommended the use of sRPE-TL in a swimming population (Collette *et al.,* 2018). Similarly, sRPE-TL was used to investigate the relationship between training load and saliva biomarkers in Paralympic swimmers by Sinnott-O'Connor *et al.,* (2018). The study found that salivary IgA, alpha amylase and cortisol responded to changes in training load (Sinnott-O'Connor *et al.,* 2018). Despite being prospective in nature, both studies had low sample sizes (<10 participants) and did not directly measure the incidence of injury or illness. A prospective cohort study which incorporated sRPE-TL and injury surveillance was published in 2019 (Tomar and Allen 2019). The study found no significant relationship between training load and injury. However, the study duration was short (7 weeks), and a very low injury incidence was recorded (n=3). The population included was also described as competitive but the training demands were deemed to be low for a typical competitive swimming population (Tomar and Allen 2019). To satisfy the gaps in the research, future studies should be prospective in nature, with larger and better-defined sample sizes. Research should also meet the recommendations set out by the IOC/FINA injury/illness surveillance consensus statements. The combined use of both an internal and external training load measures is advised, with the use of sRPE-TL warranting further investigation. A more global investigation should also occur with injury surveillance broadening the scope past shoulder injuries. Expanding the study design to include illness surveillance is important, and subsequently recording more pathologies beside URTI is advised.

This programme of research strives to explore the highlighted gaps in previous research related to training load monitoring and injury/illness surveillance in competitive swimming. This research will examine the landscape of monitoring practices in both the academic and applied settings. It will design a training load monitoring system which is grounded in both internal and external load measures and utilise the sRPE-TL method. The training load monitoring system will be designed in conjunction with consensus guidelines and best practice. The injury surveillance aspect of the system will globally capture all injuries sustained, having a wider focus outside of shoulder injuries. The illness surveillance aspect of the system will provide further detail on the illness profile in competitive swimmers and capture a wide array of pathologies. Both the injury and illness surveillance system will be built on the recommendations of the FINA and IOC consensus guidelines to improve methodological consistency in the research presented. Subsequently, a prospective longitudinal data collection of pre-defined key training load metrics will take place allowing for an investigation into the relationship between training load and injury/illness incidences in a competitive swimming environment.

1.2 Thesis Aims

(1) To explore best practice in monitoring training load and injury and illness surveillance in competitive swimming environments and (2) To investigate the relationships between training load and injury and illness in competitive swimmers.

1.3 Thesis Objectives

The objectives are as follows:

1. To gain an understanding of the training load monitoring practices used within competitive swimming research *(Chapter two).*
2. To investigate the relationship between training load and pain, injury, and illness within competitive swimming research *(Chapter two).*
3. To determine the current applied training load monitoring and injury surveillance practices within competitive swimming environments *(Chapters three and four).*
4. To design, implement and evaluate a sport specific integrated training load monitoring and injury/illness surveillance system for use within competitive swimming environments *(Chapter five).*
5. To explore the relationship between training load and aggregates of training load and injury and illness in competitive swimmers *(Chapter six).*

1.4 Thesis Structure

This programme of research consists of seven chapters.

Chapter one introduces the research thesis and the key concepts involved in this programme of research. It highlights current gaps in the literature and presents a clear rationale and recommendations for future research. It also defines the research aims and objectives and provides a link between the present research gaps and the goals of this programme of research.

Chapter two presents a systematic literature review examining the relationship between training load and pain, injury and illness in competitive swimming (Barry *et al.*, 2021). The review explores important variables associated with training load monitoring in the sport and outlines the relationships with pain, injury, and illness. Methodological inconsistencies are highlighted within the research including highly variable operational definitions for pain, injury, and illness across studies. Study designs are often retrospective and cross sectional with low study quality. Training load measures across studies are also conflicting. These methodological inconsistencies make inter-study comparisons difficult and render any investigation into the relationship between training load and pain, injury, or illness impractical. The review provides practical recommendations for future research, including the need to conduct longitudinal prospective studies, employing training load monitoring based on the sRPE method.

Chapter three examines the training load monitoring practices employed by practitioners working within competitive swimming (Barry *et al.*, 2022a). This research, conducted using an international survey, identifies the training load monitoring practices within the applied setting and presents the data collection and analysis approaches employed. It also details specific barriers and facilitators experienced, which include stakeholder engagement, resource constraints and the functionality and usability of the system. The findings of this chapter outline that large variability in monitoring training load is highly specific to the research environment as found in Chapter two. Chapter three shows that the applied environment is much more consistent in the training load monitoring practices employed. Chapters two and Chapter three provides a solid basis for the design and implementation of the training load monitoring system outlined in Chapter five.

Chapter four identifies and details the injury surveillance practices being used by practitioners in competitive swimming environment (Barry *et al.*, 2022b). This chapter explores the nature of injury surveillance in competitive swimming environments and highlights the data collected, injury definitions used, and the practitioners' perceived effectiveness of the injury surveillance practices. Thematic analysis is also used to analyse and present the barriers associated with injury surveillance within this population. Barriers included; poor communication and a lack of engagement within the injury surveillance processes. The findings of this chapter, combined with Chapter two provide strong evidence for the design and implementation of the injury surveillance aspect of the integrated system described in Chapter five.

Chapter five presents the design, implementation and evaluation of an integrated training load injury/illness surveillance system to be used within competitive swimming (Barry *et al.*, 2023). This chapter builds on the previous gathered research to design an integrated training load monitoring platform to be used in parallel with injury/illness surveillance. The chapter also outlines the auditing process to safeguard an accurate implementation strategy and an extensive qualitative stakeholder evaluation of the system.

Chapter six explores the relationship between training load and injury and illness in competitive swimmers building on previous chapter recommendations. Utilising the system described in Chapter five, training load monitoring using sRPE derived metrics was carried out across two seasons. In addition, injury/illness surveillance, conducted in line with the most recent consensus statements, was also carried out in parallel with the training load data. The relationship between the training load data, and its aggregate measures, and the incidence of medical attention injury and illness is explored. The results presented medical attention injury and illness epidemiological data for the cohort. The findings highlighted a lack of association between key training load variables, injury, and illness.

Chapter seven provides a comprehensive discussion of the overall findings. It also presents the conclusions of the programme of research, the most significant limitations that were identified, recommendations for future research and outlines practical suggestions on how best to implement the findings of this research into an applied competitive swimming environment.

Chapter 2 The Relationship between Training Load and Pain, Injury, and Illness in Competitive Swimming: A Systematic Review

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2.1 Abstract

Introduction: Research suggests that the frequency of training, combined with the repetitive motion involved in high volume swimming can predispose swimmers to symptoms of over-training. The prevention of pain, injury and illness is of paramount importance in competitive swimming to maximise a swimmer's ability to train and perform consistently. A significant factor in the prevention of pain, injury and illness is the appropriate load monitoring and management practices within a training programme.

Aims: The aim of this systematic review is to investigate the relationship between training load and pain, injury, or illness in competitive swimmers.

Methods: The databases SPORTDiscus, CINAHL, Scopus, MEDLINE and Embase were searched in accordance with PRISMA guidelines. Studies were included if they reported on competitive swimmers and statistically analysed the link between training load and either pain, injury, or illness. The methodological quality and study bias was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist.

Results: The search retrieved 1,959 articles, 15 of which were included for review. The critical appraisal process indicated study quality was poor overall. Pain was the most explored condition (N=12), with injury (N=2) and illness (N=1) making up the remaining articles. There was no evidence of an association between training load and pain, while there may be some evidence to suggest a relationship between training load and injury and illness.

Conclusions: The relationship between training load and pain, injury and illness is unclear owing to a host of methodological constraints. The review highlighted that youth, masters, and competitive swimmers of a lower ability (e.g., club versus international) may need consideration when planning training loads. Winter periods, higher intensity sessions and speed elements may also need to be programmed with care. Monitoring practices need to be developed in conjunction with consensus guidelines, with the inclusion of internal training loads being a priority. Future research should focus on longitudinal prospective studies, utilising the sRPE monitoring method and investigating the applicability of ACWR (EWMA). Improved methods and study design will provide further clarity on the relationship between load and pain, injury, and illness.

Keywords; *Internal Load; External Load; Surveillance; Monitoring; Elite Swimmer*

2.2 Background

Aquatic sports were one of the original sports in the modern Olympic Games, and have since grown to have the second highest athlete participation, with 900 competitive swimmers participating at the 2016 Rio Olympic Games ('Rio 2016 - swimming | FINA.org - official FINA website' 2020). In competitive swimmers, injury prevalence ranges from 32.2% to 74.6%, with the shoulder accounting for a large proportion of injuries, followed by knee and lower back injuries (Toomey *et al.*, 2018). The incidence of overuse injuries (1.48) surpass that of acute injuries (1.10), when adjusted per 1000 exposure hours in competitive swimmers (Ristolainen *et al.,* 2009). Despite 81% of Olympic swimming events being contested in under two minutes and twenty seconds, the traditional training practices of competitive swimmers are high in volume (Nugent *et al.,* 2019). The extensive nature of training means there is a significantly higher incidence of injury in training than in competition (Soligard *et al.,* 2017). An abundance of research suggests that the high frequency of training (Weldon and Richardson 2001), as well as the repetitive motion (Pink and Tibone 2000) can predispose swimmers to symptoms of overtraining (Khodaee *et al.,* 2016). Overtraining is defined as the accumulation of training or non-training stress resulting in a long term decrement in performance capacity (Lehmann *et al.,* 1999). Overtraining can often have related physiological signs and symptoms of prolonged maladaptation (Meeusen *et al.,* 2006), leading to disturbances in the endocrine, immune, musculoskeletal and neurologic systems (Myrick 2015).

Prevention of pain, injury and illness is of paramount importance within elite sport, not only to safeguard the long-term health of the athlete, but to maximise their ability to train and perform without interruption (Palmer-Green *et al.,* 2013). Finding a balance between training load and recovery is crucial in the prevention of overtraining (Kenttä and Hassmén 1998). To this end, the dose-response relationship needs to be monitored. While the response aspect of this paradigm is more easily measured, the dose imposes more logistical challenges (Lambert and Borresen 2010). The incidence of injury in swimming is seen as being low in comparison to other sports, but the prevalence of overuse injuries is high (Matsuura *et al.,* 2019). This further emphasises the importance of load monitoring among elite swimmers (Pollock *et al.,* 2019), and also quantification of the training load in order to identify the effects of training (Mujika 2017). Training load can be divided into internal and external loads, with external loads describing the quantification of work and internal loads describing the response to that work (Drew and Finch 2016). In swimming, distance, time or speed are habitually used to monitor the external training load, with heart rate typically used to monitor internal training load (García-Ramos *et al.,* 2015). A range of other methods such as self-administered questionnaires, sport-specific performance test and blood screening have been used as methods to reduce the risk of overtraining (Pollock *et al.,* 2019).

The links between various measures of training load and either pain, injury and illness has been examined across a variety of sports (Jones *et al.,* 2017; Eckard *et al.,* 2018; Johnston *et al.,* 2019). While training load, pain, injury and illness have become key terms within sport science, a lack of consistency in their definitions has also arisen (Jones *et al.,* 2017). The rise to prominence of training load monitoring (Newton *et al.,* 2019) and injury surveillance (Palmer-Green *et al.,* 2013) practices over the past decade has seen a subsequent increase in the need for consensus statements. Sports such as cricket, football, rugby union, rugby league, tennis, athletics and horse racing have all published epidemiological consensus statements in recent years (Bahr *et al.,* 2020). Many of these statements attempt to improve consistency in reporting guidelines to enable the comparison of methodologies and findings. A consensus statement from Fédération Internationale de Natation (FINA) in 2016 (Mountjoy *et al.,* 2016), provided clarity on the reporting of injuries and illness in aquatic sports, but did not address the monitoring of training load within the sport and its links with injury surveillance. In the same year, Drew and Finch (2016) published a systematic review investigating the relationship between training load, and injury, illness and soreness in a broad range of sports. The review categorised injury and illness into medical attention and time loss definitions, while it also expanded into the area of overuse injuries. The term soreness in this review was identified as the prevalence of symptoms irrespective of medical attention or time loss. Including this term broadened the reviews focus to papers that may incorporate 'athlete's self-reported injury' (soreness or pain) as recommended by the Injury Definitions Concept Framework (Timpka *et al.,* 2015; Drew and Finch, 2016). The review concluded that there is moderate evidence of a relationship between training and competition load and the incidence of injury, illness and soreness. Their findings highlighted that training load should be monitored, using sRPE to avoid acute spikes in load (Drew and Finch 2016). This review included 35 studies; however, only one swimming paper met the inclusion criteria. More recently, a systematic review completed investigated the link between swim training volume and shoulder pain (Feijen, Tate, Kuppens, Claes, *et al.* 2020) . The review encompassed 12 studies and highlighted that swim training volume was linked with shoulder pain in adolescent competitive swimmers. While the review provided worthwhile information, several limitations were acknowledged. The review solely focused on measures of external training load (i.e., volume) and limited the scope to shoulder pain. The International Olympic Committee (IOC) consensus statements on load in sport and risk of injury (Soligard *et al.*, 2016), and risk of illness (Schwellnus *et al.,* 2016) have stated injury aetiology is multifactorial and that load monitoring needs to include a combination of both external and internal loads.

To date, no review has completed a comprehensive assessment on the relationship between internal and external training load and pain, injury, or illness in competitive swimming. This review aims to provide a clear consensus for practitioners working within competitive swimming on the relationship between training load and pain, injury, and illness. Using the most recent guidelines on training load and injury/illness surveillance, it is intended to close a gap within the literature in competitive swimming as other sports have done in recent years. Consequently, the purpose of this systematic review is to determine if a relationship exists between training load and pain, injury and illness in competitive swimmers.

2.3 Methods

2.3.1 Literature Search

The search strategy (presented in appendix 2.1) followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) Guidelines (PRISMA-P Group *et al.,* 2015). The keyword search string included combinations of the following: Training Load, Swimming, Competitive, Injury, Pain, Illness. Each keyword was broken into its individual Medical Subject Headings (MeSH), terms or synonyms and joined where appropriate by Bolan terms “AND”/ “OR”. A copy of the keyword search string is provided in the electronic supplementary material. Relevant studies were then identified through running the keyword string through five targeted databases: SPORTDiscus, CINAHL, Scopus, MEDLINE and Embase.

2.3.2 Selection Criteria

Once the search was conducted, results were filtered for English language within each database. No date limits were applied. Remaining results were then stored on a reference management tool (Zotero.org) for manual screening. Using the reference management tool, duplicates were removed, and titles were initially screened for relevance to the subject matter by a single reviewer (LB). Articles clearly outside the scope of this review were excluded. Titles and abstracts were then screened for the inclusion criteria by two reviewers (LB, TC). Articles were segregated into “YES”, “NO”, “MAYBE” folders according to their eligibility.

The following inclusion criteria had to be present in order for the study to be considered: 1) the study had to be printed in the English language in a peer-reviewed journal and excluded case study, case series, reviews, interventions, conference proceedings and study designs; 2) the method of the study had to clarify that participants were competitive swimmers; 3) one or more measures of internal or external training load had to be reported; 4) an outcome measure of pain, injury or illness had to be reported, which could be self-reported or diagnosed by a health professional; and 5) a statistical analysis of the difference or association between training load and pain, injury or illness had to be reported.

Full text copies of both the “YES” and “MAYBE” articles were sourced and rescreened for inclusion. A comparison of both reviewers’ results was made with a third independent reviewer (ML) acting as adjudicator in the event of a disagreement. Once consensus was reached, a full search for additional papers of the final articles reference lists was carried out. Any articles sourced through secondary means (e.g., reference list search, etc.), were screened by both reviewers and included where appropriate. **Figure 2-1** presents a flow chart diagram of the systematic search process.

2.3.3 Data Extraction

Key information pertaining to the inclusion criteria were extracted from each study, using a standard data collection form. Study design, population characteristics (i.e., number of participants, level of ability, sex, and age), training load measured (internal or external), outcome (measure of pain, injury, illness), method of collection for both training load and outcome, definition of outcome used, key results or findings were extracted. If any key information was not available, the corresponding author was contacted. If no response was received after a period of six weeks, the information was deemed unavailable. Findings included those that tested for significant difference (*p*-values between groups) as well as those that tested for an association (Odds Ratios between exposure and outcome). The data extraction table was cross-checked for accuracy by a second reviewer (TC). Studies were grouped by outcome for comparison purposes.

2.3.4 Training Load Measures

Internal and external training load measures were defined and extracted based on process outlined previously (Eckard *et al.,* 2018). Internal training load was defined as the athlete's response to an external stimulus (e.g., RPE, heart rate (HR), etc.). External training load was defined as any external stimulus applied to the athlete independent of their athlete characteristics (e.g. distance, time, etc.) (Eckard *et al.,* 2018). Method of collection was designated as either being self-reported (SR) when the athlete themselves recorded the load, or "third party" when the load data was collected and reported by a designated person within the coaching or research team.

2.3.5 Operational Outcome Definition

The definition used for pain, injury or illness was extracted and categorised where possible according to Mountjoy *et al.*, (2016) and Langhout *et al.,* (2019). Pain, injury, or illness could be categorised as "non-time loss", "medical attention" (MA) or "time loss". Medical attention is where a qualified clinician has assessed the athlete's medical condition (Mountjoy *et al.,* 2016), Time loss was defined as one which led to the athlete being unable to participate in full FINA activities (Mountjoy *et al.,* 2016), and non-time loss was any physical complaint as a result of competition or training but without time-loss (Langhout *et al.*, 2019).

2.3.6 Critical Appraisal

The Joanna Briggs Institute (JBI) Critical Appraisal Checklists for cohort and cross-sectional studies were utilised to assess the risk of bias for each individual study as relevant to their study design (Joanna Briggs Institute 2019). Two reviewers (LB, TC) individually critically appraised 15 studies (10 cross-sectional, 5 cohorts). Each tool included between 8-11 questions with a focus on the appropriateness of the study design, presence of selection bias, validity and reliability of methods, the handling of confounding factors and appropriateness of the statistical analyses used. Authors assigned a "Yes", "No", "Unclear" or "Not Applicable" to each question, depending on the perceived risk of bias. Study quality was considered poor if they had ≥3 "no" or "unclear" responses as outlined previously (Nour *et al.,* 2018). Discrepancies between the two reviewers were resolved through discussion and a third party (CP) was consulted in the event an agreement could not be reached.

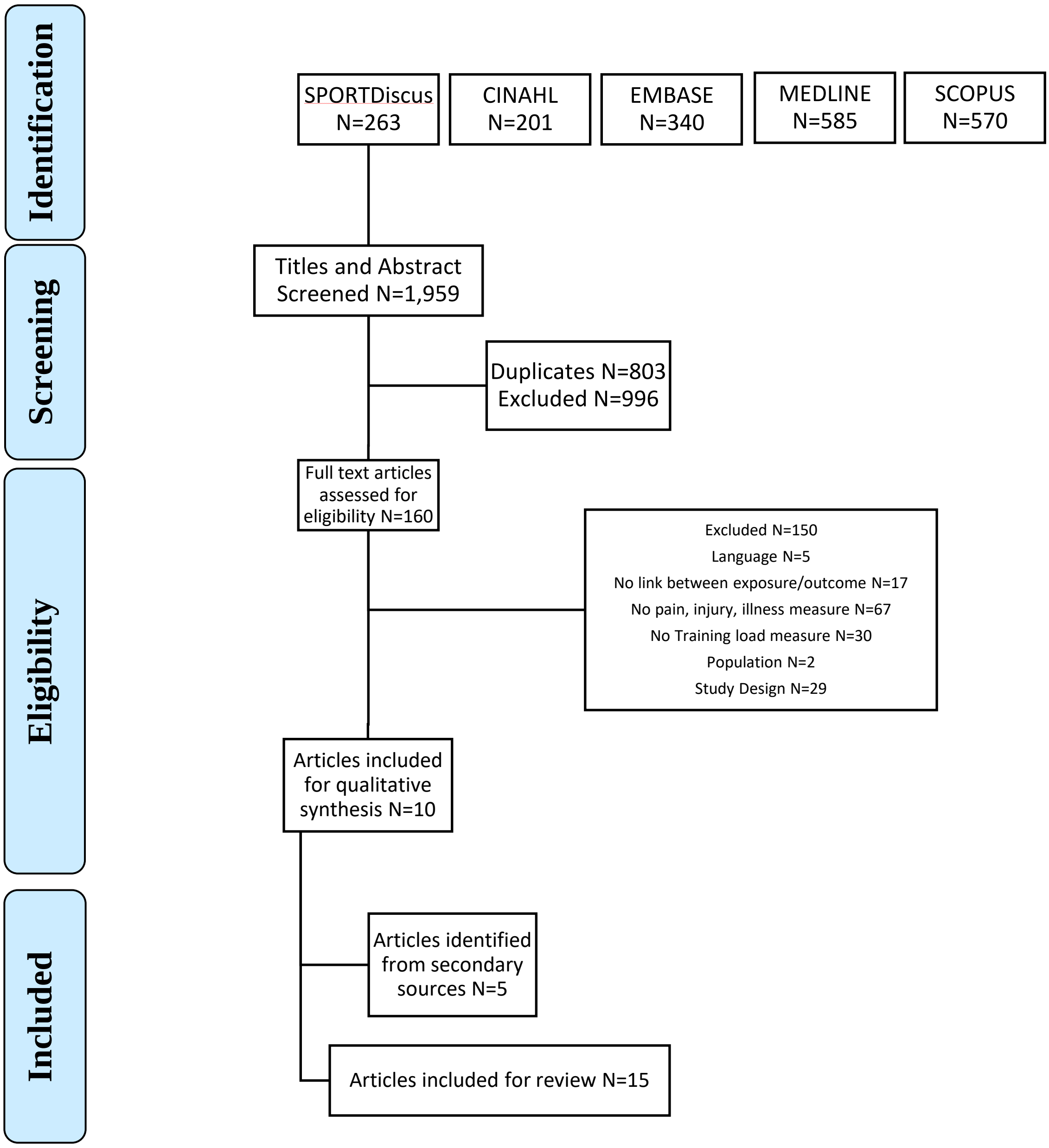

Figure 2-1 Preferred Reporting Items for Systematic Review flow diagram representing the systematic search process.

2.4 Results

An online systematic search retrieved 1,959 articles across five databases, 803 of which were duplicates. Initial screening of titles and abstracts excluded 996 articles, leaving 160 full text articles to be assessed. The original database search uncovered 10 articles which met the inclusion criteria, with a further 5 articles being included from secondary sources. A total of 15 articles were included for review: 5 cohort and 10 cross-sectional study designs. An outcome of pain was the most explored condition (N=12), with injury (N=2) and illness (N=1) making up the remainder of the articles. **Table 2-2** summarises the results.

2.4.1 Critical Appraisal

The overall study quality was poor, with ten of the fifteen studies scoring ≥3 in the "no" or "unclear" categories (Capaci *et al.,* 2002; Krüger *et al.,* 2012; Tate *et al.,* 2012; Walker *et al.,* 2012; Harrington *et al.,* 2014; Ristolainen *et al.,* 2014; de Almeida *et al.,* 2015; Hellard *et al.,* 2015; Martins *et al.,* 2018; Tomar and Allen, 2019). Tessaro *et al.,* (2017) was the only study to receive a positive appraisal in all eight categories, while Krüger *et al.,* (2012) had the most "no" or "unclear" responses. A consistent weakness of all the studies was related to managing confounding factors. Twelve studies identified confounding factors, but only six (Capaci *et al.,* 2002; Tate *et al.,* 2012; Walker *et al.,* 2012; Harrington *et al.,* 2014; Hellard *et al.,* 2015; Martins *et al.,* 2018) outlined a strategy to manage them. Strategies included excluding participants who participated in additional sports or who had a previous surgery in an area under consideration and may have impacted study outcomes. In the cross-sectional studies, all reported sufficient detail regarding the population and setting. The exposure and outcome were measured in a valid and reliable way in 27% and 67% of all studies. This highlighted that the method of monitoring exposure was a common limitation within the study design, most of which relied on self-reported questionnaires. Statistical analyses were conducted in an appropriate manner in 86.7% of all studies. **Table 2-1** presents the JBI quality checklist information for each of the included studies.

2.4.2 Participant Demographics

A total of 1510 swimmers were included in the review with 10.5% of them categorised as elite (Hidalgo-Lozano *et al.,* 2012; Hidalgo-Lozano *et al.,* 2013; Hellard *et al.,* 2015; Martins *et al.,* 2018), 35.9% club level (Capaci *et al.,* 2002; Su *et al.,* 2004; Tate *et al.,* 2012; Walker *et al.,* 2012; Tessaro *et al.,* 2017; Cejudo *et al.,* 2019), 23.1% masters level (Krüger *et al.,* 2012; Tate *et al.,* 2012), 3.2% collegiate (Harrington *et al.,* 2014; Tomar and Allen 2019) and 27.2% national level (Ristolainen *et al.,* 2014; de Almeida *et al.,* 2015). The mean age range was 8-49.5 years, with two studies not reporting age for one group, or all of their participants' demographics (Tate *et al.,* 2012; Tomar and Allen, 2019). A variety of descriptors outlining participant's level of ability, including average training distance and hours per week were recorded in the majority of circumstances. Large range training volumes in kilometres per week (25 - 58 km/week) or hours per week (4 – 24 hours/week) were reported. Ten studies reported results from both male and female participants, while one study reported solely on male participants (Capaci *et al.,* 2002) and two studies on female participants (Tate *et al.,* 2012; Harrington *et al.,* 2014). Two studies did not disclose the gender balance of their participants (Walker *et al.,* 2012; Hidalgo-Lozano *et al.,* 2013).

Table 2-1 Critical Appraisal using the JBI checklist for cohort and cross-sectional studies.

Cohort	**Were the two groups similar and recruited from the same population?**	**Were the exposures measured similarly to assign people to both exposed and unexposed groups?**	**Was the exposure measured in a valid and reliable way?**	**Were confounding factors identified?**	**Were strategies to deal with confounding factors stated?**	**Were the groups/participants free of the outcome at the start of the study (or at the moment of exposure)?**	**Were the outcomes measured in a valid and reliable way?**	**Was the follow up time reported and sufficient to be long enough for outcomes to occur?**	**Was follow up complete, and if not, were the reasons to loss to follow up described and explored?**	**Were strategies to address incomplete follow up utilised?**	**Was appropriate statistical analysis used?**
(Tomar and Allen 2019)	Y	NA	Y	N	N	UC	Y	N	UC	UC	Y
(Walker *et al.*, 2012)	N	NA	N	Y	N	Y	Y	Y	Y	Y	Y
(Hellard *et al.*, 2015)	Y	NA	Y	Y	N	UC	Y	Y	UC	Y	Y
(Ristolainen *et al.*, 2014)	Y	NA	N	Y	Y	UC	Y	N	N	N	Y
(Krüger *et al.*, 2012)	Y	NA	N	N	N	UC	N	N	N	N	Y

Cross-Sectional	Were the criteria for inclusion in the sample clearly defined?	Were the study subjects and the setting described in detail?	Was the exposure measured in a valid and reliable way?	Were objective, standard criteria used for measurement of the condition?	Were confounding factors identified?	Were strategies to deal with confounding factors stated?	Were the outcomes measured in a valid and reliable way?	Was appropriate statistical analysis used?
(Martins *et al.*, 2018)	N	Y	Y	Y	N	N	N	Y
(de Almeida *et al.*, 2015)	Y	Y	N	N	N	N	N	Y
(Harrington *et al.*, 2014)	Y	Y	N	Y	N	N	Y	Y
(Tate *et al.*, 2012)	N	Y	N	Y	N	N	Y	Y
(Tessaro *et al.*, 2017)	Y	Y	Y	Y	Y	Y	Y	Y
(Hidalgo-Lozano *et al.*, 2012)	Y	Y	N	Y	Y	Y	Y	N
(Hidalgo-Lozano *et al.*, 2013)	Y	Y	N	Y	Y	Y	Y	Y
(Cejudo *et al.*, 2019)	Y	Y	N	Y	Y	Y	N	Y
(Capaci *et al.*, 2002)	N	Y	N	Y	N	N	N	Y
(Su *et al.*, 2004)	Y	Y	UC	Y	Y	Y	Y	N

Y = Yes, N = No, UC= Unclear N = Not Applicable

2.4.3 Operational Outcome Definition

The definition of pain, injury and illness varied amongst the fifteen studies. Of the two injury based studies, one of the definitions required a restriction of training (Tomar and Allen 2019), with the second specifically focused on overuse injuries, outlining a definition with elements of time loss and MA criteria (Ristolainen *et al.,* 2014). Regarding illness, the definition provided was based on Fricker *et al.,* (2005) and required the athlete to have received MA and time loss away from training. Out of the three categories of pain, injury and illness, studies investigating pain used the most diverse definitions. Three studies utilised a Numerical Pain Rating Scale (NPRS) (Hidalgo-Lozano *et al.,* 2012; Hidalgo-Lozano *et al.,* 2013; Tessaro *et al.,* 2017) with two reporting a set threshold of 4/10 on the NPRS to denote significant pain (Hidalgo-Lozano *et al.,* 2012; Hidalgo-Lozano *et al.,* 2013). The remaining study did not provide a set threshold on the scale (Tessaro *et al.,* 2017). Subscales from the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire and the Penn Shoulder Score (PSS) were combined to form the Sports and Symptom Survey Form utilised in two of the studies (Tate *et al.,* 2012; Harrington *et al.,* 2014). A set injury definition (McMaster WC *et al.* 1998) was used in two studies (Walker *et al.,* 2012; Cejudo *et al.,* 2019) which classified significant interfering shoulder pain (SIP) as a pain that interfered with training or competition, or progression in training and caused a cessation or modification of training or racing. A 1-5 pain scale was used in one study which indicated if the participant had no pain at level 1, up to pain preventing competitive swimming at level 5 (Capaci *et al.,* 2002). A mixed MA/time loss definition was employed in one study (de Almeida *et al.,* 2015), which referred to the consensus statement of Fuller (2006). A clinical assessment or screening process was conducted in two of the studies (Su *et al.,* 2004; Hidalgo-Lozano *et al.,* 2013) in conjunction with a set definition. Martins *et al.,* (2018) did not provide a definition of pain but highlighted that a questionnaire which evaluated the occurrence of pain was administered. Pain was present if the responder answered “yes” to a question on the presence of pain. Similarly, Krüger *et al.,* (2012) did not provide a set definition of pain but outlined that a retrospective questionnaire was used to determine the incidence of shoulder pain over a three-year period.

2.4.4 Monitoring Training Load

All the papers included for review collected external training load, using one or more variations. Session duration was the most commonly used unit of load. Nine out of fifteen studies employed this approach and was most often recorded as hours per week. This was closely followed by session distance, which was collected in eight studies, most of which was recorded as kilometres per week. Finally, session frequency was collected in five studies, with practices per week being most frequent. Two out of fifteen studies collected internal training load, with session intensity recorded through the use of sRPE (Tomar and Allen 2019) and blood lactate concentration (Hellard *et al.*, 2015). The method of collecting training load data was reported well in the majority of cases. However, one study (Hidalgo-Lozano *et al.*, 2012) collected training load as hours/week but did not report the method of data collection. Another study reported how the internal training load (blood lactate profile) was collected, but not the external training load measure (meters/week) (Hellard *et al.*, 2015). Training load data were collected subjectively through athlete self-reporting, generally through the use of a questionnaire. A third party was used to submit the data in two instances (Walker *et al.*, 2012; Tessaro *et al.*, 2017), namely the coach, clinician or research assistant.

2.4.5 Relationship between Training Load and Pain, Injury, and Illness

Eleven of the fifteen studies stated no statistically significant differences or associations between a measurement of training load and the outcome reported (Su *et al.*, 2004; Hidalgo-Lozano *et al.*, 2012; Tate *et al.*, 2012; Walker *et al.*, 2012; Hidalgo-Lozano *et al.*, 2013; Harrington *et al.*, 2014; de Almeida *et al.*, 2015; Tessaro *et al.*, 2017; Martins *et al.*, 2018; Cejudo *et al.*, 2019; Tomar and Allen, 2019). In the remaining studies, a statistically significant difference was reported between training load and injury (Ristolainen *et al.*, 2014) and pain (Capaci *et al.*, 2002). A positive association was seen between training load and illness (Hellard *et al.*, 2015), while a negative association was reported between training load and pain (Krüger *et al.*, 2012).

Two out of twelve studies found a statistical difference or association between training load and pain (Capaci *et al.*, 2002; Krüger *et al.*, 2012). Both studies reported contrasting conclusions with Capaci *et al.*, (Capaci *et al.*, 2002) highlighting that swimmers experiencing musculoskeletal pain reported swimming significantly (p <0.05) more hours per week than those without pain (8.86±1.25 vs 8.00±1.06 hours/week). This finding contradicted Krüger *et al.*, (2012) who suggested that those swimming lower volumes (0-4,999 meters/week), were 2.8 times more likely to develop shoulder pain. The remaining ten studies that reported on the relationship between training load and pain showed no significant difference or association.

Two studies investigated the relationship between training load and injury (Ristolainen *et al.,* 2014; Tomar and Allen, 2019). Ristolainen *et al.,* (2014) found a positive relationship, and reported that the mean number of kilometres swam per year was significantly higher in injured swimmers, when compared to non-injured swimmers (1612 km/year vs. 1380 km/year, p=0.04). The second study reported no significant relationship between training load (r = -0.35), training monotony (r = 0.62), training strain (r = -0.12) or Acute/Chronic Workload Ratio (ACWR) (r = 0.08) and the incidence of injury (Tomar and Allen 2019).

The risk of illness (i.e. Upper Respiratory Tract and Pulmonary Infections (URTPI) was significantly higher (p = 0.0244) during high load training periods, while the odds of having a URTPI was 70% and 50% higher during intensive training periods than both taper and competition periods, respectively (Hellard *et al.,* 2015). High load workouts at maximal speed (blood lactate $\geq$ 10mmo$\cdot$L^{-1}) contributed considerably to the increased risk (not specified) of URTPI. While the authors highlighted that the risks of URTPI were higher for swimmers during the winter months, they also specified that national swimmers were generally more at risk than international level swimmers despite similarities in age and training prescription. This may be explained by a superior genetic resistance response to infection or improved athletic lifestyle management by international swimmers, or a lower training load threshold by national level swimmers (Hellard *et al.,* 2015).

Table 2-2 Summary of the included studies.

Reference (Study Design)	Population (N, gender, age)	Level of Competitiveness	Load	Method of Collection	Outcome (Definition)	Findings
Martins *et al.*, Cross-Sectional	42 Elite Swimmers 22M 20F Mean Age 22.9 (±4.4) yrs.	Swam average of 45.2 (±20) km/wk Competitive for 13.9(±6.9) years.	External: km/wk	Load: SR Outcome: SR	Pain NR	km/wk did not have any significant statistical association with the occurrence of pain (p =0.787)
Tessaro *et al.*, Cohort 12months Retrospective	197 Club Swimmers. 108M 89F Mean Age: 14.01 (± 2.12) yrs.	Swim average of 25.31 (±9.02) km/wk	External: freq/wk hr/session km/session	Load: SR/Third Party Outcome: SR	Pain NR	No statistically significant differences were found between pain and freq/wk (p =0.114), hr/session (p = 0.161), km/wk (p = 0.309).
Krüger *et al.*, Cohort 3 years Retrospective	282 Masters Swimmers. 138M 144F Mean age: 50 yrs males, 49 yrs females.	South African Masters Swimming Championship.	External: m/wk low (0-4,999) medium (5,000-11,999) high (>12,000)	Load: SR Outcome: SR	Pain NR	Low/medium training volume (OR 1.0) High Volume (OR 0.36, 95% CI 0.568 - 0.680; p =0.004)
Harrington *et al.*, Cross-Sectional	37F Collegiate Swimmers Mean Age = 19.5 (± 1.19) yrs.	NCAA Division I swim programs Swimming 18.8 hr/wk.	External: hr/wk practices/wk	Load: SR Outcome: SR	Pain DASH (>6/20 points) PSS (>4/10)	No significant difference was found in the hr/wk for the dominant (p = .77) or non-dominant arm (p = .97) in relation to presence of shoulder pain.

Walker *et al.*, Prospective Cohort 12 months	74 Club Swimmers 37M 37F Mean Age: 15 (± 3) yrs.	Swimming 8 (± 2) sessions/wk Average distance of 44 (± 15) km/wk.	External: km/wk practices/wk	Load: Third Party Outcome: SR	Pain/Injury Non-time loss/time loss SIP SSI	Swim training distance (km) was not a significant predictor of: SSI (OR, 1.0; 95%CI ,1.0,1.0), (*p* =0.11). SIP (OR, 1.0; 95%CI ,1.0,1.0), (*p* =0.07).
de Almeida *et al.*, Cross-Sectional	257 National Swimmers 140 M and 117 F Mean age M: 20.6 (± 3.7); F 19.4 (± 3.9) yrs.	Weekly distance 57.1 (± 29.9) km/wk.	External: km/wk	Load: SR Outcome: SR	Pain/Injury MA/Time loss	No significant difference found for weekly distance in km (*p* =0.61) when those with and without pain were compared.
Tate *et al.* Cross-Sectional	42 F Youth Swimmers Age: 8-11 yrs	Swimming 6.9 (± 2.4) hr/wk.	External: hr/wk	Load: SR Outcome: SR	Pain PSS (>2/10)	There were no significant differences in: Time swam (yrs) (*p* =0.74) Time swam/wk (hr) (*p* =0.18) Time swam/yr (hrs) (*p* =0.54)
	43F Youth Swimmers Age:12-14 yrs	Swimming 10.1 (± 4.3) hr/wk.			DASH (>6/20) PSS (>4/10)	There were no significant differences in: Time swam (yrs) (*p* =0.29) Time swam/wk (hr) (*p* =0.56) Time swam/yr (hrs) (*p* =0.69)
	84 F High-School Swimmers Age:15-19 yrs	Swimming 16.1 (± 6.0) hr/wk.				There were no significant differences in: Time swam (yrs) (*p* =0.01) Time swam/wk (hr) (*p* =0.71) Time swam/yr (hrs) (*p* =0.60)
	67F Masters swimmers	Swimming 4.0 (± 1.7) hr/wk.				There were no significant differences in: Time swam (yrs) (*p* =0.13) Time swam/wk (hr) (*p* =0.06) Time swam/yr (hrs) (*p* =0.02)

Capaci *et al.*, Cross-Sectional	38M Club Swimmers Mean age: 14.44 (± 2.4) yrs	Average training hr/wk: 8.52 (± 1.54)	External: Average training hr/wk	Load: SR Outcome: SR	Pain Non-time loss/time loss Classified into categories (1-5)	Swimmers with pain swam 8.86 (±1.25) hr/wk which was significantly different to swimmers without pain who swam 8.00 (±1.06) hr/wk.
Su *et al.* Cross-Sectional	40 Club Swimmers. 19M 21F 18 and 35 yrs.	Competitive experience >5years. Training Schedule >2 days and 10km/wk.	External: hr/wk km/session	Load: SR Outcome: SR/CA	Pain Non-time loss/CA Phase II or III - Neer and Welsh swimmer's shoulder grading system.	There were no significant differences in practice duration (*p* =0.80) and practice distance (*p* =0.33) between the healthy and impingement groups.
Hidalgo-Lozano *et al.* Cross-Sectional	54 elite swimmers. 18M, 16F Age: 18-30 yrs	European and World Championship participants. Swimming 6 hours per day for 4 days per week.	External: hr/wk	Nil	Pain Pain felt in the neck-shoulder and/or arm >3 months. >4/10 NPRS.	No correlation between shoulder pain and hr/wk (*p* =0.731) was found.
Hidalgo-Lozano *et al.* Cross-Sectional	35 Elite Swimmers. Age:18-30years	Swimming >6 hrs/wk.	External: hr/wk	Load: SR Outcome: NPRS, Anatomical Chart	Pain >3months 4/10 NPRS during arm elevation. CA +ive Neers and Hawkins test.	No correlation between shoulder pain and hours training/wk (*p* =0.129).
Cejudo *et al.*,	24 Club Swimmers.	Swimming experience	External:	Load: SR	Pain	Training hours per week was not a

Cross-Sectional	15M F9 Mean age: 15.6 (±2.2) yrs.	of 6.8 (± 2.1) yrs. Training hr/wk 15.3 (±1.7).	Practice frequency hr/wk	Outcome: SR	Non-time loss/time loss SIP	distinguishing factor between those with shoulder pain and those without (*p* =0.773, d=0.30 small)
Tomar and Allen Prospective Cohort 7Weeks	12 Collegiate Swimmers	Mean weekly training load: 260.97 ± 56.33AU	External: min/session Internal: sRPE	Load: SR Outcome: Third Party	Injury Non-time loss	No significant relationship between training load (r = -0.35), monotony (r = 0.62), strain (r = -0.12), acute/chronic workload (r = 0.08) and injury.
Ristolainen *et al.* Cohort Retrospective 12 months	154 National Swimmers. 71M 83F Mean Age 18.6 (± 2.9) yrs.	Finnish Top Level. Swimming exposure of 767 (± 326) hr/yr. Active Training (years) 9.9 (± 3.1) yrs	External: km/yr hr/wk hr/yr	Load: SR Outcome: SR	Injury Overuse injury Time loss/MA	Injured swimmers had swum significantly more than non-injured swimmers during the past 12 months (*p* =0.04) The mean number of kilometres swam was higher in swimmers with at least one joint injury compared to swimmers without such an injury (*p* =0.03)
Hellard *et al.* Prospective Cohort 4 years	28 elite swimmers. 14M 14F Age 16-30yrs	National Championship participants. >9 sessions/wk (including dryland conditioning. High motivation in the past 6 months.	External: m/wk Internal: Blood Lactate Profile	Load: External - NR Internal - Third Party Outcome: SR	Illness (URTPI) MA/Time loss	The risk of URTPI was significantly increased with high load training (OR 1.10; 95% CI, 1.01–1.19), (*p* =0.0244). The odds of having an URTPI was 70% lower during taper (OR .30; 95% CI, 0.13–0.70), (*p* =0.0054) 50% lower during competition (OR 0.50; 95% CI, 0.23–1.06), (*p* =0.0686) than during periods of intensive training.

2.5 Discussion

The aim of this systematic review was to investigate the relationship between training load and pain, injury, or illness in competitive swimmers. A clear lack of consistency within the findings was evident, with conflicting results being presented and many methodological limitations preventing accurate comparison of results. This lack of consistent reporting prevented a meta-analysis of the results from being conducted. There is no clear evidence of a relationship between training load and pain, with the majority of studies reporting no statistical difference or association between those with pain and their exposure to external training loads. This link would require further investigation using prospective study designs and coupling of both internal and external training load to get a more accurate representation. There is limited evidence to suggest a relationship between training load and injury with one study finding swimming more distance (km) in the past year increased the risk of injury (Ristolainen *et al.,* 2014). This relationship would need to be investigated further with both internal and external training loads being used to accurately measure training load. There is also limited evidence for the relationship between training load and illness based on the work of Hellard *et al.,* (2015); however, this needs further rigorous investigation in multiple swimming populations.

2.5.1 Participant Demographics

The variability in findings is in keeping with the premise that pain, injury and illness are complex and multifactorial (Wanivenhaus *et al.,* 2012; Schwellnus *et al.,* 2016), with no single variable predicting maladaptation (Soligard *et al.,* 2016). It is well documented that factors including chronological age, training age, injury history and physical capacity can impact an athlete's training response (Gabbett 2016). Chronological age and training experience were two factors which varied greatly within this review. Two studies found significant, but contrasting findings between training load and pain in this review (Capaci *et al.,* 2002; Krüger *et al.,* 2012). Capaci *et al.,* (2002) focused on male competitive swimmers with a young mean age (14.44 ± 2.4 years) and found swimming more hours per week influenced the presence of pain. This contrasts with Krüger *et al.,* (2012), who solely focused on masters level swimmers (mean age 49.6 ± 12.29 years) and found swimming lower volumes per week to be a risk factor for shoulder pain. This may be explained by the considerable changes experienced with aging, i.e. loss of muscle mass, strength and function, alterations such as sarcopenia (Volpi *et al.,* 2004). This age related decline also extends to a loss of tendon stiffness, resulting in decreased force transfer capabilities (Reeves *et al.,* 2006). The rotator cuff is among the most common clinical tendon problems for the aging population (McCarthy and Hannafin 2014), with the risk of having a full thickness tear being 2.69 times greater in older adults than adults 10 years their junior (Fehringer *et al.,* 2008). Older athletes face an accumulation of residual injuries which may limit their training volume and intensity, thus causing a reduction in training adaptations (Foster *et al.,* 2007). This can result in a cyclical pattern of reduced ability to train, causing a decreased training load and an increased susceptibility to musculoskeletal injuries. This is supported by Tate *et al.,* (2012) where the masters population swam less time per week than any other group within the study. The presence of pain at lower volumes may be a by-product of the '*injury prevention paradox'*, where higher loads are thought to have a protective effect against injury (Gabbett 2016). Masters athletes, swimming at lower loads, may be more susceptible to injury as they never reach the desired threshold of training to provide a protective effect. The reported modifications in training volume with age are thought to be as a result of changes in stroke biomechanics. It has been reported that older swimmers have altered stroke biomechanics when compared with elite swimmers. This is understood to be driven by lower values of stroke length which may be explained by lower mechanical power and muscle strength (Ferreira *et al.,* 2016). The masters population, in an effort to reduce the effects of aging and to break the cyclical pattern of load related injuries should focus on appropriate recovery strategies between sessions, increased resistance training and complementary cross-training sessions (Foster *et al.,* 2007).

The level of a swimmer is also deemed to be a contributing factor to their risk of injury. Tate *et al.,* (2012) explored the presence of shoulder pain across the lifespan of a swimmer. They found that as the competitive level increased, so did the training exposure in hours per week, up until 15-19 years old, after which it dropped off when entering masters level swimming. This study found that high school swimmers were most symptomatic and those swimmers with shoulder pain had significantly more swimming exposure than those without shoulder pain (1.5±1.14 years, p = 0.01). However, this finding was not replicated in acute swimming load (hours/week). Unfortunately, this study did not include a collegiate swimming group within the study design, leaving a gap between those in high-school and masters level. Typically, it is thought that the collegiate swimming population are at increased risk of injury in the first twelve months of joining a varsity swim team (Wolf *et al.,* 2009). This was a key finding by Wolf *et al.,* (2009) who reported the highest number of injuries during the first year of eligibility, followed by a substantial drop off in the subsequent years. In this study, male and female swimmers had a mean number of injuries of 1.21 and 1.19 in their freshman year compared to 0.71 and 0.46 in their senior year (Wolf *et al.,* 2009). This is likely due to the transition from high-school or club swimming coupled with a sudden increase in training demands, followed by acclimatisation in those that do not drop out of the sport. Of the two collegiate swimming populations included in this review, one was not a true representation of a high level varsity programme due to the low loads presented (Tomar and Allen 2019), while the second was a National Collegiate Athletic Association (NCAA) Division I population, swimming 18.8 hours/week (Harrington *et al.,* 2014). Neither study found a statistically significant relationship between training load and pain or injury, however, the stage of collegiate swimming was not investigated in either study. This could mean that the population investigated had become acclimatised to such a training demand or those who experience pain or injury during the transition from high-school to college do not continue to compete at that level (Wolf *et al.*, 2009; Harrington *et al.*, 2014).

In an elite population, Hellard *et al.,* (2015) found a higher risk of pathology in national level swimmers compared to international level swimmers. Coaches should consider the level of individual swimmers, understanding that swimmers of lower ability may be more susceptible than their counterparts. National level swimmers may be of a lower training age or capacity, causing a decreased resistance to illness in comparison to their international level counterparts (Hellard *et al.,* 2015). More mature international level athletes may also manage the training lifestyle demands better than their national level peers. Coaches should ensure that the swimmers' level is considered and modified for when planning training loads and session intensity.

2.5.2 Operational Outcome Definition

It has been clearly reported that inconsistencies in methodological approach and definitions can create significant variations in findings (Fuller 2006). While a number of consensus statements have provided clarity in the use of standard terminology, disparities in definitions stem from the specific sporting context for which the statements are developed (Bahr *et al.,* 2020). A total of four (Tessaro *et al.,* 2017; Martins *et al.,* 2018; Cejudo *et al.,* 2019; Tomar and Allen 2019) of the included studies were published after the release of the 2016 FINA consensus statement with none of them making reference to the guidelines and recommendations. A host of outcome definitions were used amongst the 15 studies included in this systematic review, showing large inconsistencies that may be a factor in the conflicting nature of the findings. Many of the definitions reported an element of time loss from the sport, a restriction in training or the need to have sought MA. While the use of this terminology is appropriate and common place in many sports, they have limitations when applied to sports such as swimming, where few traditional time loss injuries occur (Bahr 2009). As many swimmers tend to train in the presence of pain (Hibberd and Myers 2013), using a traditional time loss injury definition may mask and under-report the true impact of such pain/injuries (Bahr 2009). Successful injury and illness prevention protocols rely on the correct categorisation of surveillance data (Palmer-Green *et al.,* 2013). The consensus statement from FINA on injury and illness reporting published in 2016, provides a clear framework to be implemented in such cases (Mountjoy *et al.,* 2016). Though this consensus statement provides clarity of the use of set definitions for injury, illness, time loss and MA classifications, it also highlighted the need to prospectively monitor symptoms and complaints through the use of The Oslo Sports Trauma Research Centre (OSTRC) questionnaire. The OSTRC questionnaire has been validated in swimming, and can be implemented longitudinally to record medical conditions that include complaints not leading to absence from the sport (Mountjoy *et al.*, 2016).

While the development of a sport specific consensus statement is a positive step towards consistency in reporting, the optimisation of the dissemination procedure and uptake of the key principles is a crucial aspect of the process. Even though researchers working within a specific related field may be aware of such consensus statements, those working at a practical level may have limited knowledge. The utilisation of consensus statements can be determined by the perception of relevance within a set period of time as developments of these concepts are rapidly evolving. As consensus statements can take 12-18 months to develop, the time elapsed between evidence discussion and collation, and recommendations published is crucial (Kwong *et al.,* 2016). Developing, disseminating and assimilating consensus statements in a timely manner is essential to their effectiveness and relevance (Kwong *et al.,* 2016). Consensus statements might benefit from undergoing a "knowledge management" process. Knowledge management is the process of simplifying and improving the creation, sharing and distribution of knowledge within a system (Gasik 2011). A link between those that develop the consensus statement, and the relevant National Governing Body (NGB) should be formed as part of the dissemination process. Providing clear educational strategies to the NGB should be a cornerstone of the dissemination process, allowing the key information to be communicated and understood at the practitioner level.

2.5.3 Relationship between Training Load and Pain

The relationship between training load and pain was evaluated in twelve of the fifteen studies included in this review. A total of two studies found statistically significant differences or associations between a measure of training load and pain (Capaci *et al.,* 2002; Krüger *et al.,* 2012). A large percentage (60.5%) of competitive male swimmers reported musculoskeletal pain through the use of a questionnaire (Capaci *et al.,* 2002). Those who experienced pain spent more time training (training history (years) or training hours per week), than those without pain. This suggests that those with a longer training history, and who swim more hours per week, have an increased chance of experiencing musculoskeletal pain. This finding challenges the traditional high-volume approach which spurs the quantity versus quality debate. Nugent *et al.,* (2017) discussed this concept with expert swimming coaches. Coaches tended to defend the high-volume swimming approach, particularly in youth swimming, as it promotes a large aerobic base and aids in technical development. However, they clarified that this should transition to a quality or more intensity based training system as the swimmer improves (Nugent *et al.,* 2017). This finding is also in contradiction with the theory that training load can have a protective effect (Gabbett 2016); however, the age of those with pain was relatively young (14.78±1.56 years). A swimmer's ability to acclimatise and develop a robustness to higher training thresholds may be impacted by maturation (Difiori 2002), and therefore training hours should be gradually increased and adjusted for the pubertal development of the athlete (Corso 2018).

While maturation was not investigated in the current review, and research on the impact of maturation on injury is unclear (Bowerman *et al.,* 2014), coaches should be cognisant of the effects of an adolescent growth spurt on their training ability (Corso 2018). A similar youth age category was investigated in four studies (Tate *et al.,* 2012; Walker *et al.,* 2012; Tessaro *et al.,* 2017; Cejudo *et al.,* 2019). All four studies found no statistically significant relationship between pain and training load when hours per week, kilometres per week or frequency of sessions per week were examined. Su *et al.,* (2004) reported no difference in healthy swimmers compared with swimmers with shoulder pain (7.6±5.3 vs. 8.1±5.1 hours/week, p = 0.80) and (3.3±1.1 vs. 3.0±0.9 km/session, p = 0.33) respectively. Swim training distance was not a significant predictor of SIP or significant shoulder injury (SSI) (SIP: OR 1.0, 95% CI 1.0 – 1.0; p = 0.07 / SSI: OR 1.0, 95% CI 1.0 – 1.0; p =0.11) (Walker *et al.*, 2012). A similar finding reported no statistically significant difference between pain and weekly volume (p =0.309) (Tessaro *et al.*, 2017). Training hours/week showed no difference in those with and without pain across a number of age groups (8-11 years, p =0.18; 12-14 years, p =0.56; 15-19 years, p = 0.71; masters, p = 0.06).

Where hours per week were monitored, 12-19 year-old swimmers were training approximately 9-16 hours per week (Tate *et al.*, 2012). In youth swimming, training capacity needs to be carefully developed as their technical stroke mechanics improve. Technical aspects such as changing from unilateral to bilateral breathing may be improving, resulting in an increased risk of shoulder pain as they develop (Tate *et al.*, 2012). In populations ranging in age from 18-30 years old, the training demand typically increased, with five studies reporting average training load ranges of 18.8 - 26.8 (±4.8) hours per week, or 45 (±20) - 57.1 (±29.9) km/week. No difference was found in any of the studies for those with and without pain. These increased training loads suggest that the external training load prescribed increases with age, which is in agreement with Feijen, Tate, Kuppens, Claes, *et al.*, (2020). However, the subsequent lack of increased pain suggests that as the athlete ages, their ability to tolerate increased external training loads is improved. Another reason may be those athletes that do not experience pain are more likely to remain in the sport for longer periods. By tracking external training load (km/session or hr/week) alone, these studies may have been unable to quantify the individual response to external training load, and thus a major risk factor for musculoskeletal pain may not have been detected.

Krüger *et al.*, (2012) was the only study to find a negative association between training load and musculoskeletal pain. While the reported incidence of pain (62.4%) was similar to that of Capaci *et al.*, (2002), the population and training load measure were different. It was found that the volume of training in meters/week was negatively associated with shoulder pain, meaning those that swam a lower volume (0-4,999 meters/week) were 2.8 times more likely to develop shoulder pain than those that swam a higher volume (≥12,000 meters/week). These findings contrasted with the popular opinion that a swimmer's pain is directly proportional to training volume (Contreras Fernandez *et al.*, 2012). While the age of this population could be a significant factor in this finding as discussed in section 4.1, there is another possible explanation. This finding could also be explained by the injury prevention paradox which highlights that low load can render an athlete less prepared and more susceptible to injury (Gabbett 2016). The concept stipulates that excessively high loads may be inappropriate for individual athletes and can increase the risk of injury and illness. However, loads that are not high enough can also create an element of fragility within the athletes' ability to tolerate load and have the same outcome. This concept reinforces the idea that training loads are not high or low but are appropriate or inappropriate for a specific individual. Coaches need to consider all the individual elements when planning appropriate loads to ensure a reduced risk of pain, injury and illness (Halson 2014).

2.5.4 Relationship between Training Load and Injury

The relationship between training load and injury was assessed in two of the included studies. The studies reported contrasting findings with one (Ristolainen *et al.,* 2014) presenting the finding that injured swimmers had swum significantly more than non-injured swimmers in the past 12 months (p = 0.04). The second study (Tomar and Allen 2019) stated that no association between measures of total training load (sRPE), training monotony, strain or ACWR and incidence of injury was present. The populations and methods studied in both papers varied greatly. While Tomar and Allen (2019) used a common method of monitoring training load (sRPE), their population was not exposed to a rigorous training regime over a duration that is reflective of competitive swimming environments. Conversely, the population in Ristolainen *et al.,* (2014) was an elite group of swimmers. However, the retrospective study design, coupled with a twelve-month recall period, the measurement of external training load and no quantification of internal training load means less confidence may be placed on the results.

2.5.5 Relationship between Training Load and Illness

The relationship between training load and illness was investigated in one study meeting the required inclusion and exclusion criteria. The study utilised a prospective cohort design where training loads and illness was logged over a four-year period (Hellard *et al.,* 2015). The population observed were elite level swimmers, with both internal and external training loads being monitored. Training load was quantified in meters per week at each intensity determined by a blood lactate step test detailed by Mujika *et al.,* (1996). Findings showed a positive relationship between training loads and illness with periods of high training loads (OR 1.10, 95% CI 1.01 – 1.19; p = 0.0244) increasing the odds of illness by 50-70%. While this single study presents limited evidence, it does concur with the review of Drew and Finch (2016) who summated that the relationship between training load and illness was found to be moderate. The review found a positive relationship in sports such as speed skating, Australian football, soccer and rugby league, with no relationship in an elite running population (Drew and Finch 2016).

2.5.6 Monitoring Training Load

The studies included in this systematic review relied heavily on the use of self-reported data collected retrospectively through the use of questionnaires. This data is dependent on the athlete's ability to recall and report their individual training data accurately (Black *et al.,* 2016). Previous research has shown that quantifying exercise dosage from data collected by questionnaire may be considered as inadequate (Borresen and Lambert 2006), particularly with retrospective questionnaires, as the longer the recall period the less accurate the reported estimates (Kjellsson *et al.,* 2014). The majority of the retrospective studies used a twelve-month recall period (Walker *et al.,* 2012; Ristolainen *et al.,* 2014; Tessaro *et al.,* 2017), with one spanning a three-year period (Krüger *et al.,* 2012). Previous research has shown a twelve-month recall to be sufficient method of collecting data (Mukherjee, 2015). However, in a study comparing retrospective and prospective injury surveillance data, perfect agreement between the two methods was found when a simple yes or no answer was required. The accuracy of recall was severely diminished (approx. 40%) when specific details were required (Gabbe 2003). This shows that the use of self-reported retrospective data for establishing patterns in sport should be avoided when detailed information is needed.

The relationship between training load and pain was evaluated using external training load in all twelve relevant studies. Of the two studies examining the relationship between training load and injury, one utilised a measure of external training load, with the second study reporting both internal and external training load. Finally, the relationship between training load and illness was assessed using both internal and external training load. The results showed that session duration (hours/week) was the most widely used external training load measure with swimming durations of 4.0 (± 1.7) - 24 hours/week and was closely followed by distance per session (km). An external training load such as hours/week should be carefully implemented particularly in an advanced training environment. Beginner and intermediate athletes can focus on increases in training time to good effect; however, once a training programme has plateaued, any further increase in training hours can become unproductive resulting in session intensity being manipulated in order to achieve a training effect (Friel 2018). Monitoring training distance (km/week) can also cause issues as the swim load measure cannot be extrapolated to other cross-training modalities such as resistance training. This leads to multiple measures of load being collected but unable to be combined or aspects of the training programme not being monitored at all. Another limitation of the exclusive use of external training load methods is that it does not accurately capture the athletes' individual response to the training dose and therefore internal training load needs to be combined with external load to provide greater insight to training stress (Bourdon *et al.*, 2017). The use of sRPE has become one of the most commonly used measures of intensity in team sports. Session RPE, combined with session duration can provide an integrated training load measure capturing an athlete's external load and their individual response to it. An additional benefit of this approach is the ability to monitor sRPE globally across a training programme such as resistance training and cross training, allowing for a holistic monitoring approach to all aspects of the programme (Williams *et al.* 2017).

All but two (Hellard *et al.*, 2015; Tomar and Allen, 2019) of the included studies used external training load exclusively as a means of quantifying training load. Bourdon *et al.*, (2017) summated that an integrated approach to training load monitoring is important as no single marker of an athletes response to load can consistently predict maladaptation (Soligard *et al.*, 2016). Therefore internal and external load should be monitored in combination to provide greater insight (Bourdon *et al.*, 2017). Tomar and Allen (2019) and Hellard *et al.*, (2015) both used a combination of internal and external training load in line with current recommendations. Rating of Perceived Exertion was collected as a measure of internal training load and was monitored in conjunction with session duration by Tomar and Allen (2019). The data was analysed to provide measures of training load, monotony and strain (Foster, 1998; Foster *et al.*, 2001) as well as ACWR, as outlined by Gabbett *et al.*, (2016). These training parameters were employed to find the relationship with incidence of injury in a university swimming population over a seven-week period. No significant relationship was found between training load, strain and monotony or ACWR and the incidence of injury in this population, which contradicts earlier studies in a variety of sports (Anderson *et al.*, 2003; Gabbett and Jenkins, 2011; Hulin *et al.*, 2014). The lack of significant association could be due to the observational period being relatively short (seven weeks) or the low training load experienced by the group. A weekly mean training load of 260±56.33 Arbitrary Units (AU) appears to be relatively low, compared to other competitive sporting populations. The mean weekly ACWR was 0.94±.53 with a peak of 1.03. These ACWR are within acceptable risk ranges according to Gabbett *et al.,* (2016) and combined with the low training load are unlikely to stress the athletes beyond their capacity.

Tomar and Allen (2019) was the only study in the review to use the sRPE method (Foster, 1998; Foster *et al.,* 2001) of monitoring training load. This is in contrast to Eckard *et al.,* (2018) whose multisport review of fifty-seven studies found twenty-two (39%) of those studies measured internal training load using the sRPE method. A similar multisport review conducted by Drew and Finch (2016) found that twenty-five out of a total of thirty-five (71%) studies utilised sRPE. The significant difference between the frequency of sRPE use in swim specific research and a multisport research highlight how underutilised this method of monitoring training load is in competitive swimming research.

Research surrounding training load has evolved to understand that neither high or low training load can be considered solely at fault for pain, injury and illness (Gabbett 2016). It is more central to consider the appropriate amount of training load or rate of load application for that individual athlete in order to maximise performance while simultaneously limiting maladaptation (Gabbett 2019; Griffin *et al.* 2020a). Research into monitoring changes in training load originated with Banister's "Training Stress Balance" method and developed into the ACWR in recent years (Griffin *et al.,* 2020a). The ACWR is designed to balance the most recent training loads (acute) with the athletes' recent history of training load (chronic) in an effort to predict how fit or fatigued they are (Hulin *et al.,* 2014). The ACWR has been shown to quantify changes in training load by presenting a numerical range where training load is said to be at the "sweet spot" and injury risk is reduced (0.8 – 1.3) (Gabbett 2016). It is important to note that this sweet spot numerical range can vary per population and individual physical capacities with team sports citing a ACWR sweet spot of 1.00-1.25 (Malone *et al.,* 2017) and 0.85-1.35 (Hulin *et al.,* 2014). This is crucial to an individual athlete sport like swimming where a squad "sweet spot" range cannot be relied upon and each individual's ACWR needs to be quantified. While a number of studies have used this method to good effect in a variety of sports (Hulin *et al.,* 2014; Carey *et al.,* 2017; Delecroix *et al.,* 2018; Bowen *et al.,* 2019), the most accurate method of calculating the ACWR is contentious (Menaspà 2017; Williams *et al.* 2017). A recent review by Griffin *et al.,* (2020a) investigated the association between ACWR and injury in team sports. The review concluded that ACWR is associated with non-contact injuries which is a key finding for sports like swimming. The review also highlighted the key differences between the calculation of ACWR using the rolling average model and the exponentially weighted moving average (EWMA) model. The rolling average model divides the acute workload by the chronic workload whereas the EWMA model accounts for the decaying nature of fitness and fatigue by applying a greater weight to the most recent loads (Griffin *et al.,* 2020a). While the rolling average model has received more substantial attention in team sport research, the review states that EWMA may be a more sensitive measure (Griffin *et al.,* 2020a). The applicability of these models warrants further investigation, particularly in an elite swimming population where current research is severely limited.

Hellard *et al.,* (2015) quantified intensity levels where blood lactate concentration was mapped throughout a swim-specific step test (Mujika *et al.,* 1996). Session intensities were planned accordingly and in conjunction with meters per week. Low intensity training load was categorised as the mean percentage volume at intensity levels 1-3, while high intensity training was categorised at intensity levels 4 and 5. Results of the study showed the odds of illness were 50%-70% higher during intensive training periods. The risk of illness was also increased during winter months, and in national level swimmers over international level swimmers. Coaches should be aware of the increased risks of URTPI during intensive training periods and should accurately measure and programme the intensity and overall load of the sessions accordingly. The scheduling of intensive training periods should be strategic, keeping non-sport stress in mind and avoiding periods of high academic or professional responsibilities, or demanding competition calendars. This is particularly important during the winter months where the population risk of URTPI is already considerably high (Hellard *et al.,* 2015). The findings also showed that for every 10% increase in training load, a corresponding 10% increase in the risk of illness was likely, which is in agreement with current evidence that has shown very high training loads, very low loads and rapid changes in load can all contribute to illness (Schwellnus *et al.,* 2016). The findings indicate that recovery strategies during intensive training blocks should be given higher consideration than normal. This is particularly important directly after acute maximal speed sessions (blood lactate ≥10 $mmo \cdot L^{-1}$) as these sessions contributed most to increasing risk of illness. This finding is in line with general consensus that immune disturbances are associated with acute session intensity (Walsh *et al.,* 2011). A consensus statement (Walsh et al., 2011) highlighted that to maintain immune health, training programmes should involve gradual increases in volume and intensity and avoid sudden increases or spikes. Adding variety of stimuli including cross-training methods and paying particular attention to recovery and nutritional strategies are also important (Walsh et al., 2011).

2.6 Future Considerations

The ability to synthesise the data and summarise the findings is significantly restricted by study design, a variety of training load methods, large variations in population and operating definitions of pain, injury, and illness. The guidance of a consensus statement may have aided authors in collecting both internal and external training load, which in turn would have improved the strength of the results. However, as only four (Tessaro *et al.,* 2017; Martins *et al.,* 2018; Cejudo *et al.,* 2019; Tomar and Allen 2019) of the studies included in this systematic review were published after the introduction of the most recent FINA (Mountjoy *et al.,* 2016) and IOC (Schwellnus *et al.,* 2016; Soligard *et al.,* 2016) Consensus Guidelines covering load and the risk of injury and illness, their overall influence was diminished. Publication prior to 2016 reduced the likelihood of authors maintaining a high level of consensus in the operational definitions used for pain, injury, and illness, as well as the protocols used to collect that information. Nevertheless, only one of the four studies highlighted made reference to the IOC consensus statement (Tomar and Allen 2019), with none referencing the FINA consensus statement. This systematic review highlights the need to refer to these guidelines prior to publishing research of this nature, ideally improving the study design and consistency across training load and injury/illness surveillance methods.

Conducting a meta-analysis was not possible within this review due to the large discrepancies between the studies' definitions, analyses, data collection methods and load measures. Future research should strive to rectify the limitations presented by this review by conforming to published consensus statements. If adherence to these guidelines was to increase going forward, the publication of a meta-analysis would be of significant benefit to researchers and practitioners alike.

The FINA guidelines also recommend in and out-of-competition monitoring of athletes using a sport-specific tool such as OSTRC (Mountjoy *et al.,* 2016). This validated questionnaire has played an increasing role in sports injury and illness surveillance as it is purposefully designed for the collection of conditions that are below the time-loss threshold (Bahr *et al.,* 2020).

Load monitoring is largely a subjective practice and thus is reliant on an athlete's recall of the key variables. While subjective measures have been shown to be more sensitive and consistent than objective measures in determining homeostatic changes to load (Schwellnus *et al.,* 2016), their use in retrospective studies can lead to inaccuracies in data collection. Future research should focus on prospective cohort study designs as they are considered to be more reliable and generate real-time knowledge and allow for a more accurate estimation of the risk and incidence of injury and illness (Mukherjee 2015).

While a variety of training load measures can be used in the monitoring of athletes, it is clear that no one measure will provide a clear picture when used in isolation. The reliance upon training volume as an external training load measure in a variety of forms was unable to determine a standardised variable suitable for a swimming population. To that end, in line with recent consensus statements, a combination of internal and external training load should be used in an integrated approach (Bourdon *et al.*, 2017).

Future research also needs to explore the applicability of the sRPE method of monitoring internal training load within competitive swimming. A recent review by Eckard *et al.*, (2018) found that 22/57 articles used the sRPE method to quantify session intensity. Statistically significant results were reported in 21 studies, with one study reporting all null findings (Eckard *et al.*, 2018). The collection of sRPE in conjunction with additional external training load provides the opportunity to investigate the effect of not only increased loads, but also changes in load. Unlike similar research in other sports, no study has investigated the links between training load and the incidence of pain, injury and illness in an elite swimming population using sRPE in a longitudinal prospective cohort study.

Finally, research into elite competitive swimming populations is necessary to provide a clear picture of the associations between training load and pain, injury and illness for coaches and practitioners working at the highest echelons of the sport. Conducting research at elite level is often difficult due to the limited access, numbers of athletes and ability to implement good research processes in practical training environments. However, there is greater control and resources available at that level, with less confounding factors affecting the results. A universal classification model as seen in Swann *et al.*, (2015) should be referred to when defining the athletes level of expertise, allowing for improved clarity and comparison of populations (Bahr *et al.*, 2020).

2.7 Conclusions

This systematic review provides an appraisal of the literature examining the relationship between training load and pain, injury, and illness in competitive swimming. The findings highlight that the relationship between these variables is unclear owing to a host of methodological constraints associated with research in this field. While the relationship has yet to be established, the review highlights that youth, masters and competitive swimmers of a lower ability should receive particular attention. Planning of load within the seasonal calendar needs prudence, with winter months being a key period in the training cycle. Sessions of higher intensity and speed elements should be planned with caution. Monitoring and injury/illness surveillance practices need to be developed in conjunction with consensus guidelines, ensuring load monitoring includes both internal and external training loads. The use of longitudinal load monitoring of elite populations, utilising sRPE and investigating the applicability of the ACWR and EWMA approaches should be a priority for researchers going forward. This will not only improve the quality of the research being conducted, but it will also provide greater clarity on the relationship between training load and pain, injury, and illness.

2.8 Corrigendum to "The Relationship between Training Load and Pain, Injury and Illness in Competitive Swimming: A Systematic Review"

Lorna Barry, Mark Lyons, Karen McCreesh, Cormac Powell, Tom Comyns

Corrigendum to "The relationship between training load and pain, injury and illness in competitive swimming: A systematic review" [Physical Therapy in Sport (2021) 154–168] Physical Therapy in Sport, Volume 49, May 2021, Pages 138

The authors regret in the Future Considerations Section the following line should read:

"However, as only four (Cejudo *et al.,* 2019; Martins *et al.,* 2018; Tessaro *et al.,* 2017; Tomar & Allen, 2019) of the studies included in this systematic review were published after the introduction of the most recent FINA (Mountjoy *et al.,* 2016) and IOC (Schwellnus *et al.,* 2016; Soligard *et al.,* 2016) Consensus Guidelines covering load and the risk of injury and illness, their overall influence was diminished".

2.9 Addendum

Since the publication of this systematic review in 2021, a follow-up search was conducted to ensure the most accurate and up-to-date information was included. As within the original review, studies examining illness and training load in this population are potentially underrepresented with no one study being highlighted in this search. Five studies (Feijen *et al.* 2021; Suzuki *et al.* 2021; Thomas *et al.* 2021; Mise *et al.* 2022;

Pollen *et al.* 2022) including pain and injury were reviewed and summarised. Participant demographics were initially explored, with two studies investigating master-level swimmers (Suzuki *et al.,* 2021; Thomas *et al.,* 2021), one study investigating youth swimmers at club level (Mise *et al.,* 2022) and one study including NCAA division 3 swimmers (Pollen *et al.,* 2022). The fifth study included participants from a variety of backgrounds with ages ranging from 10-40 years. All participant ages ranged from 13 – 65 years, with a variety of descriptors outlining the participants' level of ability. The term competitive was used in all five studies as per the inclusion criteria, with one study citing swimmers training between 5533.3 – 6375.0 meters per session (Mise *et al.,* 2022). One study reported that the swimmers swam for 10 months per year with a swimming experience of 7-14 years (Pollen *et al.,* 2022). Both masters groups reported swimming frequency as days per week, with one group swimming a maximum of 3.3 ± 1.5 sessions per week (Suzuki *et al.,* 2021) and the other 3.3 ± 1.2 (Thomas *et al.,* 2021) sessions per week. Feijen *et al.*, (2020) included several descriptors for training load including lifetime exposure (4.57 ± 2.37 years), time swam per week (8.65 ± 3.15 hrs) and meters swam per week (17,277.82 ± 32,286.70 m).

Four of the five studies investigated pain in their participants with all four focusing on shoulder pain specifically (Feijen *et al.* 2021; Suzuki *et al.* 2021; Thomas *et al.* 2021; Mise *et al.* 2022). Three of these studies used retrospective questionnaires to ascertain the participants history of shoulder pain (Feijen *et al.* 2021; Suzuki *et al.* 2021; Thomas *et al.* 2021) while one prospective study had an athletic trainer visit the participants and interview them about the presence or absence of pain every 2-3 months (Mise *et al.,* 2022). Pain was defined as "significant shoulder pain that interfered with training, competition or progression in training and caused cessation or modification of training or racing" within this study. The final study reported specifically on non-contact musculoskeletal injury (Pollen *et al.,* 2022). Injury was defined as, "any non-contact musculoskeletal pain that resulted from team activities and prevented the swimmer from participating in a competition or at least 50% of 1 practice as prescribed". As per the inclusion criteria, each paper also needed to report an internal or external training load measure. These five articles consistently reported external training load measures as with the original systematic review findings. Swim distance was the most commonly reported measure with four of the five papers using this method (Feijen *et al.* 2021; Suzuki *et al.* 2021; Thomas *et al.* 2021; Mise *et al.* 2022). A variety of swim distance descriptors were used to quantify training load, with yards per day or year, average swimming distance per session in meters, and training volume in meters all featuring. Quantifying training load through duration was also common with months per year (Thomas *et al.*, 2021; Pollen *et al.,* 2022) and hours swam per week (Feijen *et al.* 2021; Thomas *et al.* 2021) both presented. The method of collecting training was either by questionnaire (Feijen *et al.* 2021; Suzuki *et al.* 2021; Thomas *et al.* 2021) or through coaches (Pollen *et al.*, 2022) or athlete interview (Mise *et al.,* 2022).

The relationship between training load and pain was examined in four studies, with one study reporting no significant difference in the number of years competing or training volume (Suzuki *et al.,* 2021). In the three remaining studies, one found that yards swam per day and per year was significantly lower in the positive pain and disability group (+PDD) (Thomas *et al.,* 2021). Conversely, the other study found female swimmers with shoulder pain had significantly longer swim distances per session (Mise *et al.,* 2022). Feijen *et al.,* (2020) found no statistical difference between the baseline characteristics of swimmers with and without shoulder pain. However, they did report that the rolling average ACWR, calculated using session volume, was a predictor for shoulder pain. The final study investigated the relationship between training load and injury (Pollen *et al.,* 2022). The study findings suggested that there was an association between injury and both high acute workload and ACWR. However, they also found that there was no association between high overall workload and chronic workload in collegiate athletes. Workload was calculated using distance swam only and did not factor in an internal training load metric.

The methodological inconsistencies in these studies extend those highlighted in the original systematic review. The discrepant findings across these five additional studies does not add clarity to the original findings which outlined no clear evidence of a relationship between training load and pain and limited evidence of a relationship between training load and injury. Even with the addition of these studies, pain is still the most frequently investigated condition with shoulder pain being prioritised. The variability in what is considered a competitive athlete was also apparent with a large range of training characteristics being present. Across the five studies, youth, collegiate and masters' groups were represented, which is consistent with the original systematic review. When these samples were compared to their participant groups in the original systematic review some similarities were found. It has been previously shown that masters swimmers with pain swam lower volumes then their non-symptomatic counterparts (Krüger *et al.,* 2012). It was suggested that the influence of age related changes in muscle mass and tendon degeneration (Barry *et al.,* 2021) could create a higher risk pain or injury at lower training thresholds. These findings are similar to that of Thomas *et al.,* (2021) who also found master swimmers with +PDD swam less than their non-symptomatic peers. Interestingly, within this study, the physical characteristics of the shoulder were also examined. The results showed that supraspinatus tendon structure was no different between groups, however, those who had a +PDD displayed reduced shoulder mobility. In contrast to this finding, the second study to include masters swimmers did find some shoulder joint structural changes (Suzuki *et al.,* 2021), where earlier initiation in swim training and a longer history of competition increased the risk of supraspinatus and subscapularis tendinosis.

Feijen *et al.,* (2020) had the most varied group of athletes (n=200) with international, national, regional or club swimmers being included. They did not breakdown the results according to cohort making it difficult to compare to previously discussed populations. However, this study did report an association between ACWR and shoulder pain. The results highlighted that ACWR was one of the stronger predictors for shoulder pain (OR, 4.13; 95%CI, 1.00 – 18.54). The authors concluded that based on these findings swimmers who were exposed to a 1-unit increase in the ACWR, saw 4.3 times increase in the odds of shoulder pain. On review of these results, the authors did not discuss what a 1-unit increase in ACWR referred to and thus limited the transferability of the results to an applied setting. The 95%CI presented with the odds ratios for this result was also very large suggesting that the finding had high levels of statistical uncertainty and could not be transferred with any degree of precision.

Youth swimmers were represented in one study (Mise *et al.,* 2022) which found different risk factors affected male and female swimmers separately. Swimming distance was significantly associated with shoulder pain in female swimmers but not male swimmers. The study highlighted that an increased focus on shoulder control through strengthening could aid their ability to tolerate greater swim distances. This finding was not evident in the original systematic review where a similar youth age category was investigated in four studies. All four studies found no statistically significant relationship between pain and training load across participant groups.

Pollen *et al.,* (2022) highlighted that in collegiate swimmers, high acute workloads and ACWR were both associated with injury. Two studies in the original systematic review investigated collegiate swimmers, however the comparison of studies is difficult based on the variety of training load measures used and hugely varied participant characteristics. Pollen *et al.,* (2022) used a swim distance derived acute workload, chronic workload and ACWR with a division three collegiate population. Meanwhile, Tomar & Allen (2019) utilised a RPE and duration-based workload metric but with a very small population with a low-level training ability. Harrington *et al.,* (2014) had a highly trained population represented at division one collegiate level and presented workload as hours per week or frequency of practices per week. The high levels of variability amongst collegiate swimmers make comparison and finding a consensus very challenging.

2.10 Link to the Next Chapter

Chapter one provided a broad outlook on the key concepts involved in this body of research. It outlines swimming as a competitive sport and describes the injury and illness profile of competitive swimmers as described in the research. It also summarises the concept of training load monitoring and outlines the most up to date consensus statements in injury and illness surveillance. Crucially, Chapter one identifies key gaps and recommendations as set out in the literature. Chapter two further investigated this gap within the research and established a deeper understanding of the relationship between training load and pain, injury, or illness. The findings of this study highlighted the reliance on external training load measures to monitor training load in competitive swimming research. It also emphasised methodological inconsistencies in the research and low adherence to the most recent FINA and IOC injury/illness surveillance consensus statements. Chapter three aimed to investigate the training load monitoring practices within the practical competitive swimming environment. The goal was to deepen the understanding of training load monitoring practices in the applied setting and better comprehend how they related to the findings with Chapter two. In sum, this study sought to examine if the methods of training load monitoring used in a research context were the methods used in an applied setting.

Chapter 3 International Survey of Training Load Monitoring Practices in Competitive Swimming: How, What and Why Not?

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3.1 Abstract

Introduction: Competitive swimming has typically been associated with large training demands. Coaches strategically fluctuate training load and recovery to push the limits of adaptation and avoid overtraining, injury or detraining. Training load monitoring in swimming has traditionally been seen to be reliant upon coaches' previous experience and intuition.

Aims: The purpose of this study is to identify the training load monitoring practices employed in real-world competitive swimming environments. The study explores data collection, analysis, and barriers to training load monitoring.

Methods: Employing a cross-sectional design, an online survey was distributed to international practitioners working in competitive swimming environments. Methods of data collection, analysis, level of effectiveness and barriers associated with training load monitoring were explored.

Results: Thirty-one responders working in competitive swimming programmes responded. 83.9% of responders acknowledged using training load monitoring, with 80.8% of responders using a combination of both internal and external training load, in line with current consensus statements. Swim volume (mileage) (96.2%) and session rate of perceived exertion (sRPE) (92.3%) were the most frequently used, with athlete lifestyle/wellness monitoring also featuring prominently. Thematic analysis highlighted that "stakeholder engagement", "resource constraints" or "functionality and usability of the systems" were shared barriers to training load monitoring amongst responders.

Conclusions: Findings show there is a research-practice gap. Future approaches to training load monitoring in competitive swimming should focus on selecting methods that allow the same training load monitoring system to be used across the whole programme, (pool-based training, dryland training and competition). Barriers associated with athlete adherence and coach /National Governing Body engagement should be addressed before a training load systems implementation.

Keywords; *Training load, Monitoring, Barriers, Coaching*

3.2 Introduction

Swimming competitions are scheduled over several days and typically incorporate heats, semi-finals, and finals. While the majority of events last no longer than two minutes and twenty seconds, the traditional training practices of competitive swimmers are high in volume (m/km/min) (Nugent *et al.,* 2019). Careful planning and periodization are at the forefront of achieving success at elite performance levels (Hellard *et al.,* 2019). Coaches strategically fluctuate training load and recovery to push the limits of adaptation and avoid overtraining, injury or detraining (Hellard *et al.,* 2019). The popularity of training load monitoring in sport has grown considerably in recent years (Newton *et al.*, 2019) and has been the focus of much interest in the scientific approach to training and recovery (Hamlin *et al.,* 2019). This is primarily due to increased sports science support (Foster *et al.,* 2017), technological developments (Hauer *et al.,* 2020) and professionalisation of sport (Gabbett 2016).

Training load monitoring is multi-dimensional, often incorporating measures of training frequency, intensity and duration, monitoring heart rate alterations, neuromuscular function, biochemical/hormonal/immunological markers and subjective wellness measures (Halson 2014). Training load can be divided into internal and external load (Bourdon *et al.,* 2017). External load is most commonly collected and includes objective measures of the work performed by the athlete (e.g., power output, speed and distance). Internal loads are the relative biological stressors imposed on the athlete (e.g. heart rate, rate of perceived exertion (RPE), session rate of perceived exertion (sRPE) and blood lactate) (Bourdon *et al.,* 2017). There is a consensus that both internal and external loads should be considered congruently, however, no one marker has been validated to identify a maladaptation to training and thus, a holistic approach to training load monitoring is needed (Soligard *et al.*, 2016).

The pursuit of best practice related to training load monitoring has caused an exponential increase in empirical and applied research (Bourdon *et al.*, 2017). Much of this research has focused on land-based sport, as opposed to Olympic aquatic sports (i.e., diving, open-water swimming, pool swimming, synchronised swimming and water polo). Three systematic reviews have been published in recent years, investigating the relationship between training load, injury, illness or soreness in a broad range of sports (Drew and Finch, 2016; Jones *et al.*, 2017; Eckard *et al.*, 2018). Of the 160 studies reviewed, just six studies included aquatic-based populations. A recent narrative review summarised the monitoring strategies used to quantify a swimmers training load within sports medicine research (Feijen, Tate, Kuppens, Barry, *et al.* 2020). The review (28 studies) highlighted that external training load (19/28) was frequently monitored through the collection of swimming volume (average distance, duration swam per week or year) and dryland volume (hours per week). The use of internal training load (23/28) was also investigated with blood lactate concentration testing and heart rate monitoring being commonly employed. However, in this research context, both heart rate and blood lactate were often used as a criterion value to determine the validity and reliability of other markers in estimating the internal training load. RPE, sRPE (8/28) and psychological parameters/scales (3/28) were used to a lesser extent within the research investigated. Collette *et al.,* (2018) and Zera *et al.,* (2015) did investigate psychological parameters in more detail and found that psychological variables have high inter/intra individual differences and can fluctuate throughout a season to align with periods of high and low training load (Zera *et al.,* 2015; Collette *et al.,* 2018)

Even with the increased popularity and implementation of training load monitoring in professional sport, research into training load monitoring in competitive swimming is growing but not widespread. This narrative review (Feijen, Tate, Kuppens, Barry, *et al.* 2020) presents a clear picture of the monitoring strategies being employed in sports medicine research. However, as the findings rely on monitoring strategies used within a research context, it may not truly reflect the practices employed in a real-world context. Therefore, this study aimed to identify the training load monitoring practices being used in competitive swimming environments, while also exploring how data collection and analysis are being implemented and what measures are considered effective. Finally, barriers and facilitators to training load monitoring were also examined.

3.3 Methods

3.3.1 Experimental Approach to the Problem

A survey was designed to explore the training load monitoring practices of high-performance support teams in competitive swimming. The overarching research question was deliberately designed using interpretive methods, rather than a leading hypothesis. An open survey was self-administered through an online platform (Qualtrics.com). The training load survey consisted of thirty-eight questions including open and closed questions, and used branch, display, and skip logic functions to tailor the content depending on the specific responses. The study is reported in line with the Checklist for

Reporting Results of Internet Surveys (CHERRIES) (Eysenbach 2004). A copy of the survey is available online (appendix 3.1) along with the CHERRIES checklist (appendix 3.2) authors used to ensure a complete description of this web-based survey was provided (Eysenbach 2004).

3.3.2 Participants

The survey was circulated globally, using swimming National Governing Bodies (NGBs) from Ireland, Great Britain & Northern Ireland, Spain, Australia, and New Zealand, as well as a number of coaching associations (International Swim Coaches Association, World Coaches Swimming Association, UK Strength and Conditioning Association). In addition, coaches, and practitioners from the NGBs were asked to circulate the survey to relevant contacts within the swimming community. It was requested that the individual whose primary responsibility was training load monitoring within their swim programme, irrespective of their job title, would be invited to complete the survey. A total of 58 responses were collected, with 31 complete responses being included. The remaining 27 responses were excluded due to not reaching a completeness rate >85% on primary questions (excluding branch logic and optional open-ended questions). Ethical approval was granted by the University's Ethics Committee (2019_10_09_EHS). Participant information sheets (including a GDPR statement) (appendix 3.3) were circulated with the questionnaire and each participant had to agree to an online informed consent form to participate in the research.

3.3.3 Procedures

The online survey was circulated primarily by email, but also through social media platforms (LinkedIn, Twitter). The aims, objectives and duration of the survey were included with each email, along with a participant information sheet. Data were collected from March 2020 to July 2020. Data gathered were identified using a code number and unnecessary personal details were not recorded or used in any part of this project. All data were stored in a locked filing cabinet in the principal researcher's office or password-protected/encrypted based on the data type. Unique responses were identified using the IP address of the participant. IP addresses were crosschecked for duplications in Microsoft Excel during analysis and not used if found to be a replication. The survey consisted of five blocks: (1) informed consent; (2) demographics; (3) training load monitoring practices; (4) barriers to training load monitoring; and (5) open-ended questions. Open-ended questions sought to give the responder the option of providing additional information on the links between training load monitoring and additional aspects of their programme and the barriers experienced with accurate training load monitoring. Participants could review questions, go back, and change answers throughout the survey. The survey was pilot tested, refined and redrafted in consultation with two academic colleagues with a background in survey design, as well as two multi-sport high-performance support staff who regularly use training load monitoring systems in a practical setting. Modifications of the survey in line with these consultations came in the form of improved technical terminology, clarity on the phrasing of the questions and removal of irrelevant questions. Finally, the survey was sent to two support staff working in a high-performance swim programme who completed the survey for a trial analysis.

3.3.4 Statistical Analyses

Responses were typically analysed using frequency analysis within Microsoft Excel. Absolute frequencies and percentages were most commonly used to report the data. Where data were qualitative, a thematic analysis was used (Braun *et al.*, 2016). The thematic analysis employed a six-step process, including data familiarisation, coding, theme selection, refining themes, defining themes and finalising the report (Braun *et al.*, 2016). Line by line coding was applied to the answers to the open-ended questions by one author (LB). Themes were then developed from these codes by two authors (LB, KM). Representative quotations were extracted and presented for each theme.

3.4 Results

A total of 31 responders participated fully in the survey. The result sections “demographics” and “barriers to training load monitoring” includes responses from all 31 responders. Five responders reported not using training load monitoring practices and therefore, sections reporting on training load monitoring practices only includes the remaining 26 responders.

3.4.1 Demographics

Out of 31 responders, 58.1% were swim coaches, 77.8% of whom had greater than ten years’ experience in competitive swimming. The remaining responders included sport scientists (19.4%), strength and conditioning (S&C) coaches (12.9%), physiologists (6.5%) and physiotherapists (3.2%). Academic and industry-specific qualifications were common aspects of the responders’ education. Almost all responders (96.8%) had some level of academic qualification, while most (90.3%) had an industry-specific qualification. Most responders (87.1%) coached athletes across a range of abilities. Practitioners of national standard athletes were most frequently represented (87.1%), followed by international level (77.4%) and club level athletes (41.9%).

3.4.2 Training Load Monitoring Practices

Out of 31 responders, five (16.1%) declared that they did not employ training load monitoring practices in their swim programme. These five responders consisted of three swim coaches (60%), one S&C coach (20%) and one physiologist (20%). The remaining 26 responders (83.9%) who did employ training load monitoring practices were asked to rank the top three goals of their training load monitoring practices. The frequency at which each goal was ranked at (one, two or three) is presented in **Table 3-1**. The goal to "monitoring athlete's response to training" was ranked most frequently at number one which was closely followed by "improve athlete performance".

Table 3-1 Rank order of the primary goal of training load monitoring practices.

Goal	**Primary Goal**	**Secondary Goal**	**Tertiary Goal**
	No. of responses per category		
Monitor athletes' response to training	9	6	1
Improve athlete performance	8	7	5
Aid coaches in planning and training prescription	5	4	5
Reduce injuries	3	4	4
To enhance training adaptations	1	3	7
Prevent over-training	0	1	3
Research purposes	0	0	0

[1]

Responders were asked to outline the methods they used to monitor training load within their programmes and to highlight the types of variables they collected. A small percentage (7.7%) of responders only collected internal training load markers, with some responders (11.5%) collecting external training load markers exclusively. A substantial number of responders (80.8%) collected both internal and external training load markers. Several responders (69.2%) used two or more methods to collect and record their training load data. The most widely used method was Microsoft Excel or similar software (44.7%), followed by a specifically designed software package (23.7%), pen and paper (15.8%) and a generic web-based tool such as Google Docs (13.2%). The responsibility of recording the data was predominantly split between the swim coach (46.2%) and self-reported by the athlete (34.6%). S&C coaches (7.7%) and sports science support staff

[1] One participant's responses are removed from secondary and tertiary goals due to an error in data collection/reporting.

(11.5%) were also reported to be responsible for data collection. Data were generally recorded immediately post-session (61.5%) or within the first hour (11.5%). Data were recorded within twenty-four hours' post-session in 26.9% of cases. Some data was recorded once a week (11.5%).

Responders were asked to outline the type of variables collected as part of their training load practices. Training volume (mileage) (96.2%) and sRPE (92.3%) were the primary data variables collected, closely followed by subjective ratings of lifestyle/wellness (73.1%), heart rate (69.2%) and total load (RPE x Duration) (69.2%). Sleep duration and quality (78.9%) were variables collected as a key lifestyle/wellness metric. Psychological questionnaires (Profile of Mood States Questionnaire, Daily Analysis of Life Demands Questionnaire, Recovery-Stress Questionnaire for Athletes, Multicomponent Training Distress Scale) (42.1%) and energy, fatigue, and soreness Likert scales (21.1%) were also frequently utilised under this category.

Biomarkers (26.9%) and objective measures of fatigue (19.2%) featured less often in the training load practices of the responders. Of those who did monitor fatigue, assessments such as a swim specific set were reportedly used (71.4%) as well as countermovement jumps (57.1%), handgrip strength (57.1%) and self-reported questionnaires (57.1%). Similarly, responders who monitored biomarkers highlighted that cardiovascular status (e.g., Serum Ferritin, Haemoglobin) (66.7%), muscle status (e.g., IGF-1, Cortisol, Creatine Kinase) (33.3%), metabolic status (e.g., Glucose, Lipids, HbA1c) (33.3%), salivary biomarkers (16.7%), as well as hydration status (e.g., Urine Specific Gravity, Osmolality) (16.7%) were used in training load monitoring practices.

Responders were also asked how training load data were sub-categorised during data analysis and how data were reported. Responders sub-categorised the data into multiple groups in 50% of the responses, with 61.5% of those categorising both swim and dryland training load separately. Categorising swim sessions by session target (speed, aerobic, race pace) was also popular (38.5%). A large portion (92.3%) of responders used two or more methods in combination to report the data, with the hierarchy of methods being presented in **Figure 3-1**.

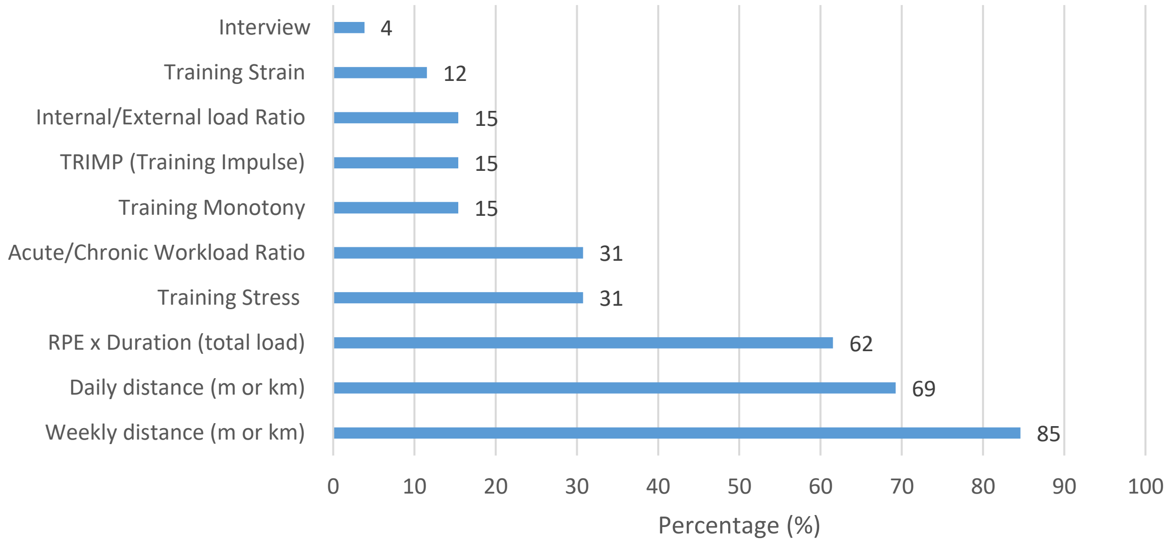

Figure 3-1 The percentage of selected training load analysis categories used by 26 responders (responders could select multiple options).

When asked who made the key decisions based on the training load data, responders indicated that either a head coach (61.5%) or a swim coach (26.9%) were largely responsible. Ninety-six per cent of responders indicated that they provided training load information back to the athlete after analysis. Fifty-eight per cent of those always provided feedback, while 38.5% provided feedback in a specific circumstance. The responders were provided with the opportunity to give further information on the circumstances where they would provide feedback to the athlete, which is presented in the qualitative data below.

Responders also contributed information on the effectiveness of their training load monitoring practices in key situations (i.e., improving performance, preventing injury, informing training prescription and enhancing training adaptations). **Figure 3-2** shows the breakdown of the responses. Monitoring training load was seen as very effective in terms of improving performance and enhancing training adaptations but only moderately effective in relation to preventing injury and informing training prescription.

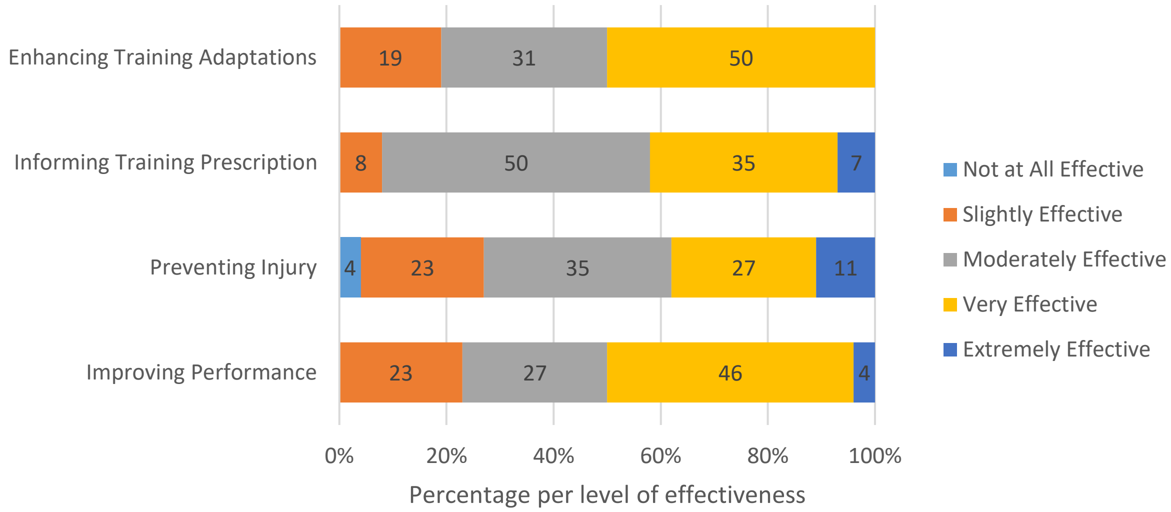

Figure 3-2 Perceived effectiveness of training load monitoring practices in key situations as reported by 26 responders.

3.4.3 Barriers Preventing Training Load Monitoring

Five responders (16.1%) stated that they did not employ any training load monitoring practices. The barriers that prevented them from employing training load monitoring practices were cited as "limited time" (50%) "lack of support from coaching team" (25%), "insufficient funding available" (12.5%) and the "age/experience level of their athletes" (12.5%).

3.4.4 Open-Ended Section

Responders were asked if they found a specific training load variable or metric most effective in helping to prevent injury. The open-ended responses highlighted the use of specific training load metrics, wellness markers and physiological assessments. Many of the responders cited specific training load monitoring metrics that they felt were helpful, such as the acute chronic workload ratio (ACWR) which is a method of quantifying fitness and fatigue by using the most recent training load (acute) with the athletes' recent history of training load (chronic) (Hulin *et al.*, 2014). Internal versus external load was also highlighted and is a method of quantifying fitness and fatigue status based on different variables used (i.e. total distance: TRIMP) (Akubat *et al.*, 2018). Variables such as monotony and strain were mentioned as being helpful. Training monotony is a measure of day-to-day training variability, while training strain is a value that represents the overall stress that the athlete was exposed to (Comyns and Flanagan 2013). Finally, training impulse (TRIMP) which is a method of quantifying physical effort using training duration and heart rate during exercise (Halson 2014) was also referred to. The word cloud below (**Figure 3-3**) highlights the interactions of the keywords within the responses. This word cloud was developed through a frequency analysis, where phrases or themes within the responses were counted. The size of the word or phrase within the word cloud is adjusted based on the frequency seen within the responses (i.e., the larger the word, the more frequently it was mentioned). In this instance three sizes (Font size 20, 40, 60) were used, the smallest words were mentioned once, and the largest words were mentioned three times.

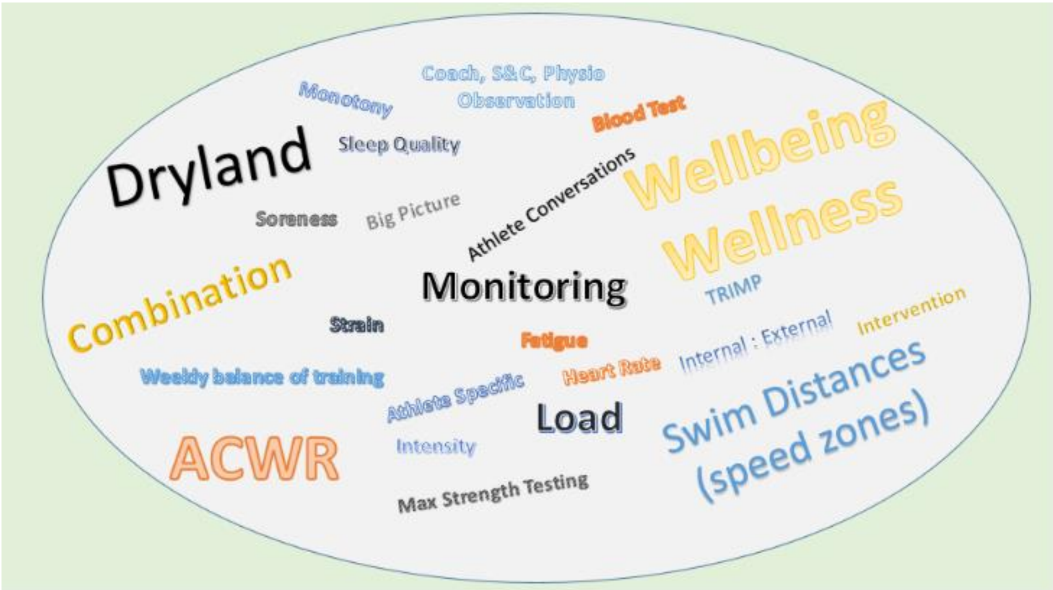

Figure 3-3 Word cloud representation of the specific variables, which are deemed to be most effective in preventing injury.

A thematic analysis was conducted for the open-ended questions. Three higher-order themes were prevalent across all questions and are presented below. **Table 3-2** highlights the higher-order themes, along with representative quotations from responders.

3.4.4.1 Stakeholder Engagement

Stakeholder (i.e., athlete, coach, support staff, NGB) engagement was a major recurring theme across all open-ended questions. Responders were asked to report on the situations where training load feedback was given to the athlete. Feedback was often provided when the athletes' data were showing abnormalities or when trying to generate athlete engagement. Feedback was provided to educate or reassure the athlete, ensuring the athlete would see personal value in the information. This theme was also prominent when stakeholders were asked about barriers to accurately monitoring training load. Training load monitoring was made difficult due to a lack of compliance from the athletes. This, coupled with a coach's reluctance to engage with the information and an unwillingness to make adaptations based on the information were considerable barriers. When asked how training load monitoring could be made easier, the role of the stakeholder was frequently highlighted. It was suggested that a top-down approach to the application of a training load monitoring culture within the system would be of benefit.

3.4.4.2 Resource Constraints

Resource constraints were another determinative factor in the application of training load monitoring. When asked if any links between training load variables warranted further investigation, logistical issues in handling the data tended to hamper progress. This theme carried over directly into the barriers of training load monitoring, where resources such as support, finances and time were highlighted as major barriers. Additional personnel, undertaking separate data collection and analysis roles, was seen as a potential solution to these issues. This opinion was echoed when responders were asked what they felt may be important in effectively monitoring and recording training load at an elite level. It was suggested that an experienced sport science support practitioner within the system would be vital to effective monitoring and recording at an elite level.

3.4.4.3 Functionality and Usability

The functionality of the technological systems involved in training load monitoring were consistently highlighted across the responses, particularly when the barriers and solutions to training load monitoring were discussed. It was emphasised that technology, including software and hardware systems, need to be more user-friendly, sport-specific, reliable, and cost-effective. Responders remarked that standard training load monitoring systems may not always be specific to swimming and the information can go against a coach's perceptions. Responders also commented that at an elite level, the data analysis must be more sensitive to additional factors outside of training load. External factors such as lifestyle stress and sleep need to be accounted for while the need for detailed biomechanical analysis is also greater, as the technical efficiency of swimming needs to be quantified.

Table 3-2 Thematic analysis with representative quotations from responders

Theme	Coding	Representative Quotes	Responder
Stakeholder Engagement	Athlete Education	*"….athlete themselves is interested in the information for their own learning"*	R1
	Athlete Reassurance	*".....reassuring an athlete in low self-confidence moments"*	R2
	Barriers	*"Athlete compliance without nagging is poor"*	R6
		"Coaches willingness to truly open up to the data and allow their prescription to be interrogated by the data for the good of the swimmer's prescription. i.e. coach ego"	R7
		"Compliance of athlete to complete daily - this is helped greatly when coach and support team can see the value in the data and are on board"	R28
	Facilitators	*"Better coach buy in and drive for the athletes to complete rather than support staff. More drive from the National program to make it part of an athlete contract."*	R6
Resource Constraints	Logistical Issues	*"We have a HUGE amount of data from training, but nobody who can actually turn them into proper investigation/results"*	R5
	Time & Resources	*"Not enough support help. Too many athletes. Not enough money to pay for it"*	R1
		"Time to get all data accounted for logged and assessed. Financial resources"	R12
	Workforce	*"Having a separate member of staff that's sole responsibility is to record this data could also be easier and take the load off the coach"*	R27
		"It's vital to have very experienced sports science support".	R1
Functionality & Usability	Technology	*"more reliable measurement tools, easier automatic analysing"*	R25
		"adapted software to world class swimming"	R5
	Monitoring Limitations	*"On occasion the self-reporting of wellness and internal loads can be at odds with the external loads provided. i.e. there have been times when the data is saying back off a bit but the athlete is saying no I'm good let's go"*	R24
		"Capturing information on the non-structured load experienced by the athlete i.e. demands in school or at home"	R15
	Logistical Issues	*"The ability to accurately perform any dose response/ training performance modelling is currently limited in swimming as it is hard to accurately measure the internal/external training load and determine the physiological performance of an athlete at a given point in time given the large role that technique plays on how fast a swimmer moves through the water"*	R17

*TL = Training Load

3.5 Discussion

This study aimed to identify training load monitoring practices in competitive swimming and is the first to explore these concepts concertedly in this population. The survey explored how data collection and analysis is implemented, what metrics are being utilised and their perceived effectiveness. The barriers and facilitators to training load monitoring were also investigated. The findings show that swimming coaches are primarily responsible for training load monitoring, while physiotherapists and S&C coaches were represented to a lesser extent and tended to work in swimming for the least amount of time. The lower responses from support staff may be linked to the relatively new influence of these practitioners in competitive swimming. The majority of responders worked with multi-ability groups, highlighting the need for a training load monitoring system to be age/ability appropriate. The key finding that 83.9% of responders participated in some level of training load monitoring is higher than amateur rugby (Griffin, Kenny, Comyns and Lyons 2021) and highlights how swimming has incorporated the implementation of sports science support.

The hierarchy of training load monitoring goals (**Table 3-1**) illustrates that responders were more driven towards performance outcomes than injury prevention. While historically, training load monitoring was performance-orientated (Foster *et al.,* 2017), its utilisation for injury risk mitigation has increased considerably (West *et al.,* 2020). Research suggests that using training load monitoring as a predictor for injury is not best practice and may encourage a risk-averse culture of protecting athletes rather than preparing them for the training load needed to promote physical adaptation (Impellizzeri *et al.,* 2020). The primary role of training load monitoring should be to act as a safeguard for the coaches' periodization strategy. It can be used to assess if the athlete trained as planned or coped as expected. This allows both the art and science of coaching to work in harmony. Based on these goals, monitoring the athletes' perception of effort, as well as the amount of work completed is essential.

The widespread implementation of both internal and external training load markers is in accordance with the consensus statement recommendations on training load monitoring (Bourdon *et al.,* 2017). The high prevalence of sRPE as an internal training load measure is in agreement with other sport disciplines. The popularity of monitoring external training load as the weekly or daily volume (m/km/min) is a common theme in endurance-based sports, particularly in swimming and running where it is easily quantified and prescribed (Casado *et al.,* 2019). Nevertheless, caution is needed as training stress can be underestimated using training volume (m/km/min) in isolation (Paquette *et al.,* 2020). The addition of an internal training load metric such as sRPE or total load (RPE x Duration) provides a more complete quantification of an athlete's overall training load stress. The use of volume (m/km/min) or mileage as a key external training load measure was anticipated. However, the high prevalence of subjective internal training load (sRPE) is more surprising. The use of sRPE was seen to be limited in a recent systematic review examining pain, injury and illness in competitive swimmers (Barry *et al.,* 2021). This review concluded that monitoring training load in competitive swimming research often did not include a measure of both internal and external training load, while the use of sRPE needed more extensive inclusion in the sport of swimming. These findings are in direct contrast to the findings in this paper, showing a research-practice gap.

Heart rate was another training load measure frequently employed by responders (69.2%), which is in agreement with other research (Feijen, Tate, Kuppens, Barry, *et al.* 2020). Environmentally, the swimming arena provides logistical challenges to accurately monitoring heart rate. However, new technologies have made it possible to accurately track heart rate in real-time during a session (Olstad *et al.,* 2019), allowing training load monitoring methods such as TRIMP to be utilised. TRIMP was reportedly used by 15.4% of the responders within this survey. This method has received some criticism for its use of a total session mean heart rate, encompassing both "working" and "resting" intervals during the session, possibly underestimating the total stress of the session (García-Ramos *et al.,* 2015). It also has difficulties in monitoring all aspects of a swim programme. Swimming training typically comprises of pool-based training, with a variety of session targets (speed, aerobic, anaerobic etc.) and dryland training. The use of a training load measure relying on mean heart rate may not be accurately transferable to all types of training activities (Hellard *et al.,* 2006). The responders of this survey tended to separate the swimming and dryland-based training load in most cases, while others categorised training load by session target. It would seem appropriate to use a measure of training load that accurately depicts all aspects of a modern training regime and break the training load into sub-categories such as total training load, swim training load separated per session target and dryland training load.

In addition, training load measures including subjective ratings of lifestyle/wellness were often collected by responders and primarily involved the collection of sleep duration and quality. Sleep quantity and quality have been linked to performance and is seen as an essential aspect of an athlete's physical preparation (Surda *et al.,* 2019). Swimmers have been shown to suffer from significantly poorer sleep profiles than their fellow athletes (Biggins *et al.,* 2020). This is thought to be a result of the early morning training culture (Sargent *et al.,* 2014). Sleep disturbances have also been linked to increased training load (Taylor *et al.,* 1997) and are prevalent amongst "dual career" student-athlete swimmers, particularly during periods of high academic stress and competition periods (Astridge *et al.,* 2021). This suggests that the collection of subjective wellness data, in combination with training load and sleep quantity and quality are appropriate for a swimming population and are particularly necessary for student-athletes.

Monitoring training load is used to determine the individual athletes' response to training and to regulate the training stimulus to improve the effectiveness of training, without increasing the risk of maladaptation (Bourdon *et al.,* 2017). Responders indicated that training load monitoring was very effective in improving performance and enhancing training adaptations. Responders also found training load monitoring to be moderately effective in terms of injury prevention and moderately effective in terms of informing training prescription. The prediction of performance or injury has been a major debate topic in recent times (McCall *et al.,* 2017). Despite this, research has yet to conclusively cite training load monitoring as a definitive predictive tool (Akenhead and Nassis 2016). This is primarily due to the multifactorial nature of sport and quantifying training load alone is not sufficient to accurately predict performance (Mitchell *et al.,* 2020) or injury (Impellizzeri *et al.,* 2020). Considering the lack of predictive qualities, training load monitoring should be used in combination with the practitioners' experience, allowing an informed decision-making process to occur.

A key goal of this survey was to investigate the barriers to training load monitoring and three fundamental themes emerged; 1) stakeholder engagement; 2) resource constraints and 3) functionality or usability of the systems available. Athlete adherence to providing the information, the coaches' reluctance to engage with the information provided, and a lack of sufficient financial, personnel or technological support from NGBs, are all interlinked barriers to training load monitoring. Successful implementation of training load monitoring is strongly related to end-user buy-in (Neupert *et al.,* 2019). Athletes have reported that feedback on their training load data is a significant factor in their adherence (Neupert *et al.,* 2019). Nearly all responders in this survey indicated that they provided training load information back to the athlete after analysis, with some of those only doing so when the athlete needs reassurance or when ensuring the athlete would see personal value in the information. As athlete feedback is a key consideration in creating a culture of buy-in, the method of feedback needs consideration. A training load report sent to the athletes may not be sufficient as the athlete's understanding of the information cannot be assumed. Practical, periodic face-to-face discussions may be better received, allowing the athlete to ask questions in real-time.

The coaches' reluctance to engage with the information was another frequently cited barrier. Saw *et al.,* (2017) noted that the decision to implement a training load monitoring system should be dependent on a commitment to the process from the coaching team and the NGB. This stakeholder engagement process can be improved through formal or informal education of those involved, including clear protocols on how the system is used, data responsibility and how it will benefit the sports organisation/individuals (Saw *et al.,* 2017).

The NGB can also play a substantial role in barriers surrounding "stakeholder engagement" and "resource constraints". A recent study on the complexities of implementing a training load monitoring system highlighted that while stakeholder buy-in was important, this importance needs to translate into the applied setting (Duignan *et al.,* 2019). An example of this would be a situation where an athlete, who does not adequately adhere to training load monitoring practices within a squad, continuously gets "rewarded" through NGB funding or support systems. This diminishes the importance of training load monitoring within the system and may disrupt global athlete engagement in the process.

Responders also emphasised logistical issues, time and resources and limited workforce as being major contributing factors. The NGB can play a strong role in this aspect of the training load monitoring process. The implantation and success of such a system relies on its feasibility in the applied setting (Saw *et al.*, 2017). If the available resources do not meet the demands of the monitoring process, then it may be necessary for the NGB to support the process through financial investment, staff recruitment or redeployment of skilled labour. The investment of technology may help offset the cost of practitioner hours by automating the training load monitoring process (Saw *et al.,* 2017) Our findings showed that a sole staff position dedicated to the role of training load monitoring and sport science services would be of great benefit. Amplified support from the NGB in the form of providing a skilled and knowledgeable practitioner may consequently improve the decision-making processes by reducing the lag time to process and analyse the data.

The accuracy of the data collected may also improve, thus improving the insight gained from the training load monitoring system. The influence of the NGB in reinforcing a training load monitoring culture from the top down is also of utmost importance.

While it is imperative to quantify training load, the assessment of competition load is of equal importance. An athlete's load cannot be accurately reviewed and acted upon unless all elements are considered (Mujika 2017). There is some research to suggest the reporting of competition loads are difficult, given the influence of the environment and psychological state of the athletes (Griffin, Kenny, Comyns and Lyons 2021). The ability to quantify competition loads can be hampered by the method used. Using measures such as live heart rate is not a viable option in the competition environment, while using external measures such as volume (m/km/min) may severely under-report the stress of maximal exertion in the athlete over shorter distances. Those using a subjective rating of internal training load (e.g., sRPE), alongside an external measure (e.g., duration) may be best placed to gather an accurate representation of the competition stress. The sRPE method can be applied to all elements of activity during the competition process, including on-deck mobility, priming activities, swim-based warm-up, racing and cool down.

3.6 Limitations

The survey was circulated globally (1) to NGBs from Ireland, Great Britain & Northern Ireland, Spain, Australia and New Zealand (2) to a number of coaching associations and (3) through social media outlets. However, the nature of circulating a survey internationally through specific contact points within an NGB resulted in two limitations to this study. The first is the inability to track non-respondents as well as those who completed the survey in full, outside of the initial contact point. Consequently, the response rate (as defined by Phillips *et al.,* (2017) cannot be calculated and presented. It is also not possible to confirm the degree of international representation of the data.

3.7 Practical Applications

Those wishing to implement a training load monitoring system should consider stakeholder buy-in and financial, personnel and technological resources. The NGB needs to be invested in the training load requirements of the programme, while the coaching staff also need to create a culture of importance on the collection and utilisation of training load data. This can be done by having a dedicated member of staff for training load monitoring services. Once the system is in place, athlete adherence to reporting the data can be improved through the feedback of individual athlete training load information.

Findings showed that practitioners primarily used training load data to monitor the athlete's response to training and to improve performance, while injury prevention was less of a priority. This would suggest that training load data needs to be specific to the individual athlete and reviewed with training and competition performance in mind.

Much of the research into competitive swimming relies heavily on external training load and rarely features the use of sRPE (Barry *et al.*, 2021). However, the findings of this survey highlight that both internal and external training load are frequently collected by practitioners. The frequent use of sRPE as a training load measure is a welcome finding, it does highlight that there is a gap between research and real-world application. Those wishing to design a training load monitoring system for competitive swimming should prioritise the use of sRPE. sRPE is beneficial in competitive swimming as it can transcend all aspects of a modern-day swim programme. Dryland activities, competition and swim training load can be quantified utilising the same method, allowing for an accurate measure of total training load. The reporting of training load data can be done by splitting swim and dryland activities and potentially further sub-categorising the training load into swim sessions by session target (speed, aerobic, race pace). Lifestyle and wellness data should also be considered an important aspect of the monitoring process with sleep quality and quantity used as key metrics, especially for student-athletes.

3.8 Link to the Next Chapter

The aim of this study was to identify the training load monitoring practices employed in real-world competitive swimming environments. It also explored the data collection and analysis process as well as identified barriers to training load monitoring in competitive swimming. Chapter three found that in an applied setting, training load monitoring practices were reliant on both internal and external training load metrics which contrasts with the finding of Chapter two. Chapter three also highlighted the frequent use of the sRPE method which was not reflected in the literature. Wellness measures, such as sleep duration and quality were also commonly monitored within a competitive swimming environment. The findings of this study identified that practitioners and coaches utilise training load monitoring with a view to impacting performance, whereas injury prevention was less of a priority. Barriers to training load monitoring included stakeholder engagement, resource constraints and system functionality. This chapter highlights key aspects of the monitoring system design and alongside Chapter two creates a basis for the design and implementation of a training load monitoring system. Relatedly, a similar investigation into the injury surveillance practices of real-world competitive swimming environments needs to be completed to make an informed decision on the design of the injury surveillance monitoring aspect of the system. Chapter four investigates the injury surveillance practices of practitioners and coaches working within competitive swimming.

Chapter 4 International Survey of Injury Surveillance Practices in Competitive Swimming

This chapter has been published in *Physical Therapy in Sport*:

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4.1 Abstract

Introduction: Swimmers typically train and compete with persistent health problems, with more injuries occurring during training than in competition. Injury prevention in swimming is a crucial aspect of the sport to maintain consistent training practices and prevent unnecessary performance decrements. Injury surveillance is a critical step in the injury prevention process.

Aims: The purpose of this study was to identify the injury surveillance practices being used in competitive swimming environments. It explored the nature of the data collected, the injury definitions used and the perceived effectiveness of injury surveillance. Finally, this study also examined barriers to injury surveillance.

Methods: Employing a cross-sectional design, an online survey was distributed to international practitioners working in competitive swimming environments. Injury surveillance methods, data collected, perceived level of effectiveness and barriers associated with injury surveillance were explored.

Results: Twenty-two responders working in competitive swimming responded to the survey. Fifteen responders participated in injury surveillance, with 13 responders using a recognised definition for injury. Ten responders did not use any sports injury classification system. Ten responders found injury surveillance to be very effective at identifying injury trends, while previous injury history and training load data were perceived to be influential in preventing injury. Limited time, funding and compliance were common obstacles, while poor staff communication and engagement were barriers to the effective implementation of injury surveillance.

Conclusions: The implementation of injury surveillance is related to the system objectives, competitive level of those under surveillance and the resources available. This implementation requires the balance of adhering to the principles outlined in prominent consensus statements and overcoming the barriers associated with implementing a system effectively.

Keywords; *Injury, barriers, monitoring, coaching*

4.2 Introduction

The sport of swimming began its Olympic journey in 1896 (Hill *et al.*, 2021) and was most recently featured at the 2020 Olympic Games where a record total of thirty-seven events were contested. Despite recreational swimming being categorised as suitable for all ages and genders (Trinidad *et al.,* 2021), competitive swimming at the elite level has a well-established risk of injury (Wanivenhaus *et al.* 2012; Feijen, Tate, Kuppens, Claes, *et al.* 2020; Barry *et al.* 2021; Trinidad *et al.* 2021; Hill *et al.* 2022). A competitive swimming season typically involves large training demands that can be highly repetitive and is a year-round process. (Hill *et al.*, 2015). Recently, an updated review of the epidemiology of swimming injuries described the incidence of injury (2.6-3.0 injuries per 1000 hours of exposure) as “relatively low risk” compared with other upper limb sports (Trinidad *et al.,* 2021). Overuse, non-contact injuries (Boltz *et al.*, 2021) are most prevalent in swimming, with a significantly higher incidence of injury in training compared to competition (Soligard *et al.,* 2017). Injuries in the sport are often non-time loss (Boltz *et al.*, 2021) or time-loss with low absence rates from training (Prien *et al.,* 2017). The shoulder is most frequently injured followed by the knee and lower back (Wanivenhaus *et al.,* 2012). Injury burden, including the subsequent inconsistent training period and impacted performance, can have a significant influence on a competitive swimmer’s career (Mitchell *et al.*, 2021). Many swimmers train and compete with persistent health problems (Prien *et al.*, 2017) and often use medication as a form of pain relief (Hibberd and Myers 2013; Tessaro *et al.* 2017). Chronic pain in this population, therefore, can often lead to disability or retirement from the sport (Ristolainen *et al.,* 2009; Tate *et al.*, 2012; Trinidad *et al.*, 2021).

Injury surveillance in sport provides critical information on the injury prevention practices needed to reduce the overall burden of injuries and, subsequently, improve performance (Tabben *et al.*, 2020). Injury prevention practices are a key aspect of a swim programme and are underpinned by a clear understanding of the associated risk factors (Johnson *et al.*, 2003) and high-quality epidemiological data (Ekegren *et al.,* 2014). The development of a successful injury prevention programme is dependent on reliable, valid, consistent and population-representative injury surveillance data (Ekegren *et al.,* 2014). Consistent and valid injury surveillance practices allow for the comparison of injury burden from season to season and can determine the effectiveness of an injury prevention intervention (Tabben *et al.,* 2020). Gender, previous injury history, movement biomechanics, musculoskeletal deficits and training load have been identified as risk factors in a variety of swimming populations (youth, adult, club, varsity, elite, international, masters) through injury surveillance (Johnson *et al.* 2003; Abgarov *et al.* 2012; Tate *et al.* 2012; Wanivenhaus *et al.* 2012; Harrington *et al.* 2014; Hill *et al.* 2015; Feijen, Tate, Kuppens, Claes, *et al.* 2020; Barry *et al.* 2021; Trinidad *et al.* 2021). However, it has been noted that the systematic collection of injury data is far from widespread outside of professional sport (Ekegren *et al.,* 2016).

In 2016, a consensus statement on the methodology of injury and illness surveillance in aquatic sports was published by the Fédération Internationale de Natation (FINA) (Mountjoy *et al.,* 2016). The objective of the consensus statement was to develop an injury and illness surveillance protocol that provided clear aquatic-specific definitions for the terminology and metrics used in aquatic injury and illness surveillance (Mountjoy *et al.,* 2016). This was then followed by the International Olympic Committee (IOC) Consensus Statement, which sought to improve the consistency in data collection injury definitions and research reporting (Bahr *et al.,* 2020). Despite the publication of both consensus statements, substantial methodological and reporting gaps remain in recently published injury surveillance research (Trinidad *et al.,* 2021). A similar finding was echoed by Barry *et al.,* (2021), who highlighted methodological inconsistencies in training load monitoring in competitive swimming through a systematic review of the published literature. However, in a subsequent publication, the same authors discovered, through an international survey of training load monitoring practices in competitive swimming environments, that the training load monitoring consensus guidelines (Soligard *et al.,* 2016; Bourdon *et al.,* 2017) were being followed at the practitioner level (Barry *et al.,* 2022a). The inconsistent findings between the systematic review and the survey investigation highlighted a research-practice gap within training load monitoring literature in competitive swimming. To this end, it is imperative to investigate the injury surveillance practices being implemented in practical competitive swimming environments and discover if a similar research-practice gap exists. This investigation can also provide insight which may refine future injury surveillance guidelines in competitive swimming environments. Therefore, this study aimed to identify the injury surveillance practices being used in competitive swimming environments, along with the nature of the data collected and the injury definitions being used. In addition, the perceived effectiveness of injury surveillance was investigated. Finally, this study examined barriers to injury surveillance.

4.3 Methods

4.3.1 Experimental Approach to the Problem

A cross-sectional survey was designed to investigate the injury surveillance procedures and practices in competitive swimming. Competitive swimming was defined within the survey as, "competitive swimming, where the primary purpose of the sport is competitive performance, not participation", while injury surveillance was defined as, "the method of habitually collecting data relating to the occurrence of an injury and the risk factors associated with it". An open, thirty-seven-question survey was self-administered through an online platform (Qualtrics.com). The survey included open and closed questions, and used branch, display, and skip logic functions to tailor the content depending on the specific responses. The reporting of the survey is in line with the Checklist for Reporting of Internet Surveys (CHERRIES) (Eysenbach, 2004). A copy of the survey is available online (presented in appendix 4.1), along with the CHERRIES checklist (appendix 4.2).

4.3.2 Participants

The survey was initially circulated globally to practitioners within swimming National Governing Bodies (NGBs) from Ireland, Great Britain, Spain, Australia, and New Zealand and subsequently to a number of coaching associations (International Swim Coaches Association, World Coaches Swimming Association, UK Strength and Conditioning Association) in order to increase participant recruitment. Practitioners were initially identified through NGB websites or professional contacts. In addition, coaches, and practitioners from the NGBs were asked to circulate the survey to relevant contacts within their swimming community to generate a snowball sample. It was requested that the individual who had the primary responsibility for injury surveillance within their swim programme complete the survey. Ethical approval was granted by the University's Ethics Committee (2019_10_09_EHS). Participant information sheets (including a GDPR statement) (appendix 3.3) were circulated with the questionnaire and each participant provided informed consent before participation in the research. A total of twenty-two responses were collected.

4.3.3 Procedures

The online survey was circulated primarily by email, but also through social media platforms (LinkedIn, Twitter) to maximise the survey's visibility. The aims, objectives and duration of the survey were included with each email, along with a participant information sheet. Data were collected from March to July 2020. Data gathered were identified using a code number, unnecessary personal details were not recorded or used in any part of this study and all data were stored using password-protection/encryption. Unique responses were identified using the IP address of the participant. IP addresses were crosschecked for duplications in Microsoft Excel during analysis and not used if found to be a replication. No duplications were found. The survey was designed to allow participants to review questions and change answers throughout the survey if needed. The survey consisted of five sections: (1) informed consent; (2) demographics; (3) injury surveillance practices; (4) injury surveillance effectiveness; and (5) barriers to injury surveillance. The survey was pilot tested, refined and redrafted through a three-stage process. Stage one involved discussing the optimal survey question flow to reduce respondent burden. It also involved improving question phrasing to ensure respondents interpreted the questions correctly and were not influenced by the order of the questions. Stage two included testing the survey with two academics with a background in injury surveillance research. Modifications of the survey in line with these consultations came in the form of improved technical terminology, further clarity on the phrasing of the questions and removal of irrelevant questions. The final stage involved a pilot test and trial analysis with two multi-sport high-performance support staff who regularly use injury surveillance in a practical setting. Pilot testing, outside of the academic sphere ensured the administration technique (email) was appropriate and that the terminology used transferred to the target population. Pilot testing, outside of the academic sphere ensured the administration technique (email) was appropriate and that the terminology used transferred to the target population. Post pilot testing, an individual debrief was conducted and highlighted areas of the survey that may have been problematic for the user (skipped questions, questions answered incorrectly or misunderstood). The individual debrief led to the re-ordering of questions and additional clarity of terms used such as “professional accreditation” and “questionnaires”. The addition of contextual examples and set definitions where also added to terms including “incidence”, “severity”, “injury/illness burden”.

4.3.4 Statistical Analyses

Collated data were analysed using frequency analysis within Microsoft Excel. Absolute frequencies were predominantly used to report the data. Where data were qualitative, thematic analysis techniques from Braun *et al.*, (2016) were employed. The thematic analysis employed a six-step process, including data familiarisation, coding, theme selection, refining themes, defining themes and finalising the report (Braun *et al.*, 2016). Line by line coding was applied to the open-ended questions by one author (LB). Themes were then developed from these codes by two authors (LB, KM). Representative quotations were then extracted, agreed by both authors, and presented for each theme.

4.4 Results

4.4.1 Demographics

A total of 22 responses were collected. A range of professionals (swim coach (n=9), physiotherapist (n=9), strength and conditioning (S&C) coach (n=3), athlete health lead (n=1) responded to the survey as the primary staff member responsible for injury surveillance practices. Responders had either a bachelor's degree (n=8), masters degree (n=12) or PhD (n=2), and many (n=17) had a complementary discipline-specific qualification (e.g., UK Strength and Conditioning Association, Level two/three Swim Coaching Accreditation, CORU (Irish Health and Social Care Regulator) Registration). Responders often (n=12) worked with swim squads containing multiple performance levels (international n=17, national n=12, club n=10), with group sizes ranging from 5 to 350 athletes.

4.4.2 Injury Surveillance Practices

A total of 15 responders acknowledged using injury surveillance practices, with the remaining seven citing limited time (n=4), lack of sufficient funding (n=2) and/or a lack of compliance from athletes (n=1) as being the key barriers that prevented them from employing injury surveillance practices. Responders highlighted the primary goals of injury surveillance within their programme were, "to keep a record for insurance purposes" (n=7), "to analyse in relation to other training factors" (n=5), "to inform appropriate athlete training prescription" (n=4) and/or "to highlight trends in injury occurrence" (n=2).

When asked about the detail of their injury surveillance practices, responders noted that either the FINA (n=6) (Mountjoy *et al.* 2016) or IOC (n=6) (Soligard *et al.* 2017) definition for injury was predominantly used, with one responder using the Australian Institute of Sport (AIS) definition (2014). One responder used a combination of both the IOC and FINA definitions and one relied on a custom definition which noted an injury had occurred if it related to any modification of swim training. The majority of responders (n=14) noted that they sub-categorised injuries, with all responders gathering additional injury or athlete specific detail during the recording process. The **Table 4-1** below illustrates the information gathered.

Table 4-1 Sub categorisation of injuries broken down by the number of responders.

Sub- Category	No. of Responders
Overuse injury: Refers to a condition caused without a single, identifiable event responsible for the injury.	12
Re-injury: Injury to the same location and of the same type as the index injury, where the index injury has completely healed.	11
New injury: Injury to a different location from the index injury.	8
Time loss injury: Injury that results in being unable to take a full part in future training or competition.	8
Traumatic injury: Refers to an injury caused by a single, clearly identifiable episode.	7
Medical attention injury: The swimmer needed an assessment of their medical condition by a qualified medical practitioner.	6
Exacerbation: Injury to the same location and of the same type as the index injury, where the index injury has not completely healed.	5
Index injury: The first recorded injury in a series of injuries constituting a recurrent condition.	3
Local injury: Injury to the same location but a different type from the index injury.	3
Non-Time loss injury: Injury that results in full participation but with health problems or reduced participation due to health problems.	3
Additional Details	**No. of Responders**
Date of injury	15
Body location of injury (e.g., Arm/shoulder)	15
Mechanism of injury (how the injury occurred)	12
Impact of injury (Duration (days) away from training/competition)	12
Injury type/diagnosis	11
Date of return to full participation	10
Type of session where the injury occurred	9
The severity of injury (mild, moderate, severe, Grade I, II, III etc.)	7
Injury "Aggravators & Easers" (including swim specific technical changes)	1
Sleep/ stress/ nutrition/ hydration/ general health/ musculoskeletal history (fatigue, soreness, tension, pain etc.) in the preceding weeks	1

Primarily, injuries were recorded by a physiotherapist (n=6), swim coach (n=3), sports therapist (n=2), S&C coach (n=2), sports scientist (n=1) or by the athlete (n=1). In most cases (n=12), injury diagnosis was confirmed by a doctor or physiotherapist before it was recorded and specific software (n=6) or a spreadsheet (n=5) was used to store the information. Where an injury classification system was used (n=4), the Orchard Sports Injury and Illness Classification System (OSIICS) was employed. However, a large portion of responders (n=10) used no formal classification system (one responder was unsure of the system used). All but one responder highlighted recording additional training or athlete data in conjunction with their injury data as presented in **Figure 4-1**.

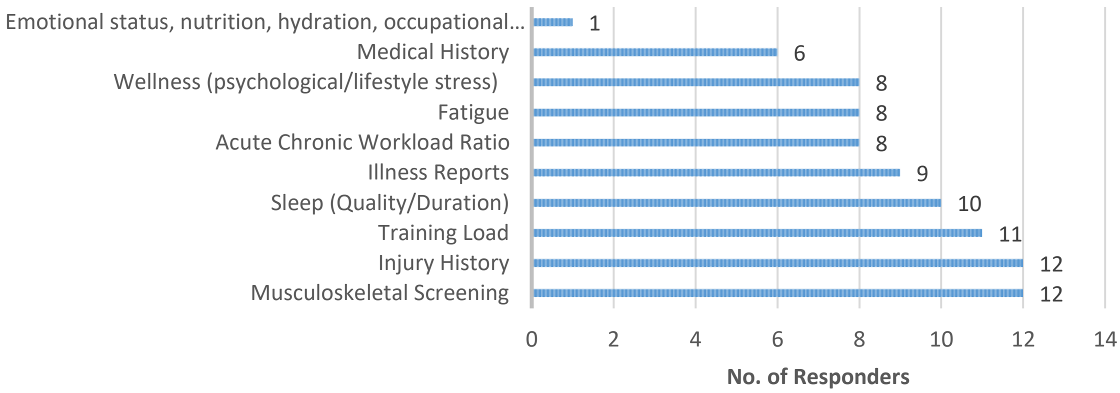

Figure 4-1 Additional athlete data (collected in conjunction with injury data) broken down by the number of responders (n=14).

Once data were collected, eight of the responders performed further analysis. Where further analysis was performed, injury prevalence (proportion of athletes affected by a specific condition at a defined period) (n=8), injury incidence (number of new occurrences of an injury in relation to the number of athletes at risk during a given period) (n=6), injury per training exposure (number of injuries recorded per training hours) (n=5) and injuries related to primary swimming stroke/distance (n=5) were most commonly used.

4.4.3 Injury Surveillance Effectiveness

Responders highlighted the effectiveness of their injury surveillance practices in key situations associated with a training environment. The most frequent response in each scenario is highlighted below in **Figure 4-2**.

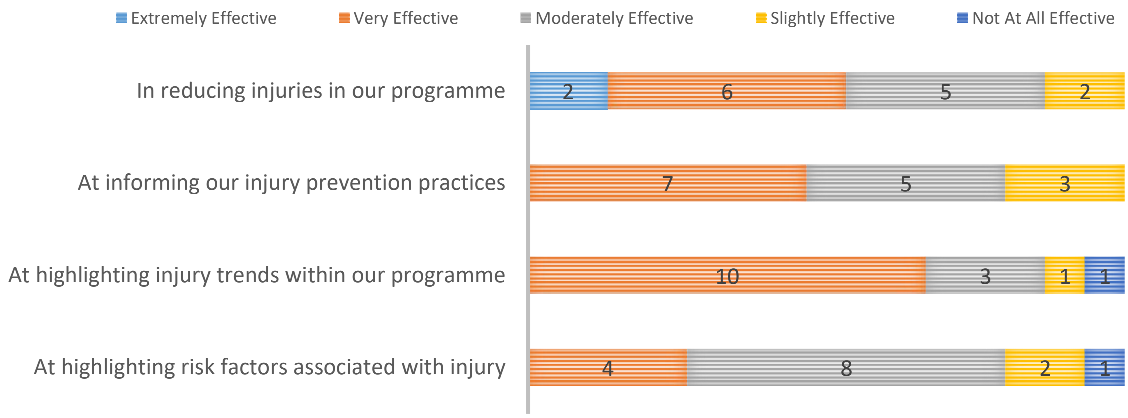

Figure 4-2 Perceived effectiveness of injury surveillance practices in key situations as reported by 15 responders.

Responders also ranked the three most influential data or metrics that they used for preventing injury. Previous injury history (n=7) and training load (n=5) were the two highest-ranked variables as presented in **Figure 4-3**.

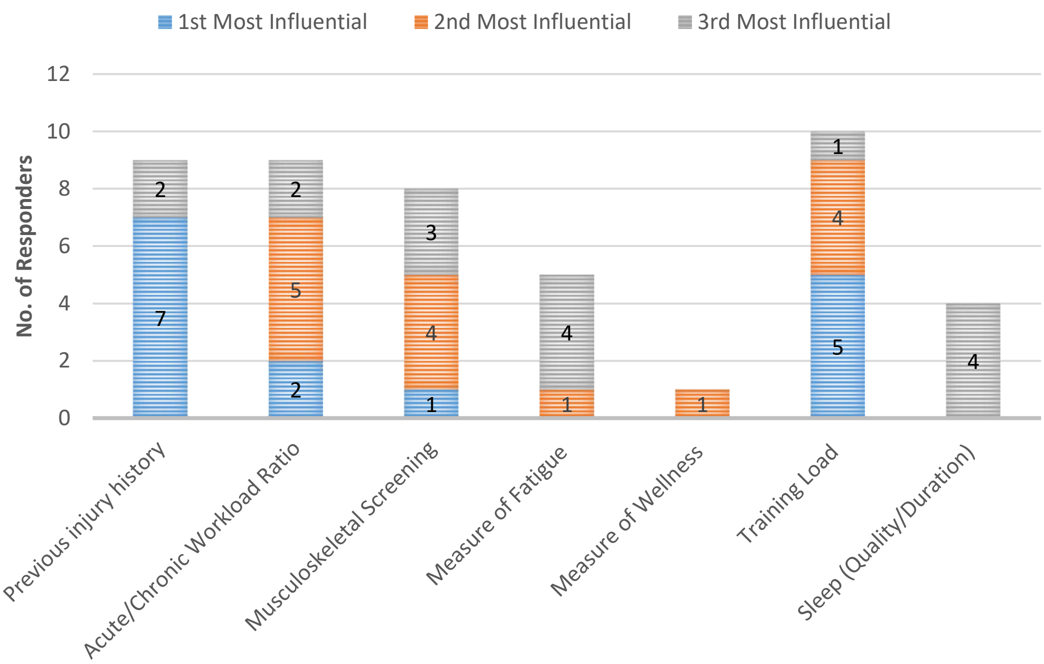

Figure 4-3 Top three most influential data or metrics used for preventing injury as reported by fifteen responders.

4.4.4 Barriers Preventing Injury Surveillance

Seven responders stated that they did not employ any injury surveillance practices. The barriers that prevented them from employing injury surveillance practices were cited as “limited time” (n=4) “lack of sufficient funding” (n=2) and “lack of athlete compliance” (n=1).

Out of the remaining 15 responders who did employ injury surveillance practices, 11 acknowledged having barriers associated with conducting an effective injury surveillance system. Five overall themes were identified, with three of them being similar to those who did not employ injury surveillance practices (a lack of funding, time and compliance). In addition to these, poor communication, and a lack of engagement from the whole multidisciplinary team (MDT) were seen as significant barriers to conducting an effective injury surveillance system and are outlined with representative quotations in **Table 4-2**.

Table 4-2 Thematic analysis of the key barriers and solutions associated with conducting an effective injury surveillance system.

Theme	Coding	Representative Quotes	Responder
Poor Communication	***Barriers***	*"A lack of effective communication with the coach/ management team at the local program."*	R3
		"I may have 3 weeks with an athlete while competing overseas that I have not met before. They may come with no handover/ medical history, no coaching guidelines and no report as to injury prevention practices and planned loading."	R3
		"Athlete reporting an injury in the first place"	R17
A Lack of Engagement		*"At the moment, our Head Coach doesn't monitor training load and doesn't entirely trust in its effectiveness"*	R10
		"Non-centralised sport - ensuring data accuracy from multiple different users"	R12
		"There is a culture of "coach knows best" at times, I find this difficult to gain decent traction in the injury prevention/ management in the local squad, as I believe the coach feels I may be undermining his authority."	R3
		"Accurate load data being filled in"	R17
Improved Communication	***Solutions***	*"If we had an online platform with the swim trainer, the fitness coach, the doctor, the player and me to share all the information."*	R2
		"Communication among the high performance swim program in (country) is necessary for best practice." *"A cloud based application for coaches and athletes to upload data every day would be best for continuity of surveillance."*	R3
Better Engagement		*"We get good compliance from medical staff, so details of an injury are well recorded. It would be ideal to match this data to training load and wellness data"*	R6

MDT = Multidisciplinary Team

4.5 Discussion

The objective of this study was to identify the injury surveillance practices being used in competitive swimming environments, along with the nature of the data collected and the injury definitions being used. The perceived effectiveness of the ability of injury surveillance to highlight risk factors of injury, injury trends, informing injury prevention strategies and reducing the overall occurrence of injury was investigated. Finally, this study also examined barriers to injury surveillance.

4.5.1 Injury Surveillance in Competitive Swimming

A key finding of this study was that 68.2% of responders employed injury surveillance practices within their swim programme. This number is lower than that of both amateur rugby clubs (91%) and schools rugby teams (86%), that did employ injury surveillance practices (Yeomans *et al.,* 2018; Leahy *et al.,* 2020). It is also lower than other forms of monitoring (training load) commonly used in competitive-level swim programmes (83.9%) (Barry *et al.,* 2022a). Injury surveillance is the first stage within the Translating Research into Injury Prevention Practice (TRIPP) framework and is highlighted as a key stage to inform all other aspects of the injury prevention paradigm (Finch 2006). This discrepancy in uptake between swimming and rugby may be due to the higher risk of injury in a sport like rugby (King *et al.,* 2019; Leahy *et al.,* 2019) where the demand for systematic injury surveillance in contact sports may be higher than in non-contact sports. This may also be related to the nature of injuries sustained in swimming, which could be deemed as manageable. The majority of swimming-related injuries are non-time loss (Powell and Dompier 2004) and may have a gradual onset (repetitive) (Trinidad *et al.,* 2021). This often leads to swimmers training and competing with symptoms of injury, as outlined by Mountjoy *et al.,* (2015), who reported that 70% of athletes attending the 15th FINA World Championships had symptoms of injury or illness in the weeks preceding and during the competition (Mountjoy *et al.,* 2015). Despite these swimmers being compromised, they participated in training and competition but stated their performance was affected (Mountjoy *et al.,* 2015). Swimming is a full-body sport, therefore specific modifications can be made to adapt the training programme to maintain a level of consistent training stimulus. In the event of non-time loss injury, many adaptations in the form of reduced training load, alteration of swimming biomechanics and the use of kickboards or pull-buoys can be introduced. The ability to manage a high proportion of injuries, while maintaining a full training programme in this manner may underestimate the burden of injuries in a swim programme. This may reduce the perceived need for injury surveillance in the sport of swimming, as demonstrated by the proportion of responders using injury surveillance in this study. However, an increased percentage uptake of injury surveillance practices in competitive swimming would lead to the improved design of injury prevention strategies as outlined in the TRIPP framework (Finch 2006).

4.5.2 Injury Definition

The injury definition used within an injury surveillance system can have a large impact on the reported outcomes (Bahr 2009; Tabben *et al.,* 2020), while the variability of definitions used across injury surveillance can limit the ability to compare outcomes (Bahr *et al.,* 2020). A key goal of this study was to discover if the methodological inconsistencies highlighted in research also exist in a practical setting. The findings of the current study showed that the majority of responders used either the FINA (Mountjoy *et al.*, 2016) or IOC (Soligard *et al.,* 2017) definition of injury. Additionally, one responder used the 2014 AIS injury definition, one responder used a combination of both the IOC and FINA definitions and one relied on a custom definition. Previous epidemiological research has shown that methodological variation between studies limits the transferability of the findings (Trinidad *et al.,* 2021). The call for a standardised injury definition to be used in injury surveillance is, without question, an essential requirement in a research context. Our findings show that the methodological inconsistencies seen previously are also present in the practical environment. However, the responders within this study highlighted that their primary goals of injury surveillance were, "to keep a record for insurance purposes", "to analyse in relation to other training factors", "to inform appropriate athlete training prescription" and/or "to highlight trends in injury occurrence". The goal, "research purposes" was selected as a tertiary goal by only one responder. As research is not a goal in these environments, the research-practice gap may not be as significant as initially thought. In the practical environment (where research is not the goal), the injury definition needs to be consistent longitudinally to allow the injury surveillance outcomes to be compared season on season and between co-operating training centres/athletes. Long-term consistency in the selected injury definition will aid in the ability to evaluate the effectiveness of injury prevention strategies over subsequent seasons. If the injury definition were to change the data would not provide a reliable picture of the effectiveness of the interventions employed (Tabben *et al.,* 2020). Similarly, a practitioner would need to be aware of the definition they are using to select an appropriate epidemiological study to compare their results to (Meeuwisse and Love 1997).

The definition selected by a practitioner must also be sport-specific and capture all the relevant issues affecting that programme. In a sport like swimming where non-time loss injuries are dominant, a time-loss injury definition would severely underestimate the true injury burden (Bahr 2009). All 15 responders who participated in injury surveillance employed an injury definition that would capture non-time loss injuries adequately. However, the use of the IOC definition (selected by six responders), which includes the need for an injury or complaint to receive medical attention for it to be deemed a recordable event, may not be suitable. Even though a medical attention-based definition is preferred to the traditional time loss (Bahr, 2009; Bahr *et al.*, 2020) as it captures a wider array of injuries and improves the quality control of recording, it still has its challenges (Toohey and Drew 2020). The main limitation is the need for consistent and adequate access to a clinician who is briefed on the injury surveillance protocols. A suitable clinician may not always be available to assess an injury, particularly at all pool and gym training sessions, during international camps or competitions.

The findings of this study showed the role of recording the injuries primarily rested with the physiotherapist; however, the responsibility also fell on the swim coach, sports therapist, S&C coach, or the athlete. The World Health Organisation (WHO) guidelines for injury surveillance (World Health Organization 2001) state that ideally, a member of the medical staff treating the injury should complete the injury surveillance record. However, they do acknowledge that administrative duties can add an unnecessary burden to medical staff and therefore a trained third party may also fulfil the role. This was deemed to be the case with many of our responders where a variety of staff recorded the data, but the majority had the injury diagnosis confirmed by a doctor or physiotherapist before being recorded. It is important to note that the FINA guidelines have broadened the scope of who can assess a medical attention injury. The guidelines state that a qualified clinician, including but not limited to a physician, physiotherapist, nurse or a physician assistant can be involved in the health care (not related to performance enhancement) of an athlete (Mountjoy *et al.*, 2016). This better suits an applied environment where medical staff can often be contracted or part-time.

4.5.3 Method of Data Collection

The protocols and procedures of data collection have been shown to influence the outcome of sports injury surveillance in research (Bahr *et al.,* 2020). The findings of this study showed that 13 responders used some form of electronic method to collect the data, whilst a relatively low number of responders used a formal injury classification system. The means of logging the information by use of pen and paper, electronically or online all have their merits and can be selected based on the specific context of the injury surveillance system, resources, level of implementation and objectives (Bahr *et al.,* 2020). This point, however, is directly linked to the recommendation that a location, type and diagnosis of injury should be recorded (Mountjoy *et al.,* 2016), allowing the grouping of data into higher-order classifications making reporting the data easier (Bahr *et al.,* 2020). The recommended use of sport-specific classification coding systems (e.g., Sports Medicine Diagnostic Coding System (SMDCS), OSIICS, etc.) would typically require an electronic database to ensure the effective and easy use of the system. However, in a less well-resourced setting, the use of pen and paper would suffice with the FINA consensus statement offering an alternative reporting method with less detailed options (Mountjoy *et al.,* 2016).

The FINA consensus guidelines also provide detail on additional injury data which should be recorded. This additional detail allows the comprehensive classification of injuries into reoccurrences, re-injuries, and exacerbations. Many additional data were collected by our responders during the recording process. The most frequent sub-categorisation of injury was an “overuse injury”. This is not a surprising result based on the frequent publication of epidemiological data highlighting that an overuse style injury is most common in swimming (Wanivenhaus *et al.,* 2012). Despite the FINA guidelines presenting a user definition for sub-categorising injuries as either overuse or traumatic, they note that defining injuries using one or the other can be challenging. The categorisation of injuries according to their acute or repetitive nature and sub-categorising by sudden or gradual onset would provide more nuanced detail (Bahr *et al.,* 2020). The addition of further detail according to the level of contact (direct, indirect and non-contact) would also give more context to the data. All responders in this study noted that they recorded additional details including date of injury and body location. The majority of responders collected mechanisms of injury, the impact of injury and injury diagnosis/type. The survey did not explore the categorisation of injury by the level of contact.

4.5.4 Data Analysis

In sport, the era of collecting "big data" is now common and often involves routinely collecting biodata or training metrics, storing it longitudinally but not necessarily using it acutely (Arnold and Sade 2017; Osborne and Cunningham 2017). This was deemed to be the case in this study where only half of the responders conducted further analysis on the data after collection and the majority of responders highlighted the primary reason for recording the data was for insurance purposes (creating a medical record of the injury, documentation for medical costs etc.). This gives the impression that the data are being collected and stored, lest it is needed. Where further analysis was conducted, injury prevalence, injury incidence, injury per training exposure and injuries related to stroke or event were mostly employed. This is in keeping with the FINA consensus statement where the method of assessing exposure is outlined as either the calculation of incidence or prevalence and/or reported by stroke type or event distance (Mountjoy *et al.,* 2016). The use of prevalence is the preferred method of expressing risk in a sport like swimming where chronic or gradual onset conditions are more frequent. (Bahr *et al.*, 2020). In this study, injury prevalence was the most frequently used method of expressing risk, closely followed by injury incidence.

In a non-academic/non-research setting, the basic reporting of incidence and prevalence may suffice, particularly when disseminating the information to coaches and athletes. As the objectives of the injury surveillance system are elevated to investigate epidemiological trends more comprehensively, the level of detail would need to increase to reflect the outcome. Additional information to support the injury surveillance data were gathered by almost all the responders, highlighting its perceived importance. Such information included musculoskeletal screening, injury history, training load and wellness data. Neither the FINA nor IOC consensus statements include in-depth guidelines regarding the integration or implementation of athlete training load, wellness or biomechanical monitoring in parallel to the primary injury surveillance system. In a research context, training load or wellness monitoring are often tracked alongside injury surveillance (Eckard *et al.,* 2018) and this is clearly common practice in a practical environment as found in the current study. The publication of guidelines on how to best integrate multiple monitoring systems in a practical environment may not only improve the standard of injury surveillance findings but also potentially improve the accuracy of injury prevention interventions.

4.5.5 Goals of Injury Surveillance

Responders recorded that one of the primary goals of their injury surveillance was "to highlight trends in injury occurrence" and noted that they found injury surveillance to be very effective for this purpose. This finding is reinforced by a comprehensive study published in 2019 which investigated injury occurrence in the Japanese national swim programme over 15 years (Matsuura *et al.,* 2019). The study highlighted an increase in knee joint injuries in the middle of the project which coincided with a change in start block dimensions (globally) leading to a potential increase in joint load. Longitudinal injury surveillance projects like Matsuura *et al.,* (2019) can provide data to inform injury prevention interventions designed and employed in the practical environment.

Responders also highlighted that injury surveillance was very effective at informing injury prevention practices and moderately effective at highlighting risk factors associated with injury. This is also highlighted by Matsuura *et al.,* (2019) where disc degeneration and spinal cramps of the lumbar region were identified as being common issues amongst Japanese swimmers. Once the issue was identified, a "Lumbar Injury Prevention" project was designed and implemented, resulting in a decrease in lumbar injury incidence during the intervention period. They identified key risk factors for injury during the surveillance period which included female gender, older age and increased years of swimming, and have targeted intervention programmes at young female swimmers to mitigate future injury in this population (Matsuura *et al.,* 2019).

4.5.6 Barriers to Injury Surveillance

The successful implementation and effective use of an injury surveillance system are reliant on maintaining high standards in all aspects of the data collection and analysis procedures (Ekegren *et al.,* 2014). In a sports setting where injury surveillance is not necessarily mandatory, upholding such high standards can be challenging (Ekegren *et al.,* 2014). The barriers to injury surveillance in a practical swimming environment were identified during this study. A third of responders did not employ injury surveillance practices in their environment largely due to limited time, funding, and compliance. Similarly, two-thirds of responders who did employ injury surveillance practices also acknowledged that limited time, funding, and compliance were barriers they experienced. This finding is similar to that within amateur rugby where player adherence, time commitments, available medical professionals and system technical issues were cited as the key barrier to implementing injury surveillance at the amateur level of the sport (Yeomans *et al.*, 2019).

Poor communication amongst, and a lack of engagement from, the whole MDT were also cited as key factors in conducting an effective injury surveillance system by responders. Responders noted that poor communication and adherence at the coaches/practitioner level was a challenge. In the primary training venue, poor communication amongst “home” staff was a barrier. This was also seen in non-centralised training centres or during competitions or camps where external coaches or practitioners may be employed. Poor communication amongst the MDT was also key findings in elite football across an eighteen year UEFA Club Injury Study (ECIS) (Ekstrand *et al.*, 2019). The study found that levels of internal communication within an MDT was associated with injury rate and player availability. More specifically, poor communication quality between the head coach and the medical staff resulted in 6-7% lower player availability and 50% higher injury burden compared with teams with moderate to high communication quality. A similar study investigated the role of the head coach further and found that coaches with a democratic leadership style, and who supported and encouraged staff development were linked to a lower severe injury rate. (Ekstrand *et al.*, 2018). This investigation into football and the similar themes found within this study highlight the importance of quality multi-disciplinary communication within the injury surveillance/prevention paradigm (Ghrairi *et al.*, 2019). Based on this finding, it would be practical to suggest improved education on the importance of injury surveillance for all staff within the swimming programme (Ekegren *et al.*, 2014). It may also be pertinent to present injury prevention strategies to a head coach in the guise of performance improvement. The relationship between injury burden and a team’s success has been documented in elite football where athlete availability was associated with league rankings (Hägglund *et al.*, 2013). In an individual sport context, a loss of training time due to injury was shown to be a determining factor in the obtainment of an athlete’s performance goals in athletics (Raysmith and Drew 2016). Studies of this nature may help educate and engage technical staff in the injury surveillance and prevention process.

4.6 Limitations

The survey was circulated globally through NGBs, coaching associations and social media outlets. This form of distribution limited the ability to track non-respondents and subsequently the response rate (as defined by (Phillips *et al.* 2017)) could not be calculated or presented. This also limits the ability to confirm the degree of international representation of the data. Additionally, as with all survey-based research, the presence of selection and response bias may have been present in this study. The authors opened the survey up to multiple avenues of distribution; however, it is likely that those who employ injury surveillance were more likely to engage with the survey than those that do not. Therefore, this may have inflated the data favourably towards those who do employ injury surveillance in their swim programme. The survey was also largely distributed through NGB channels, with a high proportion of responders working with international level athletes. The survey data may be more reflective of the upper echelons of the sport with higher levels of resources to conduct injury surveillance. This may result in the data being less representative of the global landscape of injury surveillance in competitive swimming, particularly within grass-roots swim programmes. An additional limitation was omitting a survey question related to the categorisation of injuries by level of contact. As this is a recommendation of the FINA and IOC consensus statements it could have provided valuable detail but was not included in the survey. This is something that can be addressed in future research.

4.7 Practical Application

The implementation of injury surveillance in a sporting context is related to the objectives of the system, the level of those under surveillance and the resources available. Where the injury surveillance outcomes are to be translated into research, it is imperative that strict use of the consensus guidelines is employed. The findings of this study showed that while many practical environments are collecting sufficient data (injury location, type, and severity), the inconsistent use of injury definition and low engagement of classification coding systems limits the transferability or comparison of the findings. However, where research is not the objective, as discovered in the majority of cases, the requirement is to have a consistent and sport-specific injury definition longitudinally within the swim programme. In a sport like swimming where non-time loss injuries are dominant, a time-loss injury definition would severely underestimate the true injury burden (Bahr 2009). To this end, the use of either the FINA or IOC injury definitions is appropriate. However, the inclusion of “medical attention” (as in the IOC definition) within the definition should only be considered when a consistent, trained medical professional is available to all aspects of the programme.

Similarly, the method of data collection is also resource-driven. Ideally, an electronic system could be used to reduce the time burden of injury surveillance and to improve the level of detail gathered. Preferably, a classification system would be employed with the date of injury, body location, mechanisms of injury, the impact of injury and injury diagnosis/type all being recorded. The categorisation of injuries according to their acute or repetitive nature and sub-categorising by sudden or gradual onset would provide more nuanced detail (Bahr *et al.,* 2020), particularly in a repetitive sport like swimming. The collection of previous injury history and additional training load data were deemed to be very influential concerning preventing injury, potentially highlighting the need for it to be collected in parallel with the injury surveillance system.

4.8 Conclusion

Sixty-eight percent of responders employed injury surveillance practices within their swim programme with 53% of those performed further analysis on the data once it was collected. Injury surveillance is the first step in the TRIPP framework and the implementation of such a system requires the balance of following the sound principles outlined in consensus statements and overcoming the barriers associated with an injury surveillance system. The loftier the injury surveillance system objectives the more the guidelines need to be followed to maintain strict protocols and uphold the accuracy of the data. However, in a practical setting, it may be more prudent to tackle the "how" of implementing a system including roles and responsibilities of the MDT, the communication pathways, staff engagement and education on the necessities and benefits of injury surveillance. Those who do not partake in injury surveillance cite limited time, resources, and funding as key barriers. The first step in increasing the uptake of injury surveillance in a swimming environment requires that these intertwined issues are addressed together. Injury surveillance models, where the implementation and integration are driven by the governing body, can be very successful in easing these barriers by providing tailor-made systems to domestic clubs and providing incentives for their participation (Yeomans *et al.,* 2019). Additionally, providing staff education (Ekegren *et al.,* 2014) as to the benefits of injury surveillance has been shown to improve coach engagement, particularly where the benefits are outlined with improvements to performance outcomes.

4.9 Link to the Next Chapter

A common thread on the need for a consistent methodological approach to the collection of both training load and injury/illness surveillance data has been present from Chapter one through to Chapter four. Each chapter has identified that the training load and injury/illness monitoring process would be made more robust and effective by being informed by the most recent FINA and IOC consensus statements. Chapter two also highlighted the need for published research to reflect best practice as regards the collection of both internal and external training loads. Similarly, Chapter three and four provided valuable insight into the practices of coaches and practitioners working in competitive swimming, including the metrics being collected and the barriers which are needed to be considered in the design and implementation of such a system. Chapter five has collated the findings and recommendations from the previous chapters. The chapter outlines the design of a training load monitoring system which employs the use of internal and external training load metrics in the form of swim volume (km) and sRPE-TL. The chapter also presents the design of a consensus statement led injury/illness surveillance system. The procedures involved in the implementation of the system are described in detail, while the evaluation of the system as per recommendations from the World Health Organisation is also presented.

Chapter 5 The Design and Evaluation of an Integrated Training Load and Injury/Illness Surveillance System in Competitive Swimming

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5.1 Abstract

Introduction: Quality injury/illness surveillance is a crucial aspect of injury/illness prevention, whilst training load prescription has been considered as an influencing factor. The ability to monitor training load in parallel with injury/illness surveillance may provide a clearer understanding of the aetiology and risk factors associated with injury/illness.

Aims: To design and evaluate an integrated training load monitoring and injury/illness surveillance system in a competitive swimming environment.

Methods: Employing a descriptive/mixed methods approach a training load monitoring and injury/illness surveillance system was designed, implemented, and evaluated. System satisfaction, usefulness and burden were evaluated, while barriers to the implementation and effectiveness of the system were explored.

Results: Fourteen competitive athletes and seven coaches/medical data collectors participated in the evaluation process. Most athletes were ‘extremely’ or ‘very’ satisfied with the data collection process and also found it ‘extremely’ or ‘very’ useful in the training centre environment. All practitioners were ‘extremely satisfied with the system and found it to be either ‘extremely’ or ‘very’ useful in their role. *Process constraints* and *data access and control* were significant themes related to the athletes, while practitioners highlighted *communication and cooperation amongst stakeholders, layering context to the data, maintaining data integrity* and the *coach's influence in the monitoring process* as being important to the monitoring/surveillance process.

Conclusions: Training load monitoring and injury/illness surveillance are necessary to elevate the standard of prospective injury/illness prevention research. Integrated systems should be designed in line with key consensus statements, while also being implemented in a way that counteracts the challenges within the real-world training environment.

Keywords; *Training load, injury, illness, monitoring, surveillance, swimming.*

5.2 Introduction

A competitive swimming season is a year-round process where training stimuli and recovery are carefully intertwined to allow the athlete to push limits of performance whilst avoiding overtraining, injury or detraining (Hellard *et al.,* 2019). Swimming typically involves an excess of 1000 hrs of training per year, incorporating 400-800 sessions (Tønnessen *et al.,* 2014), culminating in peak performance opportunities (Hellard *et al.,* 2019). These significant demands lead to a higher incidence of injury during training than in competition (Soligard *et al.,* 2017) and may result in swimmers training and competing with persistent health problems (Prien *et al.,* 2017).

Injury prevention in sport requires collaboration (Impellizzeri *et al.,* 2020) and a robust framework to act within (Finch 2006). The Translating Research into Injury Prevention Practice (TRIPP) framework outlines the necessity of high-quality surveillance data combined with a clear understanding of the aetiology and risk factors of injury (Finch 2006). Studies have found associations between muscular length (Harrington *et al.,* 2014), core endurance (Tate *et al.,* 2012) and shoulder pain in division one female swimmers, while training load has also been found as a contributing factor in national-level swimmers (Ristolainen *et al.,* 2014). FINA has published several studies exploring in-competition injuries and illnesses with many of these studies recommending out of competition prospective injury and illness surveillance (Mountjoy *et al.,* 2010, 2015, 2016; Engebretsen *et al.,* 2013; Prien *et al.,* 2017; Soligard *et al.,* 2017). Two studies have examined injury surveillance in national level (Matsuura *et al.,* 2020) and collegiate swimmers (Boltz *et al.,* 2021). Both studies, while robust in design, provide recommendations which include more detailed athlete exposure data (i.e., type or intensity of training, distance swam, and cardiovascular/exertional indices) in parallel with their injury surveillance procedures (Matsuura *et al.,* 2020; Boltz *et al.,* 2021). Monitoring risk factors such as training load, in parallel with the surveillance data, can give insights into the aetiology of injuries and support the translation of the information into actionable interventions.

Training load can be defined as the cumulative amount of stress placed on the athlete (Griffin *et al.,* 2020b) and can be divided into internal and external loads (Drew and Finch 2016). External loads quantify work while internal loads describe the response to that work (Drew and Finch 2016). In swimming, distance, time or speed are habitually used to monitor the external training load, with heart rate or session rate of perceived exertion (sRPE) typically used to monitor internal training load (García-Ramos *et al.,* 2015; Barry *et al.,* 2022a). Additionally, subjective athlete markers of well-being are commonly tracked in swimming (Barry *et al.,* 2022a) as a method of monitoring psychosocial stress in the athlete (Saw *et al.,* 2017; Sinnott-O'Connor *et al.,* 2018; Griffin *et al.,* 2020b). Monitoring objective and subjective metrics of this nature is essential to effective programme design (Impellizzeri *et al.,* 2020) and viewed as an influencing factor in the incidence of injury (Gabbett 2020). Monitoring systems should be feasible and scientifically grounded (Griffin *et al.,* 2020b). Barriers such as stakeholder engagement, resource constraints and system functionality need to be considered (Barry *et al.,* 2022a) while overcoming limited time, funding, compliance and poor staff communication are necessary for effective implementation (Yeomans *et al.,* 2019; Barry *et al.,* 2022b). The World Health Organisation (WHO) injury surveillance guidelines also recommend that an end-user evaluation process should be conducted after at least six months of the system being operational (World Health Organization 2001). The goal of the evaluation process is to assess the data collection process and end-user satisfaction, usefulness, and burden. This will aid in the identification of system flaws and opportunities for development and maintain system relevance within a dynamic environment (World Health Organization 2001).

Quality injury/illness surveillance is a crucial aspect of injury/illness prevention, whilst the monitoring of potential risk factors in parallel to the injury/illness surveillance period is also of critical importance. Despite much research investigating the relationship between injury/illness and training load, a causative relationship has yet to be identified (Barry *et al.,* 2021). Thus far, this lack of clarity may be down to methodological constraints in both the means of implementing the integrated system or expressing the injury/illness incidence relative to accurate training load measures (Matsuura *et al.,* 2020; Barry *et al.,* 2021; Boltz *et al.,* 2021; Trinidad *et al.,* 2021). Therefore, the primary aim of this study was to describe the design and implementation of an integrated system running concurrently throughout a competitive swim season. The secondary aim was to conduct an end-user evaluation of the integrated system and to make future recommendations regarding such systems.

5.3 Methods

5.3.1 Experimental Approach to the Problem

The nature of the problem centred on the ability to design and implement an integrated training load and injury/illness surveillance system to be used within competitive swimming. The experimental approach aligned with procedures by Griffin *et al.,* (2020b). Step one consisted of exploring current training load and injury surveillance practices which have previously been established (Barry *et al.*, 2022a, 2022b). Step two was to design and implement an integrated system. Step three was participant recruitment and familiarisation. Step four was implementing data collection, analysis, and auditing practices. Step five was the end-user evaluation of the integrated system after one year of data collection.

5.3.2 Design and Implementation

The integrated system was built on the findings of stage one. It also engaged with the FINA and/or International Olympic Committee (IOC) consensus statements (Mountjoy *et al.*, 2016; Bahr *et al.*, 2020) and guidance from Soligard *et al.*, (2016) and Schwellnus *et al.*, (2016). The integrated system was designed with two elements of data collection: 1) athlete self-reported data and 2) practitioner-reported data. Athlete self-reported data were collected through the online application Kitman Labs™ (*kitmanlabs.com*), which could be accessed through mobile phones. The practitioner data were inputted into a bespoke Microsoft Excel worksheet, designed in line with the Orchard Sports Injury and Illness Classification System (OSIICS) (Orchard *et al.*, 2020).

5.3.3 Athlete Self-Reported Data

Athlete self-reported data were divided into two categories: 1) well-being data; and 2) training load data. All streams of data collected are outlined in **Figure 5-1**. Subjective measures of well-being have been shown to respond acutely and chronically to training load and are recommended for inclusion alongside other objective monitoring practices (Saw *et al.*, 2017). In this case, sRPE –TL and session volume in meters were monitored. Athletes rated their perceived exertion on the modified Borg scale (1-10) (as adapted from the Borg CR10 scale (Borg 1998)) after each session. They were also asked to record the session volume in meters and minutes where applicable and select the activity type (e.g., swimming, S&C – strength, racing, S&C – conditioning). sRPE –TL was calculated by multiplying the sRPE by the duration of the activity, as outlined previously (Foster *et al.*, 2001; Wallace *et al.*, 2008; Griffin *et al.*, 2020b).

5.3.4 Practitioner Reported Data

A nominated physiotherapist was assigned to each training venue as the medical data collector (MDC). Data consisted of any injury or illness sustained and were defined as per Bahr *et al.,* (2020). Injury and illness were subcategorised as medical attention or non-medical attention and time-loss or non-time loss. Time-loss and medical attention are defined as per Mountjoy *et al.,* (2016). Injury/illness mode of onset was classified on a continuum consistent with Bahr *et al.,* (2020). Circumstances of injury were divided into training or competition (Mountjoy *et al.,* 2016) with a further classification as to the level of contact (direct, indirect, non-contact) (Bahr *et al.,* 2020). Illnesses were sub-categorised as communicable or non-communicable (Mountjoy *et al.,* 2016). Subsequent, recurrent or exacerbation of injuries/illnesses were classified as described in Bahr *et al.,* (2020). The severity of the injury/illness was recorded as the duration of time loss (Bahr *et al.,* 2020). Time loss was reported from the date of onset until the athlete was fully available for training and competition. Fully available was clarified as without modification of training prescription, modification of technique or deficits in performance directly related to the injury or illness. The OSIICS was employed to determine the location, type, and diagnosis of injury/illness.

5.3.5 Participants

Two of Swim Ireland's (the national governing body for swimming on the island of Ireland) National Training Centres were involved in the data collection; National Centre Dublin (NCD) and National Centre Limerick (NCL). A total of 24 athletes trained within Swim Ireland's National Centre programmes during the data collection period. These athletes are classified as World Class (n=1), Elite/International Level (n=11) and Highly Trained/National Level (n=12) (McKay *et al.,* 2022). These National Centres were identified to implement the integrated system and all 24 athletes were recruited. Athletes' education (handbook) and familiarisation began 12 weeks before the start of the formal data collection period. The MDC in each centre was provided with an education session and reference handbook on the procedures and definitions to be employed during the data collection period. Ethical approval was granted by the University's Ethics Committee (2019_10_09_EHS). All participants were provided with information sheets and informed consent forms prior to commencing the study (appendix 5.1).

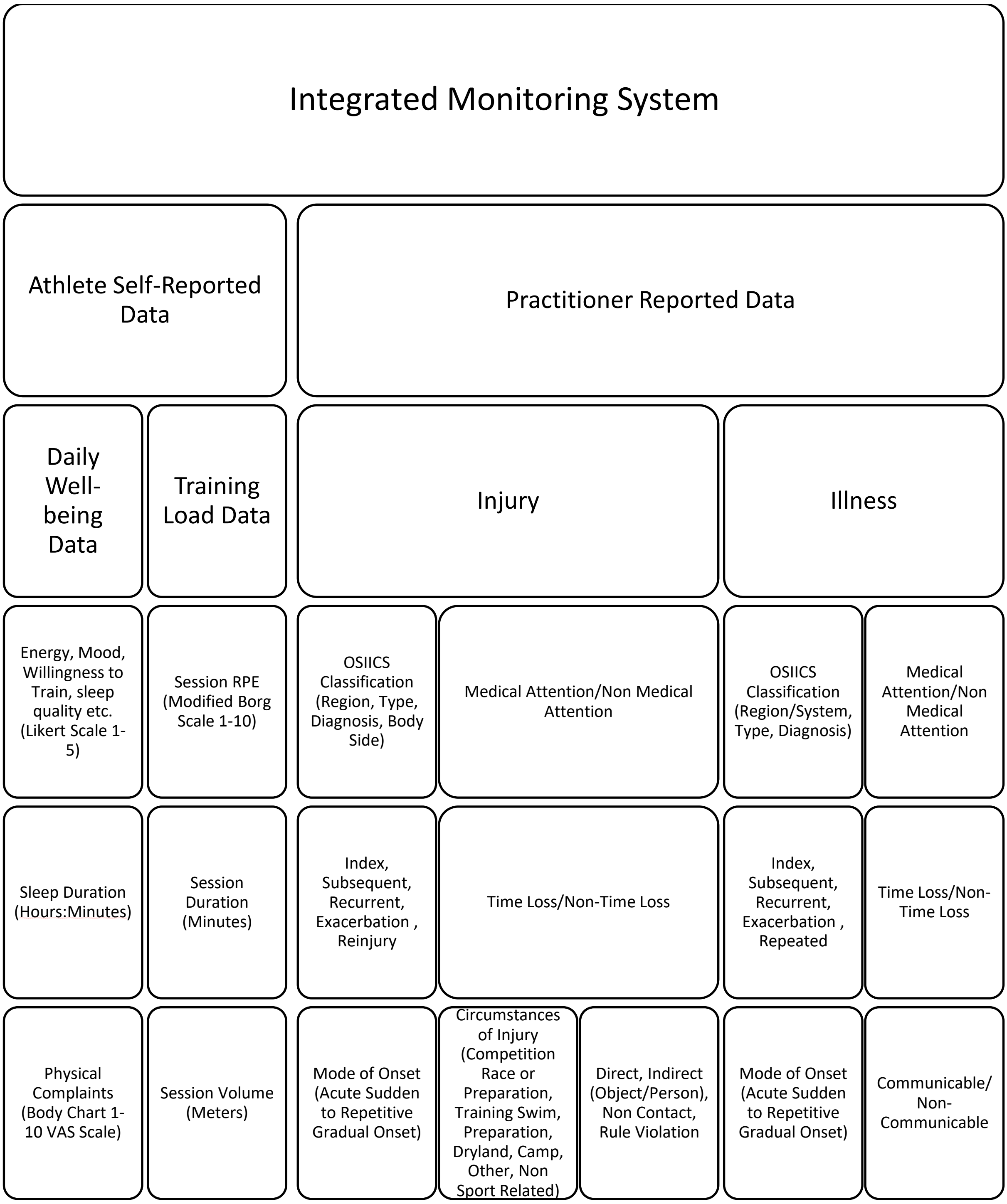

Figure 5-1 Structure of the integrated monitoring system employed.

5.3.6 Auditing Practices

Auditing procedures included sending daily text reminders to athletes to input their data. Athlete data were manually cross-checked weekly to verify the presence or absence of data. Absent or suspicious data (excessively high/low) were highlighted, investigated, and rectified where needed. A biweekly group email was sent out to the MDCs to confirm the continuity and completeness of ongoing or resolved cases.

5.3.7 Evaluation

In line with the WHO's injury surveillance guidelines (World Health Organization 2001), an end-user evaluation process should be conducted to identify flaws and opportunities for improvement. After the first season of implementation, an end-user evaluation was carried out. Survey reporting was conducted in line with the CHERRIES checklist (Eysenbach 2004) (appendix 5.2), while interviews and focus groups followed the COREQ checklist (Tong et al., 2007) (appendix 5.3). The surveys (administered via Qualtrics) were designed to evaluate aspects of the integrated system that athletes (N=24), coaches (N=4) and MDCs (N=3) were directly involved with, on a daily basis. Athletes and coaches evaluated the self-reported data collection process from their unique perspectives, while the MDCs evaluated the practitioner-reported data collection processes. Athlete surveys were circulated at the end of the domestic competitive season and before the 2020 Tokyo Olympic/Paralympic Games. The survey was circulated through email to all participating athletes and remained open for a two-week period. MDC/coaches surveys were followed up with semi-structured online focus group sessions (MDCs) or semi-structured interviews (coaches). Additional reporting details of the survey, interview and focus group design, circulation and analysis can be found in appendix 5.4. Interview/focus group scripts and prompts can be found in appendix 5.5. Copy of end-user evaluation surveys can be found in appendix 5.6.

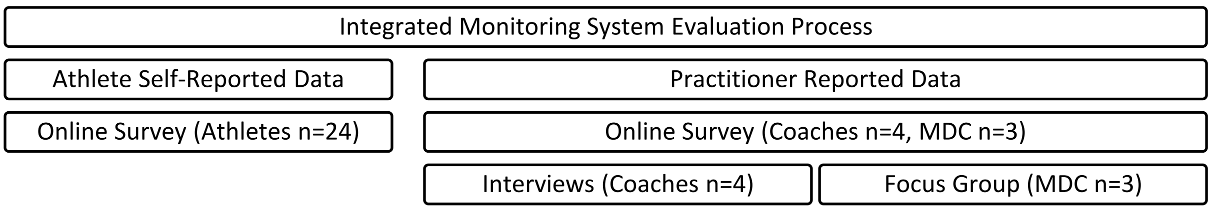

Figure 5-2 Outline of the evaluation process.

5.4 Results

5.4.1 Athlete Self-Reported Data

In total, 14/24 athletes responded to the survey. The response rate was potentially affected by the close proximity to the end of the domestic competitive season. The majority of athletes were transitioning to their off-season, selected athletes were travelling to Tokyo in preparation for the Olympics/Paralympics and 5 athletes had ceased training within the National Centres by the time the survey was circulated. The sample consisted of 10 males and 4 females, which is a representation of the athlete gender balance of the centralised swimming athlete population in Ireland. The majority of athletes noted that they were ‘extremely’ or ‘very’ satisfied (n=11) with the overall data collection process. Athletes reported that the monitoring process was ‘extremely’ or ‘very’ useful (n=12) or ‘moderately useful’ (n=2) to the training centre. Furthermore, they found the monitoring process was ‘extremely’ or ‘very’ useful (n=8) or ‘moderately’ or ‘slightly’ useful (n=6) to themselves as athletes. All athletes noted that inputting well-being data were ‘extremely’ or ‘very’ easy, with the majority echoing the same sentiment for sleep hours (n=13), physical complaint (n=11) and training load data (n=12). The remainder of responders noted that inputting sleep hours, physical complaint and training load data was ‘moderately’ or ‘slightly’ easy. Athletes were also asked how burdensome the process of inputting training load data were during competition periods, in comparison to the daily training environment. The majority of athletes agreed (n=11) that there was no difference between the two environments. However, the remaining responders noted that inputting training load in the daily training environment was ‘moderately’ burdensome in comparison with ‘moderately’, ‘very’ or ‘extremely’ burdensome in the competition environment. Athletes highlighted the measures they felt best represented their ability to train as planned were energy (n=8), followed by physical complaint (n=2), muscle soreness, sleep quality, swim volume and willingness to train (all n=1).

A thematic analysis was conducted on the open questions, with the higher-order themes of ‘data access/control’ and ‘process constraints’ featuring consistently amongst the responses.

Athletes noted that “*we can’t see if we’ve filled something already*” (R1) or “*recalling if I have filled out every piece of detail as required*” (R5) were barriers related to their access and control of the system. Athletes highlighted solutions by noting, “*If you could see what forms you've filled out…….. If you made a mistake, you could delete the volume or a session yourself…*” (R1). The athlete’s ability to see and track their recorded information, be able to modify it and take ownership of its consistency and accuracy would be of great benefit to the overall system.

The logistics of the monitoring process also increased the burden on the athlete. Athletes noted several instances where the usability of the system was seen as a barrier; for example, “*the number of different places to go in the app to fill out the data can be tedious*.” (R5) or “*typing in data, clicking buttons works well but putting numbers in can* *be slow*" (R13). Athletes also suggested that the student-athlete and early morning culture of the sport heightened the burden, "*the only issue is you have to do it in the early mornings when I'm half asleep*" (R3) and "*especially during college weeks, it can be hard to stay on top of data*" (R7). Finally, athletes proposed solutions to these issues through small adjustments to the reporting process. For example, "*I would like the volume and RPE to be on the same page instead of having to go to different places within the app*" (R4) or "*Have a box for sleep hours during the day for nap times*" (R8).

5.4.2 Practitioner Reported Data

Head coaches noted that their primary roles in the monitoring process ranged from decision making on the data provided, making data inferences, and information dissemination. Assistant coaches also noted decision making in relation to the data provided was a primary aspect of their role, but included liaising with athletes for inputting data, analysing data or data cleaning. All coaches rated how satisfied they were with the integrated system with both head coaches noting 'extreme satisfaction' and assistant coaches being either 'somewhat' or 'moderately' satisfied. Each coach also rated the system as being 'extremely useful' or 'very useful' to them in their role and noted that analysing athlete's data was either 'slightly' or 'not at all' burdensome. Coaches highlighted the measures they felt best represented the athletes' ability to train as planned were sleep quality (n=2) and sleep duration (n=2).

MDCs unanimously stated the system was either 'extremely' or 'somewhat' good in terms of their overall satisfaction with the system. They also agreed that the system was gathering sufficient injury/illness surveillance information and was a 'very accurate' representation of the actual injury and illness profile sustained over the season. The MDCs noted that the system was either 'extremely' or 'somewhat' good in terms of ease of use, time taken to record data, visual appeal, and suitability of the data fields.

5.4.3 Focus Group and Interviews

Four themes were identified from the analysis of the interviews with coaches and the focus group with the MDCs:

1) Communication and co-operation amongst stakeholders.
2) Layering context to the data.
3) Maintaining data integrity.
4) The coach's influence in the monitoring process.

5.4.3.1 Communication and Cooperation Amongst Stakeholders

This theme outlines key situations where the integrated system was a fundamental driver of multidirectional communication between the athlete, support staff and coaches. Firstly, participants described how the system provides a medium for the athlete to communicate indirectly with the coaching staff, particularly where they might find face-to-face communication difficult.

"it creates that conversation rather than them having to come to us going. "Hey look, I've got a problem". I think they find that quite difficult to communicate" (R6)

Meanwhile, it also improved the coaches' ability to have targeted conversation with the athletes about their wellbeing:

"I'm looking at.....if anyone got a niggle, has everybody slept well?....and all they do is allow, when we come out the office to say, Morning! Everything OK? Oh yeah, just slept terrible but I'm fine" (R4)

The system also provides opportunities for the coach to have more informed conversations with the wider multidisciplinary team, allowing them to highlight specific areas of concern and seek appropriate interventions:

"...communication across the staff in terms of how we as staff interact and then we can use that information to say, right? Well, there's obviously an issue here. Do we need to modify things..." (R5)

5.4.3.2 Layering Context to the Data

Many participants felt that while the primary action of collecting the raw information is useful, adding a layer of context to the data is necessary for optimum understanding and decision making. One such layer of context was ensuring the accuracy and integrity of the raw data before taking action:

"(the system) gives you snippets of information, but it doesn't then lead to a knee jerk decision. It leads to a conversation, is everything okay?.... actually, I just pressed the wrong button" (R4)

Participants also noted that they would cross-check their understanding of the data with the athlete to ensure their corresponding reaction is appropriate:

"if we have had reduced sleep or quality of sleep and we might be able to modify (the session), but we only really do that once I spoke to (the athlete) to see really how they were feeling"(R5)

A key layer of information is the athletes' chronic reporting patterns. Participants noted that the athlete's reporting history is taken into consideration before taking action:

".....if it's consistently bad or consistently good, at least it's consistent and we then start to get a gauge of where (the athlete) score themselves"(R4) or "(This athlete) always reports his mood as one so it doesn't really matter"(R4)

5.4.3.3 Maintaining Data Integrity

Data compliance and accuracy lead to data integrity and should take priority within the process. Maintaining data accuracy requires strict adherence to the consensus guidelines; however, maintaining data compliance requires a more flexible approach in the practical environment. Participants highlighted that getting a full, but not perfect, picture was deemed sufficient in their environment when it came to data compliance.

"You're inevitably never going to have everyone do it perfect all the time, so nearly perfect most of the time is quite good"(R7)

A lack of staff time and resources were two barriers to good data accuracy and compliance that were highlighted during the evaluation process.

"It's just a time to go check it up and make sure that it's all there …."(R7)

"How resourced medicine is across the board in all the high-performance sports in Ireland. It's so poor"(R2)

Athlete status or performance level (tier) was seen to impact data compliance. How established the athlete is within the training environment may lead to flexible levels of accountability in using the system consistently. Coaches noted that younger athletes who are not fully compliant, should receive education on monitoring practices and benefits to change their reporting habits.

"if they are teens or youth athletes……I think that's absolutely a question around why they need to value this, and an explanation of how you need to value it because this is what we do for you" (R4)

However, established athletes may require a more individualised approach which can affect data compliance.

“.....if I was to have a conversation with them regularly about (maintaining data collection)….I would then lose the opportunity to maybe get another meaningful message across to them.....I just decide the data is just irrelevant…”(R4)

Athlete status within the high-performance system can have a significant impact on the threshold of medical attention, thus affecting data accuracy.

“…some athletes get different treatment and preferential treatment than others and that's just a nuance of high-performance sport”(R2)

One responder summarised: *“high-performance sport is elite and it isn't equitable”(R2)*

Finally, individual beliefs and attitudes also impacted how MDCs respond to athletes and therefore can have an effect on injury/illness surveillance accuracy.

“some athletes…….are used to getting stuff escalated and then others are not….it's not necessarily related to the presentation that's in front of you…”(R2)

“….one person who might have a little sore shoulder who swims through it.....somebody else who's like, I can't swim….and you know it’s the exact same presentation”(R1)

5.4.3.4 The Coach’s Influence on the Monitoring Process

Coaches’ level of engagement with the system and its outputs can have a significant impact. Participants noted that coaches who are more data driven tend to interact with the system in a greater way.

“I think if you’re not quite as data driven, you wouldn’t see the benefit of it. I know there’s some coaches that struggle to read it, but they’re also the ones that are not data driven”(R4)

A clear aspect of this theme was that coaches interacted with aspects of the system they found to be useful irrespective of scientific rigour surrounding the measure.

“I’m not massive on RPEs, I’m not massively driven by how someone scores it and then it related to a training week and load”(R4)

All coaches highlighted that sleep (quality or quantity) was a key metric that they tracked closely in the athletes; however, they framed its importance as performance consistency and enhancement.

"certain athletes not getting enough sleep…that then means that their ability to recover from one session to the next is going to be hampered. So the quality of the next session is going to be impacted in a negative sense"(R5)

5.5 Discussion

The primary aim of this study was to describe the design and implementation of an integrated system running concurrently throughout a competitive swim season. The secondary aim was to evaluate the integrated system after a full season of data collection and to make future recommendations regarding such systems. The design and evaluation of such a system can guide the competitive swimming community in training load and injury/illness surveillance best practice. The TRIPP model highlights that only research that is adopted by applied practitioners will be successful in preventing injuries (Finch 2006). Accordingly, the design of this integrated system had to not only comply with best practice but also be adopted effectively in a real-world setting. In compliance with stage one of the TRIPP framework, the system was designed prospectively, across two separate training venues and in conjunction with injury/illness surveillance consensus guidelines (Mountjoy *et al.,* 2016; Bahr *et al.,* 2020) and training load monitoring best practice (Schwellnus *et al.,* 2016; Soligard *et al.,* 2016; Bourdon *et al.,* 2017). The adherence to key consensus guidelines maintains methodological consistency, allows accurate comparison of studies (Bahr *et al.,* 2020) and replication in a practical setting. Additionally, the integrated system sought to comply with stage two of the TRIPP model. This stage corresponds with the need to provide an aetiological understanding of the injury/illness surveillance data. In the absence of stage two, epidemiological researchers and practitioners are left with exemplar injury/illness (frequency/pattern) data ('What is Epidemiology?' 2016) but no understanding of the determining causes or risk factors (Finch 2006).

The optimal implementation of a monitoring system is underpinned by its simplicity and acceptability (World Health Organization 2001). Subsequently, the system needs to minimise burden and place the user at the centre of the design, evaluation, and improvements. This system was evaluated with these principles in mind. High levels of satisfaction in the overall system design from both the athletes and coaches/MDCs were found. Additionally, the system's usefulness and ease of use were rated positively with a low perception of burden within the monitoring process. Despite these positive findings, during the end-user evaluation, it was found that athletes highlighted some constraints within the monitoring process. Athletes noted that exam periods (where student-athlete workload increases) and early mornings were the most onerous or challenging periods. This is a key finding as academic stress has been related to the incidence of injury (Hausken-Sutter *et al.,* 2021) thus elevating the need for monitoring during such a high-risk period.

Barriers to the implementation of monitoring systems have been well documented in recent years with stakeholder compliance and engagement being significant determinants for success (Yeomans *et al.,* 2019; Griffin *et al.,* 2020b). Athlete evaluation of the system showed that data access and control is a key aspect of maintaining data compliance. Athletes noted that having access to their inputted data, with the ability to review, edit or delete data in real-time would improve data compliance and accuracy. Interestingly, the coaches/MDCs also highlighted data compliance and accuracy as a significant aspect of the monitoring process. Coaches/MDCs commented that a *"nearly perfect"* dataset was sufficient, as compliance across the whole group longitudinally was unrealistic. Diminished compliance is a common theme regarding monitoring in the research (Neupert *et al.,* 2019), and while there are strategies to improve compliance through education, there is also a practical solution to addressing the *"inevitable"* occurrence of missing data (Griffin, Kenny, Comyns, Purtill, *et al.* 2021). Griffin *et al.,* (2021) outlined a method to address missing data. However, this method needs to be investigated further within an individual sport environment. Practically, it is useful to have both interventions working in conjunction throughout the season. Long-term education of the athlete is necessary for improved compliance. However, in the short term, the ability to address missing data effectively is also pertinent for practitioners.

Coaches/MDCs also highlighted that data compliance is related to athlete status. In the practical environment, non-compliant younger athletes may receive an educational intervention into the benefits of the system. However, more established athletes may receive more flexibility within the process. Athletes within this study received education through an athlete handbook and a 12-week familiarisation process. These findings show that more continuous athlete education and feedback throughout the season may be necessary to maintain higher levels of engagement and compliance. Support staff who take an individualised approach to athlete compliance should consider the cost/benefits of this strategy. Duignan *et al.*, (2019) found athlete-specific education was a key aspect of improving engagement but also noted that inequity between adhering and non-adhering athletes diminished motivation and created interpersonal distrust and disharmony (Duignan *et al.,* 2019). An inequitable athlete environment was also highlighted within our findings where athlete status (tier level, funding, etc.) would have an impact on the level of medical attention received. Athletes in the upper tiers of the system would typically get access to medical attention at an earlier stage or a lower symptom threshold than an athlete of a lower tier. This, despite adherence to research-based consensus guidelines, could create hidden nuances when reporting medical attention data. Given this individual variation, grouping data by tier level may be the most valid (or accurate) representation of the data.

Stakeholder communication is one of the most commonly cited uses of a monitoring system (Saw *et al.*, 2015). In this instance, coaches/MDCs highlighted that the system provided a communication platform for athletes to identify any issues which they might not otherwise verbally communicate. This placed the responsibility on the coaches/MDCs to initiate a conversation with the athlete regarding their wellbeing disclosures. It also fostered a more targeted approach by the coaches/MDCs within the multidisciplinary team (MDT) by allowing them to attend to specific athletes with concerns in a more directed manner. This potentially reduces the time between wellbeing disclosure and intervention which is ideal in a performance environment. This communication pathway also allows for a layer of context to be generated. Coaches/MDCs noted that in many cases the acute response was not a *'knee jerk'* decision and action should not be taken until after a conversation has taken place. The context of knowing the athlete and their chronic reporting trends is also a key aspect of the information. Before acting, a coach can mediate their response based on their prior knowledge of the athlete's reporting history or personality traits. This response was echoed by Saw *et al.,* (2015) where they described interpreting the athlete's data based on knowing the athlete's circumstances and personality traits as being the 'art' of coaching. Keeping this in mind, coaches/MDCs should be aware that when implementing a monitoring system, there should be an inbuilt lead time where data is collected consistently, observed for trends, and understood in relation to the individual athlete before being used as a decision-making tool.

Previous research has shown that coaches not engaging with or acting upon athlete data was a significant barrier within the monitoring process (Griffin *et al.,* 2020b). In this instance, coaches highlighted many ways in which they engaged with the system;

however, it was clear that a coach's personal opinions of certain metrics dictated the degree of engagement. It was noted that coaching style may be an influencing factor with one coach stating those who are less data-driven will not see the benefits in the system. It was also mentioned the use of sRPE was not a priority based on the coach's own opinions of the metrics and not based on a scientific argument (validity, reliability, etc.) A key mismatch between the athletes' and coaches' perception of what key metrics they felt best represented their ability to train as planned also exists. Coaches very specifically value the sleep duration and quality metrics, while athletes largely prioritised the energy rating. This conflict of beliefs could lead to a degree of athlete mismanagement where coaches may not react as readily to a poor energy rating versus a poor sleep rating based on personal bias. A multidirectional feedback loop, where coaches and athletes engage in open conversation about the expectations and beliefs on the monitoring process should occur regularly to reduce this disparity.

Finally, the collection of accurate illness information was seen as a challenge. The qualitative findings highlighted that potentially the under-resourcing of medical support meant that in the practical environment MDCs were not receiving adequate information to create an accurate diagnosis record. In the absence of a sports medicine doctor attached to a training centre, athletes went to their home General Practitioner for medical attention, resulting in the subsequent diagnosis being relayed back to the MDCs by the athlete. Similarly, for an illness which did not require medical attention but was affecting the athlete (*"stuff above the throat…head cold, or maybe some mild GI symptoms"),* MDCs often relied on a coach to relay a diagnosis which was not deemed to be an appropriate reporting pathway. These barriers to reporting illness information may lead to an under-reporting of medical attention illnesses and an inaccurate reporting of non-time loss, non-medical attention illnesses in particular. Going forward, a system of this nature should be tailored to suit the available resources. In the absence of adequate medical support, symptom-based reporting by the individual athlete may be the preferred reporting avenue. Despite the inherent bias, athlete self-reported measures can broaden the scope of injury/illness surveillance and can be implemented in conjunction with a valid and reliable questionnaire (e.g. Health Problems Questionnaire) (Clarsen *et al.* 2014; Toohey and Drew 2020).

5.6 Limitations

A key strength of this study is also a weakness. Research into elite sports continuously face discord between the inherent small population to draw from and the unique viewpoint that the population can offer. To this end, limiting the research design to solely include two of Swim Ireland's National Training Centres resulted in a small participant sample size. Future research may overcome this by adjusting the study design to increase the number of data points (continuous evaluation over the season rather than cross-sectional) (Skorski and Hecksteden 2021) or expanding the study design to cooperating elite training centres internationally (Impellizzeri, 2017).

5.7 Conclusions

The integration of training load monitoring and injury/illness surveillance is necessary to elevate the standard of prospective injury/illness surveillance research in competitive swimming. The design of the integrated system provided for research-based data collection processes, which received positive appraisal. However, the design must be complemented by an effective implementation process to achieve robust and accurate data collection. A continuous end-user evaluation process is a necessary step which allows for the evolution of the system to meet the dynamic demands of a sporting environment. One key finding of the evaluation process highlighted that the resources available should align with the needs of the integrated system, allowing for improved collection of all data. Findings also highlighted that the implementation should occur gradually allowing for a period of uninterrupted data collection where staff can gain a deeper understanding of individual athlete reporting habits. Once accomplished, coaches should use the system as an "alert" to potential issues, allowing the coach to instigate communication with the athlete. Considering all information, including the athletes reporting history and personality traits before taking decisive action is advised. Furthermore, the continuous collection of accurate and consistent data should be prioritised particularly during periods of high external demands (e.g., exam periods). Athletes should receive additional attention to maintain compliance or coaches should employ different monitoring strategies during these periods (e.g., increased verbal communication/objective markers). Athlete education into the benefits and uses of the monitoring process is necessary to maintain high levels of athlete compliance, however this education needs to occur early in the monitoring process and be continuous throughout the season. Similarly, coaches need to be educated on the cost/benefits of treating higher tiered athletes differently within the monitoring process than their lower tiered counterparts. Despite creating a flexible and individualised approach for certain athletes, there is a high risk of developing an adverse athlete culture leading to larger and subsequent challenges. Future design and implementation of integrated systems needs to adhere to best practice through consensus guidelines, while also working to counteract these real-world challenges.

5.8 Link to the Next Chapter

Chapter five has collated the findings and recommendations from the previous chapters and outlined the design and implementation of an integrated training load monitoring and injury/illness surveillance system. Also, the system was reviewed after one season using an end-user evaluation process as per recommendations from the World Health Organisation. The system outlined in Chapter five was employed in a longitudinal and prospective data collection process as recommended in Chapter two. This 104-week observation period was used to collect training load and injury/illness surveillance data from Swim Irelands National Centre athletes (n=34). Chapter six presents a crucial study in this programme of research which utilises the data collected during the observation period to investigate the relationship between training load, or its aggregate measures and medical attention injuries and illnesses. Chapter one and two highlighted the need for longitudinal, prospective studies which utilised the sRPE method. The chapters also advocated for studies to align with the most recent injury/illness surveillance consensus statements. Finally, it was deemed important to provide clarity on the level of participants used within this research. These recommendations were embraced in the design of the integrated system in Chapter five and has elevated the impact of the findings of Chapter six which otherwise may have been interpreted under the cloud of methodological limitations highlighted in previous research. This study adds to the body of research discussed in Chapter two and addresses the paucity of information highlighted in the previous chapters.

Chapter 6 An Exploration of the Relationship between Training Load and Injury and Illness in Competitive Swimming

6.1 Abstract

Background: Training load monitoring has been seen as a method to reduce the risk of injury and illness in competitive sport. Traditionally, the practice of monitoring training load in swimming has been seen as overly reliant on external training load measures. The use of the sRPE method has been found to be an ecologically valid method of monitoring training load in competitive swimmers.

Aims: The aim of this study was to explore the relationship between training load monitoring, using the sRPE method, and injury and illness in competitive swimmers.

Methods: Data were collected using a prospective, longitudinal study design. Data included sRPE-TL (AU), session swim volume (km) and medical attention injury and illness surveillance data. Data were gathered from 32 athletes centralised in two (Limerick and Dublin) of Swim Ireland's National Centres over 104 -weeks.

Results: Training load monitoring showed the average weekly volume was 33.5 ± 12.9 km. The weekly total training load (AU) averaged 3,838 ± 1,616.1 AU. A total of 60 medical attention illness events and a total of 58 medical attention injury events were recorded. A multilevel logistic regression was used to analyse the association between sRPE-TL and medical attention injuries or illnesses. The analyses found no association between the results of this study, showing that Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU), 4-week Rolling Total Training Load (AU) and ACWR were not associated with medical attention injuries or illnesses in this cohort of athletes.

Conclusions: The findings suggest that using a single training load metric in isolation cannot decisively inform when an injury or illness will occur. Instead, coaches should utilise these monitoring tools to identify the competition loads for athletes and help coaches prepare for them adequately. Future research should strive to investigate the relationship between additional risk factors, in combination with training load and injury/illness in competitive swimmers.

Keywords: *Swimming, monitoring, training load, injury, illness*

6.2 Introduction

Athlete health and performance are intimately linked and have been the focus of much research examining their relationship with the goal of promoting athlete or team success (Drew *et al.,* 2017). In team sports, lower injury incidence, lower injury burden and higher match availability have been associated with positive performance outcomes (Hägglund *et al.,* 2013; Williams *et al.,* 2016). Similarly, in individual sports, the likelihood of achieving performance goals has been shown to significantly increase through minimising injury and illness-related training interruptions (Raysmith and Drew 2016). In competitive swimming, a similar association has been reported where mild illness has a harmful effect on male athletes' performance (Pyne 2005). Competitive swimmers often continue to train and compete with health issues (Matsuura *et al.,* 2020), while swimming has been shown to have a higher incidence of injury in training than in competition (Soligard *et al.,* 2017). Training demands in competitive swimming can involve completing 18,000 m daily with a high frequency of sessions across a training week (Feijen *et al.,* 2021). These demanding training regimes require stringent planning, monitoring and assessment to minimise any potential time lost from training (Pollock *et al.,* 2019). Training load monitoring is commonplace in elite sports (Mitchell *et al.,* 2020) and is used to support training practices (Hellard *et al.,* 2017) and inform the relative risk of injury and illness (Mitchell *et al.,* 2020).

Preventing injury and illness is a multifactorial process (Impellizzeri *et al.,* 2020). However, according to Gabbett (2016), training load related injuries and illnesses are preventable. Training load monitoring practices in competitive swimming research typically involve swim volume (i.e., meters, kilometres, or hours), heart rate or blood lactate (Feijen *et al.,* 2020), while the use of session rate of perceived exertion (sRPE) in a practical training environment is common (Barry *et al.*, 2022). The relationship between training load and injury and illness in a wider sporting context has been frequently researched with poorly managed training load increasing the risk of injury and illness (Schwellnus *et al.*, 2016; Soligard *et al.*, 2016). In a review investigating the relationship between training load and injury, illness and soreness in multiple sports, Drew & Finch (2016) found moderate evidence indicating a dose-response relationship between the amount of training load and injury, while there was conflicting evidence to support the relationship between training load and illness. More specific to competitive swimming, a systematic review by Barry *et al.,* (2021) found limited evidence of a relationship between training load and injury, and illness. However, the review highlighted a large variety of training load methods being employed in the research, with only one study monitoring training load using sRPE. The review concluded that future research should focus on longitudinal prospective studies, utilising the sRPE monitoring method and investigating the applicability of Acute/Chronic Workload Ratio (ACWR) through the exponentially weighted moving average (EWMA) method. The review also determined that due to a host of methodological limitations and a clear lack of consistency in reporting, further rigorous investigation into the relationship between training load and injury and illness in a competitive swimming population was needed. This finding has been echoed by Trinidad *et al.,* (2021) who also found a lack of consistent methodological approaches whilst reviewing the epidemiology of swimming injuries.

The primary aim of this research was to explore the association between training load and medical attention injury and illness (time loss/non-time loss) in competitive swimmers. This prospective research will build on the aforementioned recommendations, include internal and external load monitoring using the sRPE method and aligns with the Federation Internationale de Natation (FINA) (Mountjoy *et al.,* 2016) and International Olympic Committee (IOC) (Bahr *et al.,* 2020) injury and illness consensus statements.

6.3 Methods

6.3.1 Study design

This prospective cohort study was conducted in two of Swim Ireland's National Training Centres over two seasons, a 104-week period from September 2020 to September 2022. Data collection consisted of three separate data-streams. Athletes self-reported subjective training load data, including sRPE and session duration in minutes allowing for the total session load to be calculated (sRPE-TL), National Centre head coaches reported individual attendance records and training load data (session Pool Volume (km)) and medical data collectors (MDCs) collated injury and illness surveillance data. These data reporting processes were introduced to the National Centres at the end of the previous season allowing for an extensive period (12-weeks) of familiarisation with the process to occur. MDCs were provided with an injury/illness surveillance handbook prior to the start of data collection and an online briefing meeting was held to discuss the process of data collection.

6.3.2 Participants

A total of 34 athletes centralised in two (Limerick and Dublin) of Swim Ireland's National Centres were registered to take part in the study over the two-year period. All participants were provided with a study information sheet and an informed consent form. All athletes at each National Centre agreed to participate resulting in 100% recruitment of the available population. Athletes were assigned an ability level presented in **Table 6-3** based on the framework of McKay *et al.*, (2022). This framework was designed to practically classify the activity level and athletic ability of individual athletes, allowing for uniformity within participant demographics in research. The framework has six tiers spanning from Tier 0 (trained/developmental) to Tier 5 (World Class) (McKay *et al.,* 2022). Two athletes were removed from the final analysis. One athlete retired from swimming within eight weeks of the start of data collection due to COVID-19 training-related restrictions, while the second athlete had a pre-existing congenital disorder, which may have influenced their individual data. The participant breakdown over the two seasons is illustrated in **Figure 6-1**. This study was approved by the University Ethics Committee (2019_10_09_EHS).

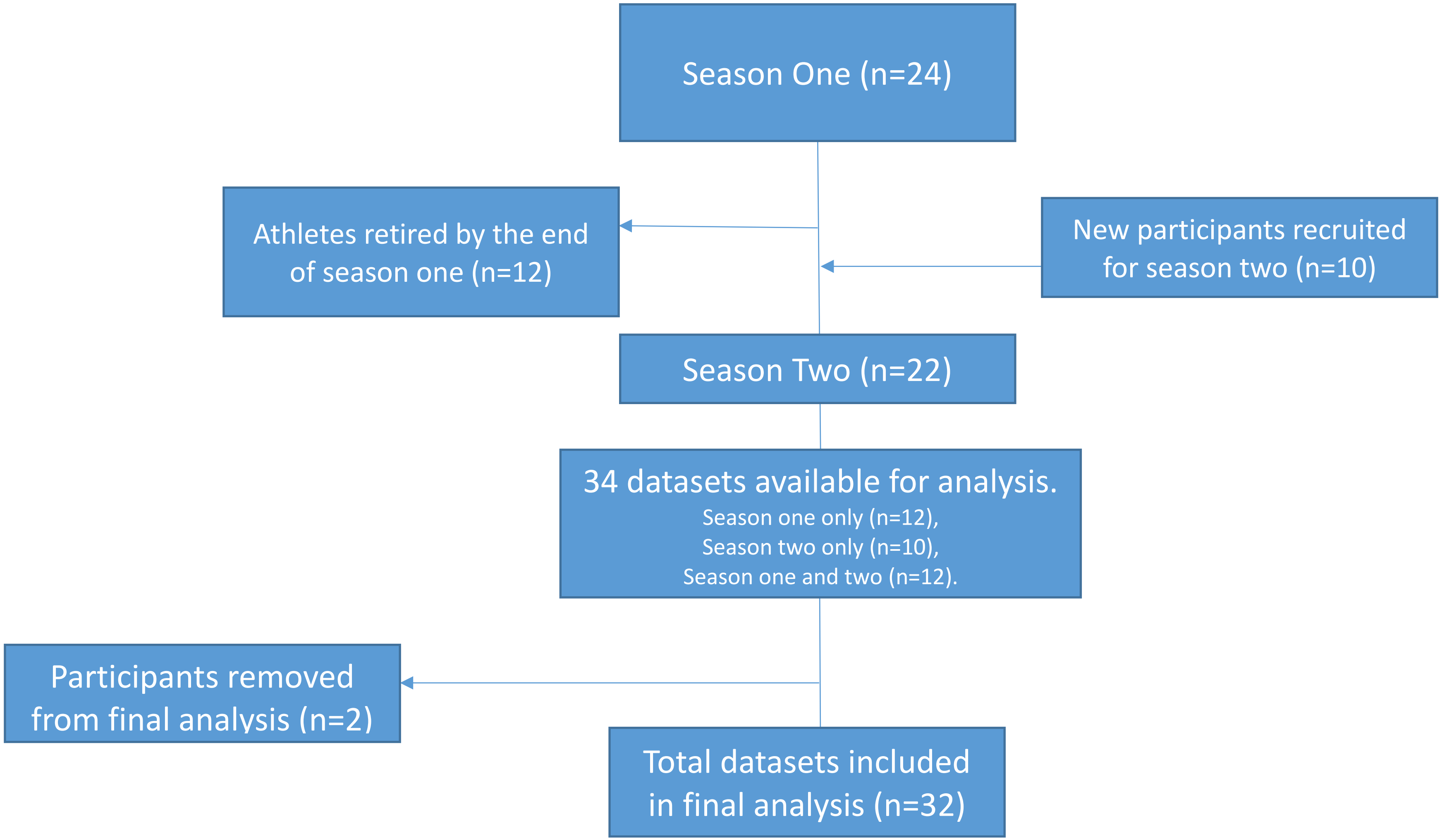

Figure 6-1 Participant breakdown over the two-year data collection period.

6.3.3 Data Collection

The data collection system and procedures have been previously outlined in Barry *et al.,* (2023). Athletes self-reported subjective training load data through the online application Kitman Labs^{TM} (*kitmanlabs.com*), which could be accessed through a mobile phone. Athletes were asked to rate their perceived effort for the entirety of a given session on the modified Borg scale (1-10) (as adapted from the Borg CR10 scale (Borg, 1998)) on the same day of completion. They were also asked to record the session duration (minutes) of the activity and select the activity type (i.e., swimming, S&C – strength, S&C – conditioning or racing). sRPE–TL was calculated by multiplying the sRPE by the duration of the activity, as outlined previously (Foster *et al.,* 2001; Wallace *et al.,* 2008; Griffin *et al.,* 2020a). Athlete self-reported data were audited for completeness on a weekly basis. Individual athletes were contacted regarding missing or suspicious data, with any omissions or errors being clarified. Coaches within each National Centre provided individual session-by-session athlete swim volumes and attendance records through a report emailed to the lead researcher. These data were cross-checked against the athlete self-reported data and any queries were taken to the relevant coach and addressed where necessary.

The injury/illness surveillance system had three MDCs on the project. MDCs were chartered physiotherapists based within each National Centre. Each MDC had sole responsibility for a set group of athletes allowing for a manageable workload. MDCs inputted injury/illness data into a bespoke Microsoft Excel worksheet, designed in line with the Orchard Sports Injury and Illness Classification System (OSIICS) (Orchard *et al.,* 2020). Injury and illness were defined as per Bahr *et al.,* (2020). MDCs were emailed biweekly with a reminder to input any injury/illness information. A monthly follow up video call to audit the data inputted was also conducted. Injury and illness were subcategorised as medical attention, time loss or non-time loss. Time-loss and medical attention were defined as per Mountjoy *et al.,* (2016). Time loss was reported from the date of onset until the athlete was fully available for training or competition. Fully available was clarified as without modification of training prescription, modification of technique or deficits in performance directly related to the injury and illness. Illness or injuries were also defined by severity as per Mountjoy *et al.,* (2016). Additional information collected also included mode of onset, circumstances of injury, injury/illness classification, location, type, and diagnosis as described in Barry *et al.,* (2023). To include the most robust injury and illness surveillance data for analysis, medical attention injury and illness were selected for analysis. **Table 6-1** outlines the key definitions used.

Table 6-1 Definitions of key terms used within the injury/illness surveillance system.

Term	Definition
Injury	Tissue damage or other derangement of normal physical function, resulting from rapid or competitive transfer of kinetic energy (Bahr *et al.* 2020).
Illness	A complaint or disorder, experienced by an athlete, not related to injury. Illnesses include health related problems in physical (e.g., influenza), mental (e.g., depression) or social well-being, removal or loss of vital elements (air, water, warmth) (Bahr *et al.* 2020).
Medical Attention	A physical complaint where a qualified clinician has assessed the athlete's physical complaint or medical condition. A qualified clinician is anyone who is involved in the health care of athletes, reviews medical or physiological information, and/or implements an action plan to improve the athlete's health, where health is considered in a broad sense but must be more than performance enhancement (Mountjoy *et al.* 2016).
Time Loss	A health problem which leads to the athlete being unable to take full part in FINA activities. If the athlete misses the rest of the training or competition session but returns for the next training/competition, this should be recorded as a time-loss incident (Mountjoy *et al.* 2016).
Severity	Mild 0-7 days missed, moderate 8-28 days missed, severe >29 days missed (Mountjoy *et al.* 2016).

Table 6-2 Description of the calculation of training load metrics.

Training Load Metric	Calculation	Description	Scaled Units
Weekly Pool Volume (km)	All session volumes (km) from Monday to Sunday are summed together to generate weekly volume.	Distance swam per week in kilometres	1.0 km
4-week Rolling Pool Volume (km)	Sum of the weekly volume for the current week and the previous three weeks.	Accumulated distance swam for 4 weeks.	10.0 km
Weekly Pool Training Load (AU)	Session RPE * Duration (minutes) = sRPE-TL. All pool session sRPE-TL from Monday to Sunday summed together to generate weekly pool (AU)	Pool training load for one week.	100.0 AU
Weekly Gym Training Load (AU)	Session RPE * Duration (minutes) = sRPE-TL. All dryland session sRPE-TL from Monday to Sunday summed together to generate weekly gym (AU)	Gym training load for one week.	100.0 AU
Weekly Total Load Training (AU)	Weekly pool (AU) and weekly gym (AU) are summed together.	All training load for the week.	100.0 AU
4-week Rolling Total Training Load (AU)	Sum of the weekly total (AU) for the current week and the previous three weeks.	Accumulated training load (AU) for 4 weeks.	100.0 AU
Acute: Chronic Workload Ratio (ACWR)	$EWMA_{this\ week} = Load_{this\ week} * \lambda_a + ((1 - \lambda_a) * EWMA_{last\ week})$ Where λ_a is a value between 0 and 1 that represents the degree of decay, with higher values discounting older observations at a faster rate. The λ_a is given by: $\lambda_a = 2/(N + 1)$ Where N is the chosen time decay constant, typically 7 and 28 days for acute ('fatigue') and chronic ('fitness') loads, respectively.	The ratio of the acute training load (past 7 days) in relation to the chronic training load (past 28 days).	0.1 AU

6.3.4 Statistical Analysis

Daily athlete training load data were accumulated and reported as weekly training load data and included the key variables as described in **Table 6-2**. Medical attention injury and illness (time loss/non-time loss) were recorded as a binary variable where no occurrence was noted as 0 and an occurrence was noted as 1. A lag period of 7 days was calculated for every training monitoring variable by moving the participant's variables back one week in relation to the incidence of injury or illness events. A seven-day lag period was chosen to overcome the potential of a time loss event creating an artificial low load on the week the event occurs and potentially a type II error occurring during analysis (Drew and Finch 2016). A time lag was also pertinent as there has been a suggestion of a delayed effect between training load exposure and injury or illness (Gabbett 2016). One week prior to injury or illness would also represent the latest period of adjustment a coach could make to their pre-planned training week, thus making it practically relevant and impactful. All training load data were scaled as shown in **Table 6-2**. sRPE was scaled as per Tiernan *et al.*, (2022), with Weekly Pool Volume (km) scaled to the nearest kilometer or ten kilometers in the case of 4-week Rolling Pool Volume (km). Data were scaled to improve the practical application of the findings.

Exploratory and descriptive analyses were undertaken using Microsoft Excel (V. 16.0.5378) and IBM SPSS (V. 26). Descriptive analysis included calculating the maximum, minimum, mean, standard deviation and variance for both within and between participant groups. Key training load variables (Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU), 4-week Rolling Total Training Load (AU) and ACWR (EWMA)) were selected for analysis. Weekly Pool Volume (km) and Weekly Total Load Training (AU) were both selected as they are the most frequently used metrics in competitive swimming (Barry *et al.,* 2022). The 4-week rolling metrics were selected to explore the accumulated effect of training load, while ACWR was a key recommendation based on previous literature (Rogalski *et al.,* 2013; Tiernan 2020; Griffin 2021; Barry *et al.,* 2021). Descriptive analysis for participants is presented in

Table 6-4. The data were visually inspected by plotting all variables using histograms and normality was assessed using Shapiro Wilks test with an alpha level set at $p<0.05$ as detailed in Griffin (2021). Assumptions for normality were not met and non-parametric tests were selected for additional exploratory analyses. Subsequent analyses included using Spearman's Rank Correlations to investigate the relationship between medical attention injury and illness (time-loss or non-time loss) and key training load variables. The exploratory analyses summary is presented in Appendix 6.

Based on the exploratory and descriptive analyses and findings, RStudio.ink (V.4.2.2) was used to further analyse the data. Visual representation of the data through dot and violin plots were created to explore the impact of medical attention injury and illness (time-loss or non-time loss) on the key training load variables. A generalised linear mixed effects model was employed to estimate both random and fixed effects. A multilevel binary logistic regression approach was taken to investigate the relationship between medical attention injury and illness (time loss/non-time loss) and key training load variables. This modelling was employed as the response variable was dichotomous. The model would also allow the analysis to assess how well the training load variables predicted the odds of an injury/illness occurring but also would provide a summary of the accuracy of the "goodness of fit". This would help determine the percent of predictions made from the model that would return a positive response (Fritz and Berger 2015). Analyses were conducted using R packages lme4 (Bates *et al.*, 2015), reshape2 (Wickham 2007), sjPlot (Lüdecke 2022), ggplot2 (Wickham 2016) and dfoptim (Varadhan and Borchers 2020). An optimiser (BOBYQA) was employed to support the model. Odds ratios and 95% confidence intervals (CI) were calculated to investigate the odds of a medical attention injury and illness (time loss/non-time loss) given key training load variables. Where an OR was >1, an increased odds of injury was reported, and where an OR was <1 a decreased odds of injury was reported (Rogalski *et al.*, 2013). This analysis was repeated for a 0-day lag period and a 7-day lag period. The probability of the analysis reaching statistical significance using the arbitrary cut off of $p < .05$ was not applied during this analysis. As this population was not a randomised sample the assumption that the findings could be applied to a random sample of competitive swimmers could not be met. It is also recognised that the context behind these data analyses and results is more valuable than a threshold of $p<0.05$ can ascertain (Wasserstein and Lazar 2016; Wasserstein *et al.*, 2019).

6.4 Results

A total of 32 athlete data sets were included for analysis. Participant demographics are included in **Table 6-3**. Participant classification is presented based on McKay *et al.*, (2022).

6.4.1 Training Load

Participants were observed for a total of 104 weeks across two seasons. Athletes typically completed 6-10 pool sessions per week (12-20 hours), depending on their specialist event. Athletes on average attended a minimum of two S&C sessions per week. Across the two seasons, the average weekly volume was 33.5 ± 12.9 km. The weekly total training load (AU) averaged 3,838 ± 1,616.1 AU, with 85% of that load coming from swimming. Due to the diverse nature of swimming events and the range of specialist swimmers included within the cohort an individual participant summary of the training load variables is presented in Appendix 6. **Figure 6-2** illustrates the mean weekly training total load (AU) for the participant group as well as the weekly occurrence of medical attention injury and illness (time loss/non-time loss).

Table 6-3 Participant demographics.

Variable	
Male	n=22
Female	n=10
Age (y)	20.3 ± 3.4
Height (m)	1.81 ± .11
Body Mass (kg)	76.4 ± 12.0
Tier 5 – World Class	n=2
Tier 4 - Elite/International	n=11
Tier 3 – Highly Trained/National	n=19

Table 6-4 Descriptive summary of the key training load variables for the participant population.

Variable	Max	Min	Mean	Stdev	Variance
Weekly Pool Volume (km)	63.20	0.00	33.54	12.88	165.79
4-week Rolling Pool Volume (km)	217.00	0.00	115.99	58.64	3436.55
Total Weekly Training Load (AU)	12280.00	0.00	3838.02	1616.13	2610514.59
4-week Rolling Total Training Load (AU)	29980.00	0.00	13162.08	6535.19	42688934.28
ACWR (AU)	3.16	0.14	1.23	0.39	0.15

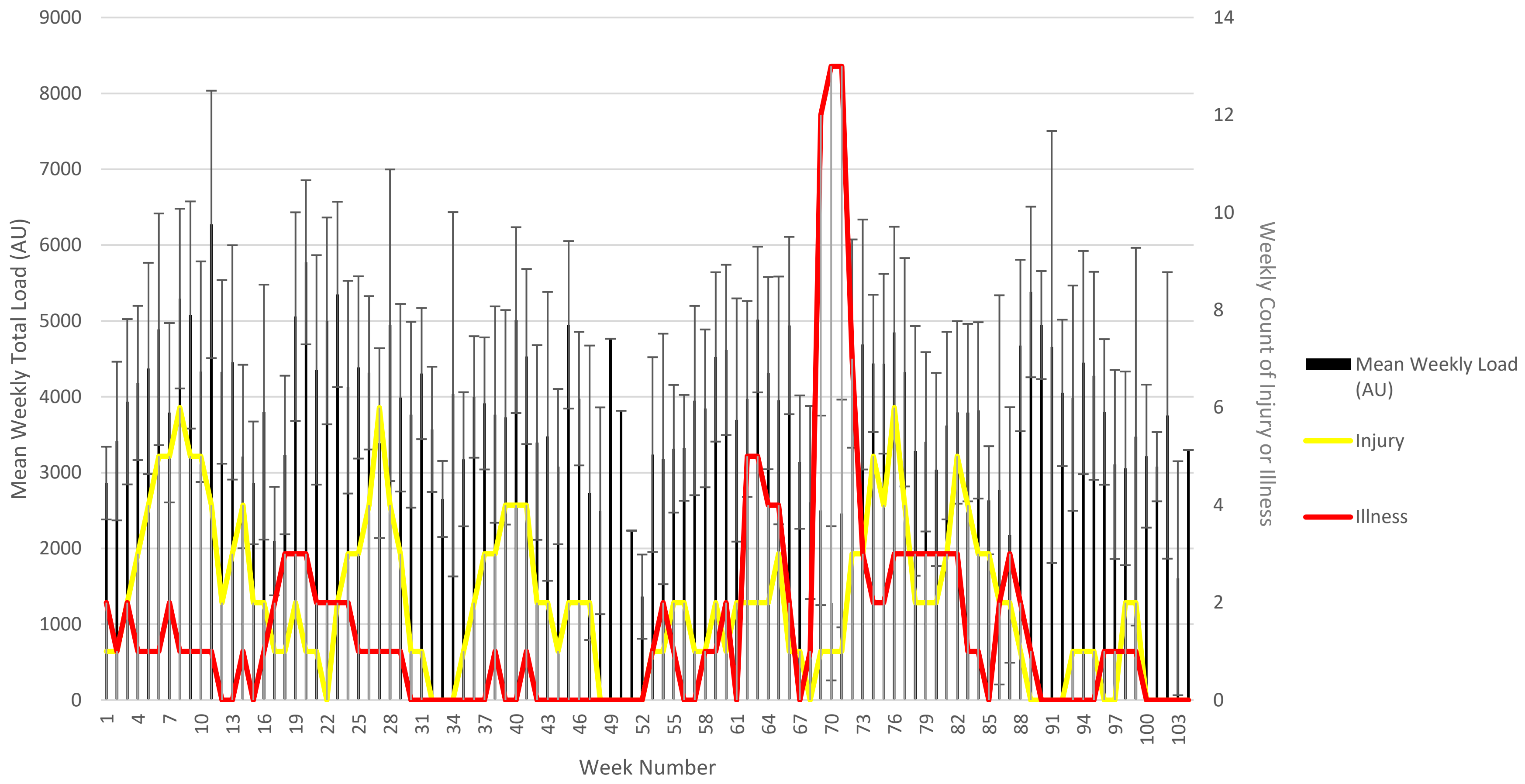

Figure 6-2 Mean ± standard deviation of the weekly total load (AU) and the weekly count of injury and illness incidence throughout the observation period.

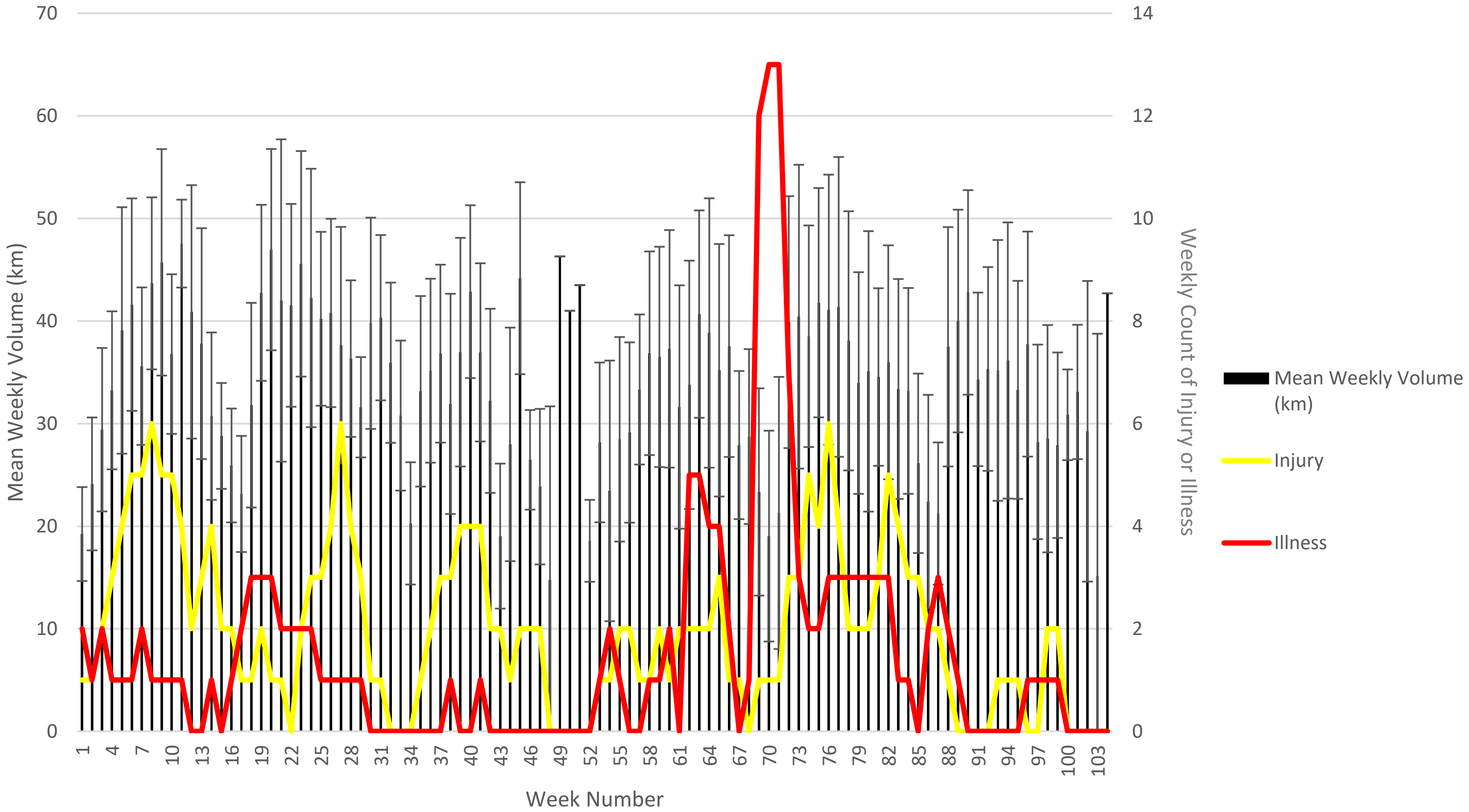

Figure 6-3 Mean ± standard deviation of the weekly swim volume (km) and the weekly count of injury and illness incidence throughout the observation period.

6.4.2 Illness

A total of 60 medical attention illness events were recorded during the observation period. A total of 84.4% (n=27) of the participants registered at least one medical attention illness event during the data collection period. The majority (93.3%, n=56) of illnesses were categorised as time loss. Time loss illness severity was categorised as mild (53.6%, n=30) or moderate (46.4%, n=26) with no illnesses categorised as severe. A large portion (76.7%, n=46) of the illnesses were categorised as “acute – sudden onset”, with the remainder being categorised as “repetitive – sudden onset” (8.3%, n=5), “repetitive – gradual onset” (6.7%, n=4) or “mixed/other” (8.3%, n=5). Communicable medical attention illnesses were most prevalent (76.7%, n=46), while respiratory infections were the most common (70%, n=42) type of illness recorded. COVID-19 was the most common diagnosis (36.7%, n=22) with upper respiratory tract infection being the second most common (21.7%, n=13). **Figure 6-2** and **Figure 6-3** both illustrate a sudden and large increase in the frequency of illness during weeks 69-72. This represents a period where, post national competition, both National Centres had a cluster of COVID-19 cases where multiple athletes contracted the infectious disease.

6.4.3 Injuries

A total of 58 medical attention injury events were recorded with 78.1% (n=25) of participants registering at least one medical attention injury event during the data collection process. Time loss injuries accounted for 36.2% (n=21) of all events, while non-time loss injuries were more prevalent (63.8%, n=37). Time loss injury severity was largely categorised as mild (95.2%, n=20), with only one injury being categorised as moderate and none categorised as severe. “Acute – sudden onset” injuries made up 44.8% (n=26) of all events, with “repetitive – sudden onset” (27.6%, n=16), “repetitive – gradual onset” (25.9%, n=15) or “mixed/other” (1.7%, n=1) accounting for the remainder. The majority of injuries were sustained during either swim specific training (46.6%, n=27) or S&C/dryland training (34.5%, n=20). Non-contact injuries were most common (79.3%, n=46) while direct contact with an object (e.g., making contact with equipment) was also a factor (19%, n=11). The shoulder (24.1%, n=14), lumbar spine (17.2%, n=10) and ankle (12.1%, n=7) were the locations most injured. However, additional injured areas included the knee (8.6%, n=5), groin/hip (8.6%, n=5), thoracic spine, neck, and hand (all 5.2%, n=3), foot (3.4%, n=2), wrist, upper arm, lower leg, head, forearm, and abdomen (all 1.7%, n=1).

6.4.4 0-Day Time Lag

A total of 20 logistic regression analyses were completed to explore the association between key training load variables and the incidence of medical attention injury and illness (time loss/non-time loss). **Table 6-5** outlines the results of these analyses. **Figure 6-4** illustrates a forest plot of the results providing a visual representation of the point estimate and its measure of effect in relation to the null hypothesis (OR=1). Confidence intervals are also presented (horizontal whiskers) for each analysis. The results in the main presented odds ratios of 1 or close to 1, resulting in no association between the training load variable and the odds of an injury and illness (time loss/non-time loss) occurring. The analysis between ACWR (AU) and non-time loss injury suggested that there was a negative association between the two variables (OR 0.89, 95% CI 0.79 – 1.00). However, the confidence interval including 1 suggest that the finding is not significant. Similarly, time loss illness was negatively associated with both Weekly Total Load Training (AU) (OR 0.94, 95% CI 0.93 – 0.96) and Weekly Pool Volume (km) (OR 0.94, 95% CI 0.92 – 0.96). These results whilst statistically significant include OR's of 0.94 meaning the effect size of the result is small (Sullivan and Feinn 2012).

Table 6-5 Logistic Regression, Confidence Intervals (95% CI) and Odds Ratio for key training load variables and injury and illness (time loss/non-time loss).

Variable		Odds Ratio	Lower 95%CI	Upper 95%CI
Non-Time loss Injury	4-week Rolling Pool Volume (km)	1.07	1.01	1.15
Time loss Illness	ACWR (AU)	1.06	1.00	1.12
Time loss Injury	ACWR (AU)	1.03	0.90	1.17
Non-Time loss Injury	Weekly Pool Volume (km)	1.02	0.99	1.05
Time loss Illness	4-week Rolling Pool Volume (km)	1.02	0.97	1.07
Non-Time loss Illness	Weekly Pool Volume (km)	1.01	0.94	1.09
Non-Time loss Injury	Weekly Total Load Training (AU)	1.01	0.99	1.03
Non-Time loss Illness	4-week Rolling Pool Volume (km)	1.00	0.86	1.16
Non-Time loss Illness	4-week Rolling Total Training Load (AU)	1.00	0.99	1.02
Non-Time loss Injury	4-week Rolling Total Training Load (AU)	1.00	1.00	1.01
Time loss Illness	4-week Rolling Total Training Load (AU)	1.00	1.00	1.01
Time loss Injury	4-week Rolling Total Training Load (AU)	1.00	0.99	1.01
Non-Time loss Illness	Weekly Total Load Training (AU)	0.98	0.93	1.04
Time loss Injury	Weekly Total Load Training (AU)	0.98	0.95	1.01
Time loss Injury	4-week Rolling Pool Volume (km)	0.98	0.91	1.07
Time loss Injury	Weekly Pool Volume (km)	0.97	0.94	1.01
Non-Time loss Illness	ACWR (AU)	0.94	0.71	1.02
Time loss Illness	Weekly Total Load Training (AU)	0.94	0.93	0.96
Time loss Illness	Weekly Pool Volume (km)	0.94	0.92	0.95
Non-Time loss Injury	ACWR (AU)	0.89	0.79	1.00

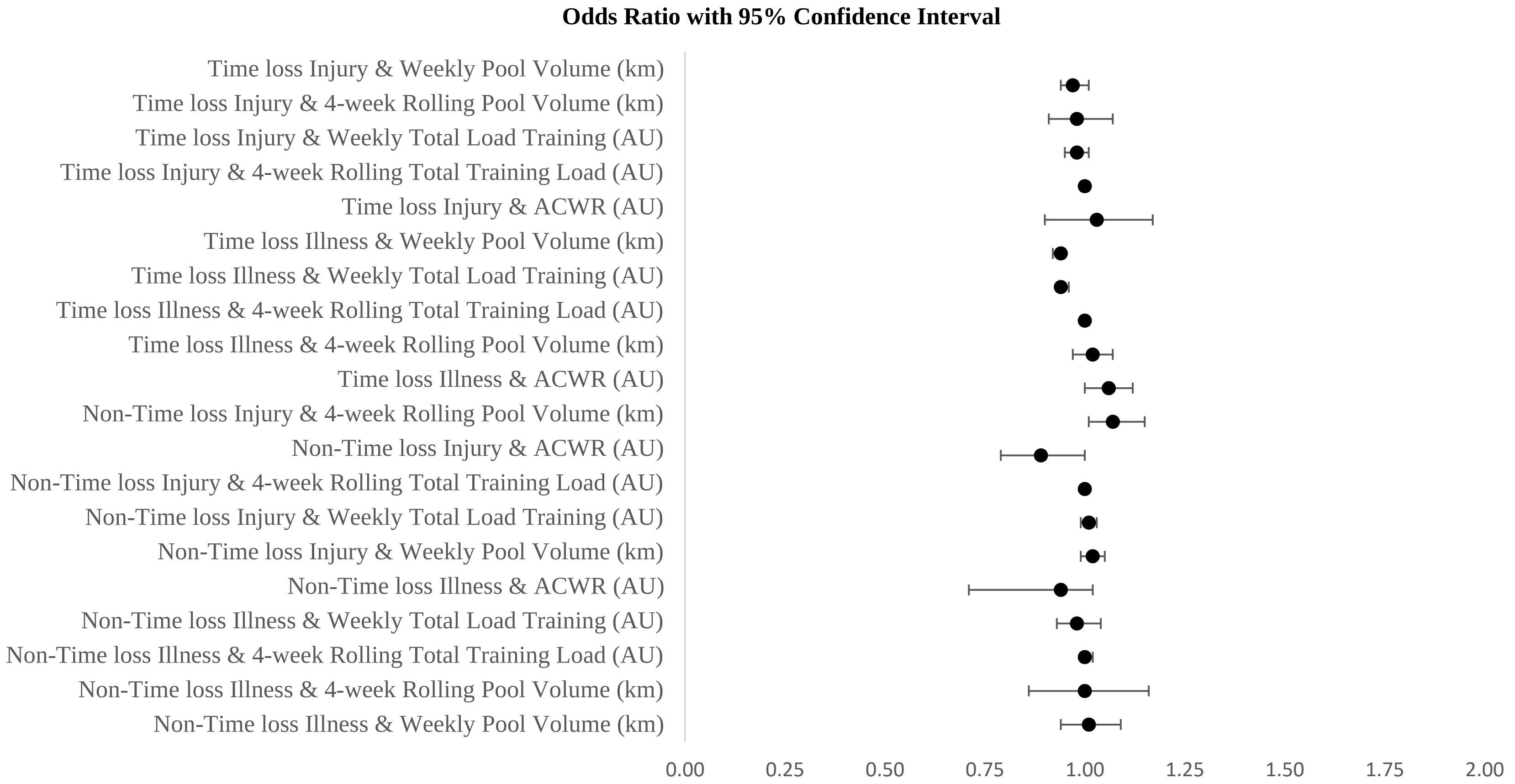

Figure 6-4 Forest plot of odds ratio and 95% confidence intervals for injury and illness (time loss/non-time loss) risk for key training load variables (0-day time lag).

6.4.5 7- Day Time Lag

A further 20 logistic regressions were completed to explore the association between key training load variables and the incidence of medical attention injury and illness (time loss/non-time loss) when a 7-day time lag was present. **Table 6-6** outlines the results of these analyses. **Figure 6-5** illustrates a forest plot of the results providing a visual representation of the point estimate and its measure of effect in relation to the null hypothesis (OR=1). Confidence intervals are also presented (horizontal whiskers) for each analysis. The results in the main presented odds ratios of 1 or close to 1, resulting in no association between the training load variable and the odds of an injury and illness (time loss/non-time loss) occurring. The analysis between ACWR (AU) and non-time loss illness suggested that there was a negative association between the two variables (OR 0.85, 95% CI 0.59 – 1.21). However, the confidence interval including 1 suggests that the finding is not statistically significant.

Table 6-6 Logistic Regression, Confidence Intervals (95% CI) and Odds Ratio for key training load variables and injury and illness (time loss/non-time loss) with a 7day-lag period.

Variable		Odds Ratio	Lower 95%CI	Upper 95%CI
Time loss Injury7	ACWR (AU)	1.09	0.98	1.22
Time loss Illness7	ACWR (AU)	1.07	1.01	1.13
Non-Time loss Injury7	4-week Rolling Pool Volume (km)	1.06	1	1.13
Time loss Illness7	4-week Rolling Pool Volume (km)	1.05	1	1.11
Non-Time loss Illness7	Weekly Total Load Training (AU)	1.03	0.98	1.08
Non-Time loss Illness7	Weekly Pool Volume (km)	1.01	0.94	1.08
Non-Time loss Illness7	4-week Rolling Total Training Load (AU)	1	0.99	1.02
Non-Time loss Injury7	4-week Rolling Total Training Load (AU)	1	1	1.01
Time loss Illness7	4-week Rolling Total Training Load (AU)	1	1	1.01
Time loss Illness7	Weekly Pool Volume (km)	1	0.97	1.02
Time loss Injury7	4-week Rolling Total Training Load (AU)	1	0.99	1.01
Non-Time loss Injury7	Weekly Total Load Training (AU)	0.99	0.97	1.01
Non-Time loss Injury7	Weekly Pool Volume (km)	0.99	0.97	1.02
Time loss Illness7	Weekly Total Load Training (AU)	0.99	0.97	1.01
Time loss Injury7	Weekly Total Load Training (AU)	0.99	0.96	1.02
Time loss Injury7	Weekly Pool Volume (km)	0.98	0.95	1.01
Non-Time loss Illness7	4-week Rolling Pool Volume (km)	0.97	0.84	1.13
Time loss Injury7	4-week Rolling Pool Volume (km)	0.97	0.89	1.06
Non-Time loss Injury7	ACWR (AU)	0.91	0.81	1.02
Non-Time loss Illness7	ACWR (AU)	0.85	0.59	1.21

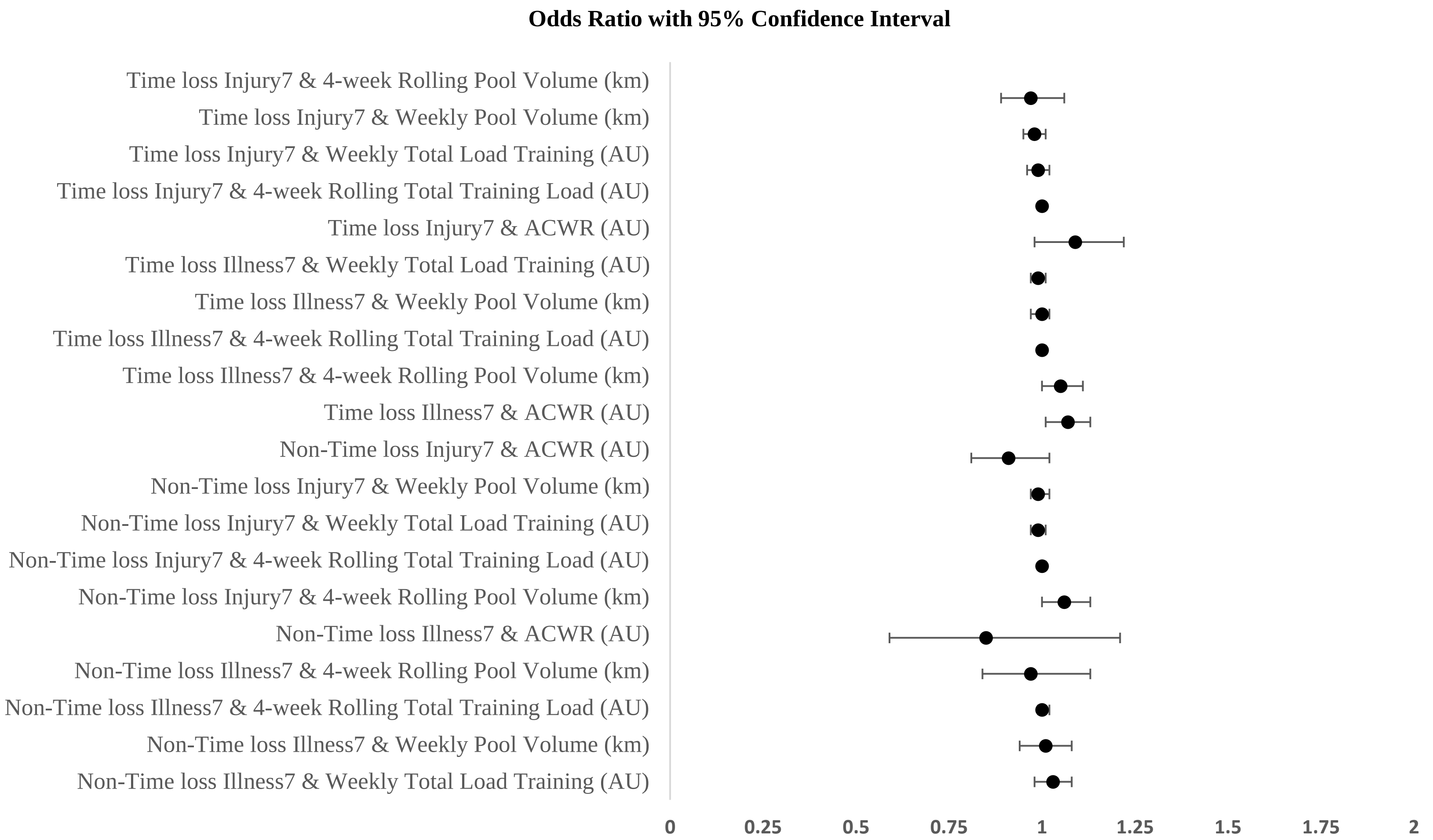

Figure 6-5 Forest plot of odds ratio and 95% confidence intervals for injury and illness (time loss/non-time loss) risk for key training load variables (7-day time lag).

6.5 Discussion

The aim of this study was to explore the association between training load and injury and illness in competitive swimmers. Building on previous literature recommendations, the exploration of the relationship between training load and injury and illness was carried out in line with both the FINA (Mountjoy *et al.,* 2016) and IOC (Bahr *et al.,* 2020) injury and illness consensus statements. It was also grounded in best practices for training load monitoring by employing the use of internal and external training load monitoring methods with a particular focus on sRPE and key aggregate measures. Fundamentally, numerous analyses examining the association between training load variables and medical attention injury, or illness (time loss/non-time loss) returned odds ratios of 1.0 or approaching 1.0. This occurred irrespective of a 0-day or 7-day lag time. These findings suggest that there was no association between the training load metric and medical attention injury and illness. Also, many of the confidence intervals coupled with the odds ratio crossed 1.0 or reported a lower or higher confidence interval equalling 1.0 suggesting the findings were not statistically significant. The primary variables included in these analyses were Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU) and 4-week Rolling Total Training Load (AU) and ACWR (AU).

Typically, Weekly Pool Volume (km), an external training load metric, has been most commonly used by swim coaches to plan and design a swim programme periodisation strategy and monitor athletes' response to training (Barry *et al.,* 2022). However, using training load monitoring for injury reduction purposes has been reported as less common (Barry *et al.,* 2022). This is despite previous research suggesting that repetitive overhead arm movements in swimming, combined with laxity, strength deficits and fatigue, are linked with shoulder injury and pain (Weldon and Richardson 2001). However, in research to date, the relationship between pool volume and injury rate has been described as "questionable" (Lippincott 2018). Tate *et al.,* (2012) highlighted that swimming exposure was a factor in shoulder pain, dissatisfaction, and disability in competitive swimmers, while supraspinatus tendon thickness was affected by the number of competitive years within an athlete's swimming career (Sein *et al.,* 2010). More specific to swim volume (km), Walker *et al.,* (2012) found no association between shoulder injury and training mileage (km). Much of the ambiguity surrounding a consensus on the relationship between these variables has been attributed to methodological inconsistencies and limitations. This study sought to address these methodological inconsistencies through the use of sport specific consensus guidelines, participant classification strategies and appropriate training load monitoring methods. Consequently, the strong methodological foundations of this study design should allay these issues.

Potentially, one finding that would require further investigation was the relationship between Weekly Pool Volume (km) and time loss illness without the 0-day time lag (OR 0.94, 95% CI 0.92 – 0.96). This result indicated that the odds of a time loss illness decreased by 6% with every one-kilometre increase in Weekly Pool Volume (km). This finding may suggest that those who swam a higher weekly pool volume were less likely to develop a time loss illness. It has previously been found that swimmers of a higher ability (international) were at a lower risk of URTPI when compared to their lower level (national) peers (Hellard *et al.*, 2015). It could be assumed in this case that those typically swimming higher weekly volumes were prescribed the increased workload due to their advanced ability. However, analysis was not segregated by athlete level and therefore this cannot be accurately determined. Hellard *et al.*, (2015) also found that periods of high loads accumulated over several weeks resulted in an increase in upper respiratory tract infections (Hellard *et al.*, 2015). This shows that investigating accumulated training load is warranted. The chronic effect of external training load was investigated using an accumulated measure of Weekly Pool Volume (km) (4-week Rolling Pool Volume (km). The findings of this study suggest that the four-week accumulated pool volume had no association with injury and illness (time loss/non-time loss). This may be related to the fact that this metric only considers the chronic impact of external training load and does not incorporate internal training load. Hellard *et al.*, (2015) suggested that there was an increased risk of illness during intensive periods of training. These intensive periods were characterised by increased loads in all training modalities, including in-water and S&C sessions. Employing training load metrics using external training load alone which does not quantify S&C training load is not suitable for monitoring the effect of total load on these athletes. A more appropriate metric would be sRPE derived metrics as they incorporate a combination of both internal and external training load and can be used to quantify all aspects of the training programme (Barry *et al.*, 2022). The investigation of the sRPE derived metrics Weekly Total Load Training (AU) and 4-week Rolling Total Training Load (AU) was a crucial aspect of our study analyses. The results of these analyses showed similar findings to Weekly Total Load Training (AU) and Weekly Pool Volume (km) and time loss illness. The findings indicated that the odds of a time loss illness decreased by 6% with every 100AU increase in Weekly Total Load Training (AU).

However, this result was not found for the 7-day time lag or when the 4-week Rolling Total Training Load (AU) was considered.

These findings contrast with previous literature in other sports which have found a positive relationship between training load metrics and injury and illness. Gabbett (2004) found a reduction in absolute training load (sRPE-TL) resulted in a corresponding reduction in injuries (Gabbett, 2004), while Rogalski *et al.,* (2013) found that an increase in the 1–2-week accumulated training load resulted in a higher risk of injury in elite Australian Footballers (Rogalski *et al.,* 2013). It is very difficult however, to compare these studies as not only are the sports vastly different, so too are the weekly training loads accumulated. This issue is acknowledged by Drew and Finch (2016) who noted that endurance-based sports typically display training load with a longer duration at lower intensity, meanwhile other sports tend to have higher intensity training with lower duration making comparisons difficult. This is a common issue with much of the research examining training load and injury and illness using the sRPE method. Much of the research is on team/field-based sports (Drew and Finch 2016; Griffin *et al.*, 2020b; Maupin *et al.*, 2020) where the training load and mechanisms of injury and illness are considerably different to the sport of swimming. As previously highlighted, swimming studies employing sRPE methods to monitor training load are not readily available for comparison (Barry *et al.,* 2021). Tomar and Allen (2019) did use the sRPE method to investigate the relationship between training load and injury. This study found no significant relationship between a variety of training metrics (weekly load (AU), monotony (AU), strain (AU) and ACWR (AU)) and injury (Tomar and Allen 2019). The authors did acknowledge that their study had a very low sample size (12 participants), short observation period (7 weeks), a very low number of injuries (3 injuries) and low absolute training load (260.97 ± 56.33) in comparison to other studies of this nature. Despite the findings of Tomar and Allen (2019) and this current study being similar, the robust nature of the study design, lengthy observation period and elite nature of the participants within this study strengthens the current body of research evidence.

In a research context, this study has addressed previous limitations (Barry *et al.,* 2021; Trinidad *et al.,* 2021) in the investigation of the relationship between training load and injury and illness. Practically, the analyses investigated both absolute and relative training load measures. The relationship between external training load measures (swim volume (km), combined internal and external measures (sRPE-TL) and ACWR were all investigated. The study design presents a strong framework for future research but also for applied practitioners to understand and transfer to their own environments. The findings of this study show that despite improving the methodological structure of the data collection procedures, understanding the mechanism for injury and illness is complex and multifactorial (Clifton *et al.,* 2016). Rarely can the mechanism of injury or illness be identified by exploring variables in isolation (Edouard and Ford 2020). This is particularly true of an endurance sport like swimming where the training load demands are often cited as a reason for maladaptation to occur (Mujika, 2017). However, while the training demands can be repetitive, they are also very systematic and are planned with care and attention in the elite setting. In this case, while there was large variability between the participants training loads, the structure of their weekly training plan remained largely stable, and the standard deviation of the weekly volume was relatively small. This may indicate that environmental reasons may be responsible as to why the training load metrics were not associated with medical attention injury and illness. The cohort selected were training in an elite environment with consistent coaching staff and support practitioners over the two-year period. This stable and high level of support and input leads to a robust training culture being implemented. This is evidenced and supported by the training load data which is best illustrated in **Figure 6-2** and **Figure 6-3**. These data suggest that the participant training programmes did not have large fluctuations and were balanced in their prescription when anecdotally compared with other swim training environments. Also, the manageable participant numbers in the training centres suggest that coaches should be able to combine the “art” and “science” of coaching to determine when their athletes were at risk of injury and illness through external stressors or training load management. As suggested in Barry *et al.,* (2023) coaches typically use training load monitoring systems as a warning or communication tool. Typically, training load information is used to aid decision making and is used alongside all key information from the multidisciplinary team. In this instance, a lack of association within this cohort could be as a result of appropriate and intuitive training load management from the coaches and an ability to tolerate the training demands by the athletes. At this elite level, coaches can observe and plan their athletes training programmes very accurately creating an environment where minor adjustments can be made regularly throughout the training session, training week, or cycle. This could reduce the likelihood of injury or illness occurring or at least reduce the severity of injury or illness to a non-medical attention issue and may relate to the lack of association found within the study analyses. This may not be the case in a less elite environment where the training structure is less consistent with less attention on the individual plan of the athlete, potentially leading to inappropriate load management. The use of training load monitoring of this nature could be more useful in a club environment where potentially the number of athletes to coaches is much greater, session attendance is more variable week-to-week and individualised planning is not as commonplace. Despite these findings, the use of this training load monitoring system is still of significant benefit to coaches by determining the athlete's individual response to the training stimulus. Based on these findings, coaches could limit attempts to predict injury and illness through intensive monitoring practices and increase their focus on individualised monitoring for improved training and performance outcomes. They can also modify any risk adverse training load strategies that may have been implemented based on previous research conducted in other sports (Gabbett 2016). Individualised training load management and performance improvements were seen as the principal reasons coaches used training load monitoring in a recent survey of international swim coaches (Barry *et al.*, 2022). In the practical environment, training load monitoring can be successfully used as part of good training load management practices. Ultimately, utilising these monitoring tools to identify the competition loads for athletes and help coaches prepare for them adequately is a significant benefit. They can also be employed to compare the planned versus actual loads the coaches prescribed against what the athlete experienced and thus creating more individualised plans for athletes (West *et al.*, 2020).

6.6 Limitations

A limitation of this study based on the findings could be the participant sample size. Future research should look to increase the sample size or the number of subsequent seasons of observation. However, it must be noted that in an elite sporting context conducting research over two seasons on a sample size of 32 athletes is atypical and should be seen as a strength of this study. To further expand the number of injuries and illnesses collected, the definition could be expanded to include non-medical attention events. This could increase the number of events and potentially strengthen the logistic regression models conducted. However, the inclusion of non-medical attention injuries increases the burden on the MDCs or coaches to collect greater amounts of data and decreases the accuracy of the event diagnosis on record. The transferability of this study is also a potential limitation that must be acknowledged. The principles of the study design are transferable, but only to environments where the resources are available (e.g., training load data collection system, MDCs, etc.) It must also be noted that the findings are less transferable to a population of lower or higher ability, or to training programmes who employ vastly different training programme philosophies.

6.7 Practical Application

This study highlights the practical application of a training load monitoring and injury/illness surveillance system in a competitive swimming environment. The methods applied illustrate to researchers and practitioners how to accurately implement such a system but also highlight the challenge in solely using training load monitoring to help in the prevention of medical attention injury and illness. The results of this study show that using training load metrics such as Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU), 4-week Rolling Total Training Load (AU) and ACWR will not definitively inform decision making when trying to prevent medical attention injury and illness. With this in mind, coaches should acknowledge that preventing injuries and illness is a multifactorial process and no single metric can predict an adverse event. Instead, coaches should rely on these metrics to plan and prepare athletes' training programmes as effectively as possible. It also suggests that coaches can streamline their training load monitoring data outputs to include metrics which help them compare, organise, and plan training load prescription and periodisation with a more holistic and athlete centred mindset. Practitioners in youth or development setting should look to embrace these training load monitoring practices, particularly when coach to athlete ratios are not optimal or during high-risk training scenarios such as integrating a new athlete or transitioning from a club to collegiate programme. This was highlighted in Wolf *et al.,* (2009) the collegiate swimming population are at increased risk of injury in the first twelve months of joining a varsity swim team. This is likely due to the transition from high-school or club swimming coupled with a sudden increase in training demands, followed by acclimatisation in those that do not drop out of the sport. In these cases, if both club and collegiate settings had sRPE based training load monitoring methods in place the athlete could transfer from one setting to another with a training load passport. This training load passport would detail their training load history and inform future coaches of their training load capabilities, reducing the risk during the transition period. Future practitioners should look to integrate these training load monitoring practices to safeguard for healthy and evidence-based training prescription and periodisation programmes and adopt these processes where training prescription and athlete management is a concern.

Chapter 7 Discussion, Strengths and Limitations, Practical Applications, and Conclusions

7.1 Discussion

The aims of this programme of research were to (1) explore best practice in monitoring training load, injury, and illness surveillance in competitive swimming environments and (2) Investigate the relationships between training load and injury and illness in competitive swimmers. The research also sought to explore the barriers and limitations associated with monitoring training load and conducting injury/illness surveillance in this population and in real-world training environments. Consequently, it was essential to implement a research-driven prospective data collection process which was immersed in best-practice research. Ultimately, this programme of research provides a basis for informing future injury/illness prevention guidelines and training load and injury/illness surveillance practices within competitive swimming.

This chapter synthesises the key findings of this programme of research. The construction and direction of this body of research are discussed in relation to three prominent themes. The themes: *methodological considerations and recommendations, the relationship between training load and injury and illness* and *the importance of illness surveillance* are presented and discussed individually but are intricately linked. This chapter also presents the strengths of the research and highlights the limitations involved. The practical applications and recommendations for future research are also outlined.

7.1.1 Methodological Considerations and Recommendations

Conducting a systematic review of the literature related to training load and pain, injury and illness was a crucial initial step in the design of this body of research. Despite the relationship between training load, injury and illness being the aim of this programme of research, the inclusion of pain within the systematic review was a critical component. This decision was fundamentally based on previous research, the nature of the sport and the design of the systematic review search strategy. Previous research has included broader terms within systematic reviews to account for the nature of prevalence-based definitions for overuse injuries which are recorded using athlete-reported symptomology (Drew and Finch 2016). In the case of Drew and Finch (2016) the term ‘soreness’ was included in the search strategy to include studies with a less traditional injury definition. This ideology relates strongly with the recording of overuse injuries in endurance sports where pain may be the primary symptom with secondary impairment and disability (Bahr 2009). The inclusion of studies focusing on overuse injuries or pain in this research was a vital element and therefore adding the term pain, alongside injury and illness was a prudent decision. Exploratory searches conducted using solely injury and illness terms yielded a narrow view of the research involved. The addition of the term pain (and its synonyms) broadened the search and gave a more extended view of the topic under investigation. This decision proved essential when the final results showed that pain was most frequently explored out of the 15 studies included in the original analysis.

The systematic review highlighted that pain was a key term used within swimming research. It also discussed pain in an applied setting where it was found to be a common condition in the training environment (Hibberd and Myers 2013). A study investigating shoulder pain in club swimming found that 72% of swimmers use pain medication to continue training (Hibberd and Myers 2013). With this in mind, the systematic review noted that using a traditional time loss injury definition may mask and under-report the true impact of such pain/injuries (Bahr 2009). A key recommendation from the systematic review highlighted the need for research of this nature to be aligned with injury and illness consensus guidelines. Creating consistency in the study designs by aligning with the FINA/IOC consensus guidelines was an important thread throughout this programme of research. An integral step in the process was selecting the most appropriate injury and illness definition. Encompassing an injury definition which would be sport specific to swimming and attend to the complexities surrounding the overuse injuries and the common presence of pain was of paramount importance. Both the FINA (Mountjoy *et al.,* 2016) and IOC (Bahr *et al.,* 2020) injury definitions were considered at great length. Importantly, both definitions included terminology which would allow overuse injuries and general physical complaints from the athlete to be captured adequately. However, the very specific nature of the FINA definition (Mountjoy *et al.,* 2016) which directed that the physical complaint or observable damage to the body had to occur during participation in training or competing in aquatic disciplines was thought to be a limitation. Employing this definition would narrow the type of injury captured to those which specifically occurred during training or competition and would neglect to capture those that reportedly occurred outside of this environment but were considered to be a direct result of training load. Subsequently, the decision was made to incorporate the IOC injury definition which was described as a more inclusive definition in Bahr *et al.,* (2020) and could be further subcategorised as medical attention, time loss or occurring (directly, indirectly or not at all related) due to participation in training or competition (Bahr *et al.,* 2020).

A secondary recommendation from the systematic review, which was directly tied to the FINA consensus statement, was the use of symptom-based reporting through the OSTRC questionnaire. The consensus statement highlighted that the use of a health problems questionnaire would help with prospective monitoring of athletes out of competition environments. This questionnaire has been validated for use with swimming populations (Clarsen *et al.,* 2014) and is designed to allow for athlete self-reporting of health problems as well as detailed information on the injury and illness (Mountjoy *et al.,* 2016). This recommendation was trialled during the prospective data collection familiarisation period where the athletes were directed to complete the OSTRC questionnaire at the end of each training week. However, the athletes reported that having an additional questionnaire to complete alongside their daily monitoring system (Kitman Labs^{TM}), was overly burdensome and the NGB, supported by the coaches and athletes requested it not be included in the prospective injury and illness surveillance process. This decision was made with consideration to the findings in Chapters three and four. Both chapters explored the barriers associated with implementing a training load monitoring and injury surveillance system. Engagement from the NGB, coaches and wider MDT were all discernible barriers when implementing an effective training load and injury surveillance system. Chapter two highlights that the successful implementation of a training load monitoring system is directly associated with end user engagement (Neupert *et al.,* 2019), with the goal of reducing the level of burden on those within the data collection processes.

A key discussion point within the systematic review was the type of training load metrics being employed within competitive swimming research. A large focal point of the discussion centred on the over-reliance on external training load metrics to monitor and present training load. Much of the research discussed external training load in terms of session duration, session distance or session frequency. Despite the common thread of external training load being utilised, the metrics were expressed in a wide variety of ways/units (hours/week, km/week, hours/session, km/session, practices/week, km/year, hours/year). This lack of consistent reporting rendered the ability to make comparisons between the training load presented in each study difficult and negated the ability to conduct a meta-analysis to support the systematic review. Subsequently, the systematic review put forward several future study recommendations. Firstly, as per the consensus guidelines on training load monitoring in athletes (Bourdon *et al.,* 2017), a combination of internal and external training load should be employed. This is crucial when exploring the athlete's response to training load as only an internal training load variable can provide the necessary information. It is also of critical importance when investigating the relationship between training load and injury and illness. Bourdon *et al.,* (2017) summated that an integrated approach to training load monitoring is important as no single marker of an athlete's response to load can consistently predict maladaptation (Soligard *et al.,* 2016). Therefore, internal and external training load should be monitored in combination to provide greater insight (Bourdon *et al.,* 2017). Bourdon *et al.,* (2017) also recommended that objective and subjective tools should be employed to ensure an equal balance between athlete perception and quantifiable practice. Based on these recommendations, the systematic review discussed the use of the sRPE method of monitoring training load. This method combines an external and objective measure of training load (session duration in minutes) and the internal and subjective metric sRPE to create a numeric representation of the overall load of the session (sRPE-TL). Each chapter outlined the value of sRPE in training load monitoring and have summarised the many ways it has been employed in the research across different sports. However, the systematic review uncovered its underutilisation in competitive swimming research as only one study (of low quality) (Tomar and Allen 2019) used this method. This finding was subsequently explored in more detail, and it was hypothesised that while the sRPE method was underutilised in competitive swimming research, it may be more frequently employed in a practical setting. Chapter three was designed to explore how data collection and analysis are being implemented and what measures are considered effective in a practical setting. The barriers and facilitators to training load monitoring were also examined. A key finding of Chapter three was the widespread implementation of both internal and external training load markers and the high prevalence of sRPE as an internal training load measure. This is in direct contrast to the findings of Chapter two. These opposing findings highlighted a research - practice gap where it is evident that research practices in competitive swimming need to follow best practice and applied practices in relation to training load monitoring.

Additionally, the systematic review highlighted the need to investigate the links between training load and the incidence of injury and illness in an elite swimming population using sRPE in a longitudinal prospective cohort study. This recommendation is directly tied to the need to adhere to strong methodological study designs and the consensus guidelines. The systematic review highlighted that similar to the large variation in training load methods employed, the operational definitions for injury and illness also had substantial inconsistencies. Injury and illness definitions were often based on the principle of time loss, restriction of training (Tomar and Allen 2019) or medical attention (Ristolainen *et al.,* 2014). As discussed previously in Chapter four, while the use of this terminology is appropriate and common place in many sports, they have limitations when applied to sports such as swimming, where few traditional time loss injuries occur (Bahr 2009). Based on previous findings regarding the research practice gap within the monitoring of training load, it was imperative that a similar investigation was conducted into the collection of injury surveillance data in a practical and competitive swimming environment. This was conducted through an international survey of injury surveillance practices as presented in Chapter four. The findings showed that in most cases either the FINA (Mountjoy *et al.,* 2016) or IOC (Soligard *et al.* 2017) definition of injury was employed, with a small percentage of responders using custom definitions. This was a positive finding as it showed that sport specific definitions have largely been employed. However, there was still an element of variation in the applied setting. The importance of this finding was discussed in Chapter four, where responders highlighted that they were not collecting this data for research purposes. Given that research is not a priority within these environments, an injury definition that is consistent, and appropriate, over an extended period of time, may be more suitable, than what is currently used within the literature. The survey did reveal that the goals of injury surveillance were primarily "to keep a record for insurance purposes", "to analyse in relation to other training factors", "to inform appropriate athlete training prescription" and/or "to highlight trends in injury occurrence".

The international survey presented in Chapter four also highlighted that only half of the responders conducted further analysis on the data after collection. Where further analysis was conducted, injury prevalence, injury incidence, injury per training exposure and injuries related to stroke or event were mostly employed. Interestingly, the consensus guidelines focused largely on the methodology of injury and illness surveillance and did not expand into how to handle the data after the collection phase. The consensus statement provided guidelines on how to report data through incidence and prevalence and briefly stated that assessment of risk factors should be included in the injury and illness surveillance projects to facilitate the development of preventative interventions (Mountjoy *et al.,* 2016). The objective of the statement was to enhance athlete health and performance through improved quality of injury/illness surveillance data collection and to aid the development of preventative measures. Based on these findings, it seems that those within a practical environment would benefit from additional guidance on how best to progress from the data collection phase. Additional detail on how to collect and analyse the data in relation to additional risk factors and subsequently monitor and inform injury prevention strategies would be beneficial. Chapter four highlighted this key finding and suggested that the publication of guidelines which outlined how to best integrate multiple monitoring systems in a practical environment may not only improve the standard of injury surveillance findings but also potentially improve the effectiveness of injury prevention interventions. Chapter five and six sought to address this recommendation by describing the design and implementation of an integrated monitoring system and subsequently using the system for a two-year training load and injury/illness observation period. The system was designed and implemented with specific attention to the barriers and facilitators highlighted by practitioners working within competitive swimming and a crucial end-user evaluation process being performed after year one as recommended by WHO (2001) and Yeomans *et al.,* (2019). An key finding within the end-user evaluation was that coaches deemed athlete wellbeing (sleep duration and quality) metrics more important than sRPE when trying to understand what key metrics they felt best represented their athletes' ability to train as planned. This is an interesting finding as the survey findings emphasised that a significant percentage of coaches collected sRPE data (second only to weekly/daily distance (m or km)). It was also noted that coaches only found training load monitoring to be moderately effective in relation to preventing injury and informing training prescription. This identifies a key issue in the training load monitoring process. Despite critical data being collected, confidence in its application to inform injury prevention and training prescription is apparently low. This may be driven by a host of conflicting evidence in other sports as to the accuracy of a relationship between training load and injury and illness (Drew and Finch 2016; Eckard *et al.,* 2018). A pivotal step in this process was to explore the relationship between commonly used measures of training load and the incidence of injury and illness in competitive swimming.

The comparison of injury and illness data to previous research is problematic as the injury and illness operational definitions used, and the training load methods employed, are not consistent. However, Trikha *et al.,* (2022) outlined musculoskeletal injuries and illness contracted by NCAA swimmers. Their findings have some similarities, and it can be assumed that the population would be of a similar standard. Trikha *et al.,* (2022) found shoulders to be the most common body part injured in their study, with injuries to the spine/back and knee also being relatively common. Only 17.3% of the collegiate swimmers were impacted by injury at any point during a season. However, of those that did get injured, 50.4% of them occurred in pool training, 13.5% in the weight room and

3.9% during competition. This pattern has also been observed by Soligard *et al.,* (2017) who reported a higher incidence of injury in training than in competition. The injury profile outlined in Chapter six also found shoulders to be the most common location of injury, followed by lumbar and ankle. Some similarities were evident regarding the distribution of where injuries were occurring. The pool training environment accounted for almost half of the injuries in both instances, but there was a divergence in dryland or S&C related activities. In contrast, this programme of research illustrated a much higher occurrence of injuries during S&C activities and while a comparison on the type, amount, intensity of training load being applied in Trikha *et al.,* (2022) is not possible, it should be a consideration for future seasons in the present cohort.

The presentation of training load information alongside injury and illness epidemiological data is a critical part of broadening the understanding of the aetiology of injury and illness. The comparison of Trikha *et al.,* (2022) and the findings of the longitudinal study highlight that a lack of training load exposure data has limited the context of the information available and diminished the transferability of the findings. This was a finding also previously discussed, where two injury surveillance studies (Matsuura *et al.,* 2020; Boltz *et al.,* 2021) presented high quality injury data, but limited training load exposure data. Matsuura *et al.,* (2019) calculated incidence rates as the number of events per competing athlete and per 100 athletes by body part over the course of the whole study period. Boltz *et al.,* (2021) did not calculate incidence rates but instead opted for the rate per 1000 athlete exposures (AE). Scheduled team practice and competition were considered a reportable exposure for analysis. The authors described an AE in this case was one athlete participating in one exposure event (Boltz *et al.,* 2021). The FINA consensus statement has recommended the reporting of incidence rates as the number of new injuries/illnesses per 100 athletes, per 1000 athletes exposures, or per 1000 athlete-days or per 1000 hours of exposure (Mountjoy *et al.,* 2016). Practically, applying these incidence rates or exposure data to a competitive swimming environment is not always transferable or quantifiable. Research has presented swimming incidence rates in relation to swim distance. Walker *et al.,* (2012) stated that shoulder injury rates occurred at a rate of 0.2 to 0.3 injuries per 1000 km of swimming. However, they also presented the data as recommended by the FINA consensus guidelines as 0.9 injuries per 1000 hours (Walker *et al.,* 2012). This method of presenting both pieces of information may be considered both academically and practically beneficial for future research. Similarly, with the high frequency of training load being expressed as sRPE-TL in a practical environment as discussed in Chapter three expressing injury incidence rates per 1000AU could be of benefit to the applied setting.

7.1.2 The Relationship between Training Load and Injury and Illness

An important aspect of this research was exploring the relationship between training load (using the sRPE method), injury and illness in a competitive swimming population. The final study outlines the analysis of two seasons (104 weeks) of training load and medical attention injury/illness surveillance data. The aim of the study was to explore the relationship between training load and injury and illness in this cohort. Even though the integrated training load and injury/illness surveillance system outlines the collection of athlete self-reported physical complaints, non-medical attention injury/illness and medical attention injury/illness, it was decided to solely investigate the medical attention injury/illness data. Medical attention injury/illness data was considered the most robust data as each diagnosis was confirmed by a physiotherapist. These results are outlined in detail in Chapter six. The findings show that the low confidence that coaches have in the ability of training load (as suggested in Chapters three and five) to prevent injury is justified. Training load expressed as Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU) and 4-week Rolling Total Training Load (AU) and ACWR was found to have no association with either injury or illness. This finding is consistent, irrespective of a 7-day time lag or a 0-day time lag. This finding could be due to a host of reasons, with particular emphasis on the training environment being investigated. The training load demands of the National Centres investigated are presented in Chapter six. The average weekly volume across the two seasons was 33.5 ± 12.9 km. Meanwhile, the weekly total training load (AU) averaged 3,838 ± 1,616.1 AU, with 85% of that load coming from swimming. Anecdotally, this would be considered a very measured training exposure for athletes of a national and international level in the world of swimming. This average weekly volume may be influenced by the variety of swim events (distance and stroke) of the included athletes. Largely, the cohort included sprinters and middle-distance swimmers, with the majority of the swimmers specialising in distances of 400m or less. This distribution of events would suggest the average weekly volume may be lower due to the inclusion of sprinters and not long-distance (800-1500m) swimmers. However, despite this observation, it is apparent that the training philosophy of the National Centres was not centred on a volume based approach (Nugent *et al.,* 2017). An abundance of research suggests that the high frequency of training (Weldon and Richardson 2001), as well as the repetitive motion (Pink and Tibone 2000) can predispose swimmers to symptoms of overtraining (Khodaee *et al.,* 2016). **Figure 6-2** and **Figure 6-3** illustrate the mean weekly swim volume and mean total training load over the observation period. Interestingly, both figures present training patterns which are cyclical in nature and have an undulating form. This may highlight that the planning of the training loads in these elite environments are systematic in nature and are planned with care and attention. Chapter six highlights that there was large variability between the swimmers' training loads. This may suggest a highly individualised approach to planning the weekly training loads. At this elite level, coaches can observe and plan their athletes training plans very accurately, potentially creating an environment where minor adjustments can be made regularly. This could reduce the likelihood of injury and illness occurring or at least reduce the severity of injury and illness to a non-medical attention issue and may relate to the lack of association found within this body of work.

One aspect of the findings of Chapter six relates to the exploration of the ACWR and its relationship with injury and illness. The findings in Chapter six found no association with ACWR and medical attention injury and illness. This finding was consistent regardless of a 0-day or 7-day time lag. The concept of using ACWR in this population has not been well examined with only one study (Tomar and Allen 2019) investigating its applicability to injury included in Chapter two. This study has been discussed at length, with the discussion highlighting the study flaws related to very low sample size, short observation period, a very low number of injuries and low absolute training load in comparison to other studies of this nature. However, it also must be noted that the authors chose to employ the ACWR rolling average method which has been described as less sensitive by Griffin *et al.,* (2020a). Collette *et al.,* (2018) also investigated the use of ACWR but with the more sensitive EWMA approach in a swimming population but found that it was a less valid measure than the Acute Recovery and Stress Scale (ARSS) to monitor the recovery – stress continuum in athletes. Unfortunately, this study did not collect injury/illness surveillance data. It has been discussed that in individual sports, like swimming, the use of a measure like ACWR is not as applicable due to the periodisation strategies applied to the competition calendar (Boullosa *et al.,* 2020). Team sport competition calendars tend to be dense in nature with frequent competitions throughout the year resulting in time restricted workload accumulation periods and no true peaking events (Boullosa *et al.,* 2020). This is contrasted with individual sports where there are prolonged periods of loading with less frequent tapering and peaking events. These tapering and peaking events are commonly associated with periodisation models and modern elite training environments have adopted the multifactorial approach of periodising not only training load but also recovery, psychology support, dietetics and skill acquisition (Boullosa *et al.,* 2020). These individual sport principles and practices have reduced the value of a metric like ACWR being necessary to avoid sudden changes in load and subsequent increased risk of injury and illness. This would link directly in with the suggestion that the training environment, culture, and philosophies of the National Centres could have impacted the association between training load and injury/illness as discussed in Chapter six. This issue has been highlighted previously where Carey *et al.,* (2018) suggested that analysis of this nature needs a higher proportion of injury/illness events to non-events to provide a strong model. The study suggested that future research needs to increase the number and variety of predictors or greatly increase the number of observations and potential injury data by elongating the observation period to greater than ten seasons (Carey *et al.,* 2018). However, it cannot be assumed that by elongating the observation period in elite sporting settings that the proportion of injury/illness events to non-events would change.

7.1.3 The Importance of Illness Surveillance

The exploration of illness within competitive swimmers was a pivotal aspect of this programme of research. The illness profile of a swimmer has been less well established than the injury profile. The exploration of the influence of training load as a risk factor for illness has also not been as well explored in this population. The systematic review documented only one study (Hellard *et al.,* 2015) which investigated the relationship between training and illness. This study quantified training load in meters per week at each intensity, determined by a blood lactate step test detailed by Mujika *et al.,* (1996). A positive relationship was discovered with periods of high training loads (OR 1.10, 95% CI 1.01 – 1.19; p = 0.0244) increasing the odds of illness by 50-70%. Unfortunately, as this odds ratio is related to a small effect size (Sullivan and Feinn 2012) and was not supported by additional literature, the positive relationship was characterised as being found with limited evidence and should be interpreted with caution. The review highlighted the need for illness to be included in future research, as per the FINA consensus statement by Mountjoy *et al.,* (2016).

Research has shown that swimmers regularly train and compete with persistent health problems (Prien *et al.,* 2017). This research has outlined that significant immune deficiencies are not commonplace in swimming, but minor illnesses such as URTIs occur more frequently (Hellard *et al.,* 2015). The pulmonary issues in swimming are thought to be related to regular exposure of chemical compounds in the swimming environment coupled with the training load associated with the sport (Khodaee *et al.,* 2016). The high incidence of URTIs was also seen in collegiate swimming at NCAA Division I level (Trikha *et al.,* 2022). This study analysed the injury/illness surveillance data for 641 collegiate swimmers over four seasons. The findings showed that 24.3% of all illnesses were recorded as URTIs over the observation period and that URTIs were the most common non-musculoskeletal issue experienced (Trikha *et al.,* 2022). The authors agreed with Khodaee *et al.,* (2016) and summarised that the high prevalence of URTIs was due to intense training in a chlorinated environment, vitamin D deficiency being common in this population, or sustained variations in ventilation during sport, affecting the airway epithelium (Trikha *et al.,* 2022). The authors also concluded with the recommendation that routine screening procedures for these respiratory illnesses should be considered which is in line with guidance from Mountjoy *et al.,* (2016). This illness profile was similar to what was seen through the 104-week observation period within this programme of research. A total of 60 medical attention illnesses were recorded with respiratory illness being most prevalent. Taking COVID-19 diagnosis aside, URTIs (21.7%) were the most common illness contracted by the swimmers. Seasonal differences were not statistically analysed; however, **Figure 6-2** and **Figure 6-3** showed that the frequency of illness increased above two incidences per week on five separate occasions. Three of these occasions were during the winter months (December-February), with one occasion occurring in late autumn (October-November). One occasion was in week 87 (April) and while this was not during the winter months, it was only a one-week spike which was less than the rest of the occasions (average of 4.75 weeks). This finding is in accordance with Hellard *et al.,* (2011), who noted that there was a higher risk of infection during the winter period, which they defined as September to March. They concluded that the winter period, coupled with intensive periods of training would lower the athletes' ability to resist viral or non-viral pathogens which naturally surge during the winter months (Hellard *et al.,* 2011). This pattern was also echoed by Hellard *et al.,* (2015) who found that URTPIs were 2.62 times higher during the winter months. The severity of illnesses in the longitudinal study was considered generally mild to moderate, which is higher than that of the injury severity which was largely described as mild. This increased severity of illness in comparison to injury adds weight to the need for adequate illness surveillance and robust investigation into the risk factors associated with it.

The systematic review did not unearth the same methodological limitations for the collection and reporting of illness as was discovered with injury. This is due to a lack of research as opposed to the methodological issues being present. The design and implementation of the integrated training load monitoring and injury and illness surveillance system has previously been described. The illness surveillance procedures within this chapter were largely driven by the FINA and IOC consensus guidelines. The system was designed to collect time loss and non-time loss illness as well as medical attention and non-medical attention illness. Illness was classified as communicable or non-communicable, with a series of subcategories to provide additional context to the illness record as outlined in Chapter five. The evaluation of this system after one year of data collection was a critical step in the implementation process. End-users were asked to evaluate the system and provide recommendations for its evolution in accordance with the WHO injury and illness surveillance guidelines (World Health Organization 2001). A key finding in the evaluation process was the collection of accurate illness information was deemed as a challenge for the MDCs. The National Centre structures involved did not have direct access to a sports medicine doctor for all levels of athletes within their tiered system. Athletes of a lower tier often used a personal general practitioner for issues needing medical attention resulting in the subsequent diagnosis being relayed back to the MDCs by the athlete. A secondary issue related to non-medical attention illness (*"stuff above the throat…head cold, or maybe some mild GI symptoms").* MDCs regularly received delayed and second-hand information from the coach regarding these issues. Despite there being more illness recorded than injuries throughout the observation period, the MDCs suggested that these barriers may have led to an under-reporting of illness in the first year of data collection. The MDCs recommended that future systems should have adequate personnel to diagnose these issues for all levels of athlete or in the absence of adequate medical support, symptom-based reporting by the individual athlete may be the preferred reporting avenue. This action item was considered for year two of illness surveillance, where similar to injury reporting an athlete illness self-reporting option was added to their daily monitoring system.

The longitudinal data collection took place from September 2020 to September 2022, which was throughout the COVID-19 pandemic. The recording of illness during this period took an unexpected level of importance in elite sport, which otherwise may have been of secondary importance to injury surveillance in previous research. For context, during season one (September 2020-August 2021) a severe level of restrictions was in place enforcing significant athlete isolation from the general population and normal daily activities. These restrictions were largely removed in season two and a large portion of the athlete population returned to unrestricted school or college and activities of daily living. A total of 122 illnesses were recorded throughout the observation period; however, only 26.2% of them occurred in season one. The remainder occurred during season two showing an imbalance in the distribution of illnesses. Two things may have impacted this increase in illness incidence. Firstly, the addition of a self-reported illness pathway for athletes after the end-user evaluation process may have improved the reporting pathway and increased the number of reports to the MDCs. Secondly, the government restrictions in season one followed by the easing of restrictions in season two potentially created an initial decrease and then subsequent increase in illness in this population. A similar effect was demonstrated in Israel, where social restrictions were associated with a significant decrease in infectious diseases, while the easing of restrictions were met with an increase of non–SARS-CoV-2 respiratory and gastrointestinal infections (Amar *et al.,* 2022). However, as the illness surveillance process only began in September 2020 there are no baseline data to make a comparison to in this Irish population. Therefore, the rationale for the imbalanced distribution is merely hypothetical and provides further support for the continuous and longitudinal prospective monitoring of these populations.

Research Summary

7.1.4 Key Findings

The key findings of this programme of research are presented in depth in each individual chapter. These findings are summarised as follows:

7.1.4.1 Study 1

A systematic review of the literature found no clear evidence of a relationship between training load and pain in competitive swimmers, while there is limited and conflicting evidence to suggest a relationship between training load and injury and illness. External training load methods were most frequently employed in the research, with internal training load measures rarely featuring. The ability to synthesise the data within the review was hampered by study design, inconsistent training load monitoring methods, large population classification differences and varying operating definitions of pain, injury, and illness.

7.1.4.2 Study 2

An international survey investigating training load monitoring practices used by competitive swimming practitioners and coaches found that monitoring practices are centred on an athlete's response to training and improving performance. Injury prevention is considered less of a priority, with research purposes not being a consideration. Practitioners frequently employed both internal and external measures of training load, which highlights a disparity between the methods used within the research environment and in an applied setting. To optimise the implementation of a training load monitoring system, stakeholder buy-in and financial, personnel and technological resources need to be considered and addressed.

7.1.4.3 Study 3

An international survey investigating the injury surveillance practices used by practitioners and coaches found that injury surveillance was carried out less frequently than training load monitoring in competitive swimming environments. Regarding those that did employ injury surveillance practices, only half of them conducted further analysis on the data after it was collected. This is linked to the primary goal of data collection which was to keep a record for insurance purposes and like study two, using the data for research purposes was a minor consideration.

7.1.4.4 Study 4

This study outlined how to integrate both IOC/FINA consensus guidelines into the design of the injury/illness surveillance practices. The evaluation of the system found that athletes noted periods of high stress were the most challenging to maintain consistent reporting practices. Athletes also noted that having access to their reported information was key to maintaining compliance and accuracy. Coaches and MDCs highlighted that the monitoring system was used as a communication pathway to transfer information from athletes to coaches and among the MDT, and that information needs to be considered with the athletes reporting history and reporting trends in mind. Finally, the evaluation process highlighted that the accurate collection of illness information was challenging in the absence of a sports medicine doctor being attached to the training environment. Symptom-based reporting methods, where the athlete self-reports illness information, may be more advantageous where resources do not match the goals of the illness surveillance process.

7.1.4.5 Study 5

The prospective study was 104 weeks in duration and the final analysis included 32 swimmers, ranging from national to world class level. Injury and illness epidemiological data were presented showing that illness occurrence was greater than injury. Training load data highlighted that an average of 33.5 ± 12.9 km was swam each week, while swimmers had an average total weekly load of 3,838 ± 1,616.1 AU. Binary logistic regression was employed to analyse the association between training load metrics and medical attention injury and illness. Results showed that Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU), 4-week Rolling Total Training Load (AU) and ACWR had no association with medical attention injury and illness. These findings were consistent regardless of a 0-day or 7-day time lag.

7.2 Strengths and Limitations

A significant strength of this research is its grounding in the applied setting. Chapters three to six have outlined findings with specific involvement from the swimming community. Public patient involvement (PPI) in research is a means of involving people in all aspects of the research process as partners rather than just participants. Actively involving the target research participants is seen as a marker of good research practice as it leads to improved study design, relevancy and outcomes uptake (Blackburn *et al.,* 2018). This programme of research was designed with a PPI process in mind. The initial programme of research design was developed with three governing bodies. The University of Limerick acted as the academic partner, while the Irish Research Council was the primary funding body. Swim Ireland acted as a secondary funding source and was a key industry partner with collaboration in the research question, project design, participant recruitment, facilitating data collection, evaluation processes and joint dissemination of the research findings. Major aspects of the programme of research are designed with the input and guidance of key stakeholders in Swim Ireland while the international survey provided an opportunity for the wider swimming community to share their lived experience. The lived experience was also a significant part of the design, implementation, and evaluation of the system where key proponents of the monitoring process were engaged in the end-user review process. This is a significant step in participant action research where the focus is on creating action through a data collection, reflection and action in a corkscrew cycle (Baum 2006).

The longitudinal and prospective nature of the final study is a crucial aspect of this research and elevates the strength of the body of research. Initial research highlighted the lack of longitudinal, prospective research conducted on a truly elite sporting population. This was supported by Mountjoy *et al.,* (2016) where they echoed the need for out of competition prospective injury and illness surveillance. Conducting research at elite level is often difficult due to the limited access, numbers of athletes and ability to implement good research processes in the practical training environments. However, there is greater control and resources available at that level, with less confounding factors affecting the results. This study not only included longitudinal prospective study design but was carried out in an elite training environment with high level swimmers and professional coaches and support services. This enables a high level of quality control to be maintained throughout the observation period. This research has filled a significant gap in the research by adding considerable new knowledge to the body of literature investigating the association between training load monitoring and injury/illness surveillance in competitive swimming.

A key strength of this research was the stakeholder investment within the data collection process. The three MDCs were all chartered physiotherapists working within Swim Ireland's National Centres and had an invested interest in the success of the project. It has been shown in previous research (Wik *et al.,* 2019) that physiotherapists invested in the data collection process reported a greater number of non-time loss injuries and injuries with a lower severity than their non-invested counterparts. Designing injury/illness surveillance data collection processes with the stakeholders at the centre of the research design is a significant strength of this programme of research. The consistency of the MDCs over both seasons is also a strength of the research. The same MDCs recorded the injury/illness surveillance data across both seasons which has been highlighted as a key methodological strength in surveillance research (Wik *et al.,* 2019). In a practical sporting environment, the turnover of staff season to season within a clinical setting can be expected. However, this disruption has the potential to create variability within the data collection process which may compromise the outcomes of an otherwise well-designed system. These key strengths to the injury/illness surveillance led to very robust and accurate data collection processes and improved the integrity of the data and subsequently the research outcomes.

A significant strength of this research was the use of an ecologically sound form of training load monitoring in sRPE (Wallace *et al.,* 2009). However, a limitation of this programme of research may be the lack of an objective internal training load measure in parallel with the subjective measure (sRPE) collected. Sessional rate of perceived exertion as a training load measure should be seen as good representation of the overall load placed on the athlete and not the physiological or biomechanical load (Coyne *et al.,* 2018). The addition of an objective internal training load measure, such as heart rate would provide an objective measure of the training load and compliment the subjective nature of sRPE, allowing quantification of both the internal (physiological) and holistic load on the athlete.

Swim Ireland has a competitive swimming membership of almost 8,000 athletes. The membership gender balance noted at the time of registration highlights a greater proportion of female competitive swimmers (58%). At the upper levels of the sport, the gender balance shifts towards male athletes, with 68% of centralised athletes being male. As the centralised athletes were the selected population for the study in Chapter six, the gender balance within this project was more heavily weighted towards male athletes. The Sex and Gender Equity in Research (SAGER) guidelines recommend that data reported be disaggregated by sex and gender where possible and relevant (Heidari *et al.,* 2016). Chapter six in this programme of research has not disaggregated the data as the sample size and unbalanced nature of the data (69% male) suggests it would not be prudent to further distil down the results. The gender balance is not seen as a limitation of this study as it reflects the true centralised environment; however, the inability to separate the findings by gender, in order to improve the transferability of the results, could be viewed as a limitation.

Research into elite sport often has to accept limitations in sample size and the subsequent consequences of not detecting an effect of relevant magnitude (Skorski and Hecksteden 2021). The sample size of the longitudinal study was impacted by not only the elite status of the athletes but the limited number of centralised athletes within the Irish swimming performance system. To overcome this limitation, the study was designed to incorporate a two-year data collection which bolstered the number of available data points per athlete throughout the data collection.

The data collection period of 2020/2021 season was largely carried out under a host of changing government lockdown restrictions, while 2021/2022 season was not impacted by government imposed COVID-19 mandates. Recent research has shown that amateur athletes had an increase in injury incidence after the lockdown period (Tondelli *et al.,* 2023), while professional athletes had no increase after the lockdown period (Waldén *et al.*, 2022). The impact of illness over this time period is less well documented in the literature; however, one study highlighted that medical guidance surrounding illness during the COVID-19 pandemic created increased time-loss through the return to play process (Hull *et al.*, 2022). This may largely be down to government restrictions dictating athlete removal and a set isolation period at the earliest signs of illness and/or medical guidelines highlighting the need for a minimum graded return to play period after COVID-19 infection (Elliott *et al.*, 2020). The collection of injury and illness surveillance data through the COVID-19 pandemic provides key information during a crucial time period in elite sport, however the validity of extrapolation of the findings to less volatile periods is a potential limitation of the study.

The injury surveillance practices in competitive swimming were explored within this programme of research with the aim of informing the subsequent data collection process and system design. However, the authors did not gather information on the illness surveillance practices of practitioners within the competitive swimming community. This aspect of the data collection process was largely guided by FINA and IOC consensus statements but was not informed through an international survey as was done with training load and injury monitoring processes. The addition of practitioner feedback may have provided further insight into the illness data collection strategy.

7.3 Future Research Directions

It has been shown that a research practice gap in the methods used to monitor training load in competitive swimming exists. Contrary to typical research practice gaps, this deficit largely lies within the research associated with training load monitoring and injury/illness surveillance in this global sport. This programme of research sought to bridge the gap between the academic sphere and the practical environments, however future research needs to build on this programme of research and key findings. Suggestions for future research include:

- This programme of research has provided a best-practice framework for sport specific training load monitoring and injury and illness surveillance. Future research should conduct similar prospective and longitudinal studies to investigate the relationship between training load and injury and illness in these competitive swimming populations. This would allow for greater clarity and allow for a meta-analysis to be conducted.

- With the benefits of a sport specific injury and illness surveillance consensus guidelines document, FINA should look to provide its stakeholders with a sport specific training load monitoring consensus statement which guides not only the training load monitoring process but also illustrates how best to integrate the guidelines with their injury and illness consensus statement guidelines. This would be of significant benefit to future researchers and help elevate the standard of training load monitoring practices in competitive swimming going forward.
- The factors that influence both injury and illness are multifactorial and therefore the scope of investigation into the relationship between training load and injury and illness should be broadened to include additional risk factors. This would include more holistic athlete data, such as daily well-being, where early signs of negative adaption could identify prior to an injury or illness occurring. Future research could also examine the influence of previous injury/illness history would have on the relationship between training load and injury/illness.
- Non-medical attention injuries or illnesses as well as self-reported physical complaints, soreness, stiffness, discomfort could present as an early warning sign for a subsequent time loss event as per Whalan *et al.,* (2020). This programme of research aimed to identify how best to collect both medical attention, non-medical attention, and self-reported physical complaints. However, the sole focused on medical attention injury/illness was deemed a primary starting point for analysis. Future research should build on this by including a separate analysis of non-medical attention injury/illness and pain which may inform the greater landscape of injury/illness incidence and burden in competitive swimming.
- Collaboration and multicentre research has been recommended as *"the cornerstone to future high quality sports injury research"* (Nielsen *et al.*, 2020). This research has been conducted in conjunction with key stakeholders in the competitive swimming community (i.e., NGB, physiotherapists, coaches, and athletes), while also integrating the expertise of academics in both sport and exercise sciences, health, and rehabilitation. The project also collaborated with an expert statistician to understand the most appropriate data analysis and interpretation. This programme of research also involved a multicentre data collection process which improved the sample size. However, the population within the two national centres are largely homogeneous and were exposed to a relatively consistent training philosophy across both centres. Future research should look to expand on this collaboration and multicentre nature of this study

to incorporate multiple training venues with more diverse populations, training methods and methodologies. This diversity within the data collection could improve the generalisability of the research findings to a larger population of competitive swimmers.

- The gender balance in this programme of research was weighted towards male swimmers (69% male). This naturally occurred due to the overall gender balance within Swim Ireland's National Training Centres. The inclusion of a wider multicentre data collection process, including programmes outside of the Irish system, could potentially improve this and allow the findings to be segregated by gender.

7.4 Practical Applications

This programme of research has resulted in several findings which can be applied to the practical environment, with specific focus on both researchers and practitioners working in real-world settings. The practical applications are as follows:

- The methodological considerations exposed and addressed throughout this body of research should guide those practitioners carrying out training load monitoring and injury/illness surveillance in an applied setting. Specifically, those wishing to maintain highly consistent data collection processes can use the body of research as a framework to act from.
- Those wishing to implement a training load monitoring system should consider stakeholder buy-in and financial, personnel and technological resources. The NGB needs to be invested in the training load requirements of the programme by dedicating a member of staff to these services. This will aid in reducing the burden of the data collection process. To increase athlete adherence in the monitoring process, frequent, consistent, and relevant feedback should be provided. Coach engagement in the process can be improved through framing the training load monitoring process in a more performance orientated manner. The training load monitoring system should prioritise the use of sRPE. In competitive swimming, sRPE is beneficial as it can transcend all aspects of a modern-day swim programme. Dryland activities, competition and swim training load can be quantified utilising the same method, allowing for an accurate measure of total training load.

- The implementation of an injury/illness surveillance system should be preceded by a strong understanding of the system goals and contrasted to the resources available. Where the injury/illness surveillance outcomes are to be translated into research, it is imperative that strict use of the consensus guidelines is employed. However, where research is not the objective, the requirement is to have a consistent and sport-specific definition longitudinally within the swim programme. Either the FINA (Mountjoy *et al.* 2016) or IOC (Bahr *et al.* 2020) definitions are appropriate in competitive swimming. Ideally, an electronic system for data collection should be employed to reduce the time burden of injury/illness surveillance and to improve the level of detail gathered. A classification system such as the OSCIIS is of great benefit to accurate injury and illness diagnosis, while the categorisation according to their acute or repetitive nature and sub-categorising by sudden or gradual onset would provide necessary detail.
- Once the system has been designed and the resource needs have been met the implementation and data collection procedures require a continuous end-user evaluation process. This allows for the evolution of the system to meet the dynamic demands of a sporting environment. The integration of the system should occur gradually allowing for a period of uninterrupted data collection where staff can gain a deeper understanding of individual athlete reporting habits. The system should act as an "alert" to potential issues, allowing the coach to instigate communication with the athlete while always considering the athletes reporting history and personality traits before taking decisive action. Athlete and coach education into the benefits and uses of the monitoring process is necessary to maintain high levels of athlete compliance, however this education needs to occur early in the monitoring process and be continuous throughout the season. Coaches also need to consider the cost/benefits of treating higher tiered athletes differently within the monitoring process. Despite creating a flexible and individualised approach for certain athletes, there is a high risk of developing an adverse athlete culture leading to larger and subsequent challenges.
- The monitoring of illness needs also to be well resourced with the aim of having adequate medical support in place for all levels of athlete within the system. Where this cannot be achieved, symptom-based reporting by the individual athlete may be the preferred reporting option. This can be conducted using basic symptom reporting avenues or through the inclusion of the OSTRC questionnaire.

- The findings of this programme of research suggest that there was no association between Weekly Pool Volume (km), 4-week Rolling Pool Volume (km), Weekly Total Load Training (AU) and 4-week Rolling Total Training Load (AU) and ACWR and medical attention injury and illness. Practically, this finding suggests that those monitoring training load with a goal of predicting medical attention injury and illness should allocate their resources elsewhere. However, the practical application of this system has strengths in being used to guide coaches' periodisation plans and to compare the coaches planned training volume and intensity against what the athlete is subjectively experiencing. This system is also useful in identifying the competition loads for athletes and help coaches prepare for them adequately.
- At this elite level, coaches can observe and plan their athletes' training plans with a high degree of accuracy and with input from the wider MDT. These minor adjustments can be made regularly throughout the training session, training week, or cycle, potentially reducing the likelihood of injury or illness occurring. This may not be the case in a less elite environment where the training structure is less consistent with less attention on the individual plan of the athlete. The use of training load monitoring could be more useful in a club environment where potentially the number of athletes to coaches is much greater, session attendance is more variable week to week and individualised planning is not as commonplace.

7.5 Conclusions

The integration of training load monitoring and injury and illness surveillance is necessary to elevate the standard of athlete welfare, training practices and periodisation in competitive swimming. Previously, the relationship between training load and injury and illness in a competitive swimming population was unclear due to a host of methodological constraints. This programme of research found no association between sRPE derived training load metrics and the incidence of medical attention injury and illness in this competitive swimming population, over a two-year period. This lack of association was present, regardless of a 0-day or 7-day lag, suggesting that a well-controlled and structured training programme minimises the likelihood of training related injuries and illness. Importantly, this programme of research also confirmed that sRPE as a training load monitoring tool is an appropriate method of monitoring training load in this cohort. sRPE can be implemented effectively in a wide array of competitive swimming settings (beginner to elite) and can encompass all the training methods used in a modern-day swim programme (pool training, S&C training, cross training, and competition). Finally, this programme of research has also identified that injury and potentially more significantly, illness surveillance are a critical component to monitor longitudinally. Longitudinal injury and illness surveillance in conjunction with training load monitoring will provide for detailed information on the aetiology of injury and illnesses, safeguarding against inappropriate loading strategies.

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Appendices And Supplementary Files (Separate Digital File)