

MODELLING OF INTRINSIC AND EXTRINSIC INJURY RISK FACTORS IN ELITE TENNIS

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STATEMENT OF AUTHORSHIP AND SOURCES

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Danielle Gescheit

Date: 27/09/2018

ACKNOWLEDGEMENTS

*‘Surround yourself with the dreamers,
and the doers,
and the believers,
and thinkers,
but most of all,
surround yourself with those who see greatness within you’*

I must start by thanking the A Team; my supervisors. We have been on a long roller-coaster ride together throughout my Honours and now my PhD. There is no chance I would have survived either without you by my side. Stu, I will always cherish our lengthy chats about research and life. You have opened my eyes and mind to a new way of thinking and I am forever grateful. Machar, you took me under your wing in 2011 and had belief in me right from the start. Thank you for being my mentor and paving my professional pathway; words cannot describe how appreciative I am. Rob, your clarity in thinking and doing is inspiring and it brought so many new lenses to this thesis. Thank you for always being in my corner and pumping up my tyres (even if it meant you had to deflate them a bit first ;)). Steph, thank you so much for all your assistance and for putting up with my never-ending stream of questions along the way. The novelty and insight that this thesis provides is largely owing to your statistical guidance and I am extremely appreciative. Justin, thanks for being the fresh-set-of-eyes that all the studies and presentations needed. You have always been a great support and I value having had you on board.

To my sister and biggest advocate, Jazz. Thank you for always picking me up when I was down, being the shoulder to cry on, the ears to listen to my rants, the punching bag to my

harsh words and the bricks and mortar to my support network. You have always been my number one believer, even when I didn't believe in myself. Thank you for everything, I love you more than you know. Mum and Dad, thank you for also coping the hits and being an endless source of love and support. It was so comforting to know that you were always there and I love you both dearly. Grandma and Grandpa, it is your strength that I tried to emulate during the tough times. You both fought for your lives and it has always help me put things into perspective. Completing a PhD is nothing compared to what you have both endured and I am so inspired by you both. Adam, Claire, Jesse, Lee, Coco, Chou Chou, Gucci, Sim and Len, thank you for your constant support along the journey too. I love you all.

Thank you to all the players whose data made this thesis possible. I hope the findings come full circle and are able to help you in your careers. I would also like to thank all the Performance staff at Tennis Australia who assisted me along the way. I would like to make special mention of Al Murphy, Mel Omizzolo, Ryan Cope, Anne-Marie Cavanagh, Callum Beale, Alex Jago, Gemma Harper, Emma Shoemaker, Lauren Gerhard, Nicole Pratt, Darren McMurtrie, Ricky Arner, Olivia Cant and Molly Connolly who helped and supported me not because they had to, but because they wanted to. The same goes for the staff and PhD students at ACU. I would specifically like to thank Paul Tofari, Jill Leckey, Chris Swain, Jack Hickey, Josh Ruddy, Nirav Maniar, Brett O'Connell, Geri Naughton and Doug White.

This thesis is dedicated to all I have thanked.

It wouldn't have been possible without each and every one of you.

Thank you.

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LIST OF PUBLICATIONS RELATED TO THIS THESIS

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Wood TO, Omizzolo M, Reid M. Injury epidemiology of tennis players at the 2011–2016 Australian Open Grand Slam. *Br J Sports Med* 2017;51(17):1289-1294. doi: <http://dx.doi.org/10.1136/bjsports-2016-097283>.

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Wood TO, Omizzolo M, Reid M. A multi-year injury epidemiology analysis of an elite national junior tennis program. *J Sci Med Sport* 2018; In Press. doi: <https://doi.org/10.1016/j.jsams.2018.06.006>.

SUPPLEMENTARY PUBLICATION:

Reid M, Cormack SJ, Duffield R, Kovalchik S, Crespo M, Pluim B, **Gescheit DT**. Improving the reporting of tennis injuries: the use of workload data as the denominator? *Br J Sports Med*. doi: <http://dx.doi.org/10.1136/bjsports-2017-098625>.

LIST OF MANUSCRIPTS CURRENTLY IN REVIEW

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Reid M. Predictive modelling of injury in tennis: determining the best internal workload calculation and timeframe. Br J Sports Med, **Under Final (minor) Review.**

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Kemp J, Reid M. Multivariate modelling of intrinsic and extrinsic risk factors to injury in elite junior tennis players. Br J Sports Med, **Under Review.**

CONFERENCE ORAL PRESENTATIONS RELATED TO THIS THESIS

Gescheit DT, Cormack S, Reid M, Kemp J, Duffield R. Injury epidemiology of elite tennis players at the 2011-2016 Australian Open. Sports Medicine Australia Conference 2016, Melbourne, Australia.

This oral presentation was shortlisted for best paper at the SMA conference.

Gescheit DT, Cormack S, Duffield R, Kovalchik S, Reid M. Measures of load and injury in tennis: are there relationships? European College of Sport Science Conference 2017, Essen, Germany.

This oral presentation won the German Tennis Federation award for best tennis research at the ECSS conference.

Gescheit DT, Cormack S, Duffield R, Kovalchik S, Reid M. The load and injury paradigm in tennis: Can injuries be predicted? Exercise and Sport Science Australia Research to Practice Conference 2018, Brisbane, Australia.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
ACWR	Acute:chronic workload ratio
ATP	Association of Tennis Professionals
AUC	Area under the curve
CI	Confidence interval
COD	Change of direction
CV	Coefficient of variation
EWMA	Exponentially weighted moving average
GE	Game exposures
HR	Hazard ratio
ICC	Intraclass correlation coefficient
ITF	International Tennis Federation
ME	Match exposures
OSICS	Orchard Sports Injury Classification System
ROC	Received operated characteristic
RPE	Rating of perceiving exertion
RR	Rate ratio
SD	Standard deviation
SE	Set exposures
SMDCS	Sports Medicine Diagnostic Coding System
sRPE	Session-RPE
WTA	Women's Tennis Association

ABSTRACT

Elite tennis places high physical, physiological and psychological stresses on its players which can amplify injury risk and limit player development and performance (1, 2). Therefore, understanding what and why injuries occur in both elite junior and professional tennis is critical in mitigating the risk. Unfortunately, current research on elite tennis injury is sparse. What is available is limited by methodological design and conflicting findings. Consequently, this thesis aimed to address these gaps through a more complete examination of the injury epidemiology and aetiology of elite tennis injuries throughout the entire player pathway.

Specifically, Study 1 examined the epidemiology and in-event treatment frequency of injury at the 2011-2016 Australian Open tournaments. Injury incidence was defined as a medical consultation by a tournament physician, and in-event treatment frequency as the mean total number of follow-up medical/physiotherapy consultations (2013-2016 tournaments only). Data were collated by sex, injury region and type and reported as frequencies per 10,000 game exposures. Incidence rates $\pm$ 95% confidence intervals (CI) and rate ratios (RR) were used to test effects for injury, sex and year. Female players were found to experience more injuries than male players over the 6-years (201.7 vs 148.6). The shoulder (5.1 ± 1.1 injuries per year) and knee (3.5 ± 1.6) were the most commonly injured region among females and males respectively. The torso region attracted high in-event treatment frequencies in both sexes. Muscle injuries were the most common type of injury, yet stress fractures more than doubled over the 6-year period. Overall, there were sex differences in injury incidence at the Australian Open, however the in-event treatment frequency of injuries was similar for both males and females.

Where Study 1 detailed the injury epidemiology of professionals at the Australian Open, Study 2 focused on the incidence and severity of injuries of elite junior tennis players from a national program over multiple years. Injury data were collated by sex, age and body-region for all nationally-supported Australian junior players (58 males, 43 females, 13-18 y) between 2012-2016. Injury was defined as a physical complaint from training/matchplay determined by presiding physiotherapists and doctors that resulted in interrupted training/matchplay. Severity represented the days of interrupted training/matchplay per injury. Injury incidence was reported per 1,000 exposure hours. Incidence rate change and $RR \pm 95\% CI$ assessed changes over time. No difference in male and female injury incidence existed (2.7 ± 0.0 v 2.8 ± 0.0), however male injuries were more severe (3.6 ± 0.6 v 1.1 ± 0.9 days). The lumbar spine was the most commonly and severely injured region in both sexes (4.3 ± 0.2 , 9.9 ± 1.4 days) with shoulder injuries the second most common in both sexes (3.1 ± 0.2) and registering the second highest severity in males (7.3 ± 1.4 days). The body-region findings are relatively consistent with the body-region findings discovered in Study 1. Independent of sex, the injury incidence increased with age from 2.0 ± 0.1 (13 y) to 2.9 ± 0.1 (18 y). This study concluded that despite no sex-based difference in injury incidence, male injuries resulted in more interrupted days of training/matchplay.

The profiling of injuries across the elite tennis pathway highlighted high risk sexes, ages and body-regions of injury. An understanding of why these injuries occur is important. As the volume and intensity of training is commonly associated with injuries in sport, the aim of Study 3 was to determine the best internal workload model and timeframe to predict injury in elite tennis. Daily training loads, recorded as session-RPE (sRPE)(3), and injury incidence data (2012-2016) from nationally ranked tennis players ($n = 101$, 19.1 ± 2.8 y, 91 ± 112 peak national ranking) were obtained. Injuries were defined as per Study 2. Multiple workload metrics, including variations of acute:chronic workload ratios (ACWR) and exponentially

weighted moving averages (EWMA) as well as daily loads, monotony and strain were assessed over numerous timeframes (8 time points between 1-60 days) to predict subsequent injury. The predictive performance of the models was assessed via area under the curve (AUC) of receiver operator characteristics (ROC) curves and reported as $AUC \pm 95\%$ confidence limits, sensitivity and specificity. It was found that the daily rolling average load and EWMA models performed best ($\geq 0.76 \pm 0.04$ AUC), largely owing to predicting non-cases rather than injuries (≥ 0.16 sensitivity, ≥ 0.74 specificity). There were no differences between timeframes. All other models performed relatively poorly ($0.50-0.66 \pm 0.0$). Non-injured players experienced higher loads compared to injured players (mean $\pm$ SD; 714 ± 521 au, 565 ± 426 au). Overall, the best predictive workload-injury models used daily rolling averages and EWMA regardless of the tested timeframes. This suggests load model selection is more important than timeframe selection for predicting injuries in tennis.

The applied impact of Study 3 may be limited by the fact that only internal loads were related to injury outcomes, without the consideration of other risk factors. Therefore, Study 4 examined the association of intrinsic and extrinsic risk factors with injuries in elite junior tennis players over a 500-day period (26 males, 23 females, 15.6 ± 2.0 y, 143 ± 128 peak national ranking). Daily training loads, training types, perceptual wellbeing and soreness as well as baseline musculoskeletal function and physical capacity measures were collected from junior players in a national program. Training loads included serve counts and sRPE calculated as daily load and 21-day rolling average in the lead up to injury. Seventy-eight injuries occurred which were defined in the same way as Studies 2 and 3. Univariate Cox Proportional Hazard models determined the first factor in the forward step selection for the multivariate Cox Proportional Hazard model. The multivariate model then determined the aggregated factors with the strongest association to injury, with results reported as hazard ratios $\pm 95\%$ CI. The multivariate analysis revealed that lower serve counts (-0.02 ± 0.00) and

a higher number of sore body-regions on the day of injury (0.84 ± 0.48) combined with lower multistage fitness test scores (-0.46 ± 0.23) and slower change of direction (COD) speed (3.47 ± 2.88) were best at detecting injury hazard. Internal loads quantified as daily rolling averages (as per Study 3) did not feature in the multivariate model outcome in Study 4. Perhaps the inclusion of an external load measure, or the combination of other risk factors, limited the influence of internal load in explaining injury hazard. In conclusion, the interplay of serve loads, regions of body soreness, aerobic capacity and COD speed provided the highest association with injury. These risk factors have currency as injury prevention and training monitoring tools in high-performance tennis.

In summary, this thesis provides insight into the epidemiology and aetiology of tennis injuries throughout the elite pathway. The findings highlight that there are consistencies in the body-region of injuries in both elite junior and professional players, however sex-based differences are apparent. Study 3 showed that there is some injury predictive power in univariate internal training loads, yet it appears limited to detecting when injuries do not occur. Consequently, the multivariate analysis of injury risk conducted in Study 4 found that the collection of serve loads, soreness and physical capacities should be monitored as part of an injury prevention program for elite tennis players.

1. CHAPTER 1: INTRODUCTION AND OVERVIEW

Elite junior and adult tennis players experience congested tournament and travel schedules interspersed with time-restricted training blocks during the in-season, coupled with a short off-season (1, 2, 4). Within-event, players are exposed to high-intensity intermittent activity with multiple changes of direction, accelerations and decelerations, as well as large mechanical and rotational forces over an undefined period of time (5). As most tennis tournaments are a knock-out format and offer multiple events (i.e. singles and doubles), these physical requirements are extensive, but also uncertain, and this lack of uniformity may have implication for injury (6). Consequently, an understanding of the epidemiology and aetiology of elite junior and adult tennis injuries is important to provide direction for evidence-based risk mitigation strategies across the entire elite tennis pathway (7, 8). However, current research is limited due to distinct gaps in the breadth and depth of the available injury epidemiology and aetiology literature in tennis (9-12). Specifically, there are discrepancies in the injury incidence reports by sex and body-region (9, 10), limited profiling of injury severity (13), as well as no assessment of the changes in injury incidence over time. Additionally, an understanding of the relationship between risk factors and elite tennis injuries remains large unexplored (12) which restricts the targeting of risk mitigation strategies. Therefore, this thesis aims to systematically profile injury occurrence and incidence in both elite junior and professional tennis players and determine their relationship with modifiable intrinsic and extrinsic risk factors.

The epidemiological profile of elite junior and adult tennis highlights injury incidences of between 4.9 and 55.6 per 1,000 match exposures, or between 0.6 and 6.1 injuries per 1,000 athletic exposures (9, 11, 14-16). These injury rates include junior national and international tennis players in competition and training, as well as professional players in national and

Grand Slam events, which somewhat explains the broad ranges observed in injury incidence (9, 11, 14-16). It is worth noting that the variability in exposure measures utilised to report relative injury rates (i.e. match versus athletic exposures) limits the ability to make comparisons between studies and thus occludes deeper understanding of injury rates relative to the specific training/match demands. Regardless, attempted comparisons in injury incidence by sex and body-region show conflicting findings. For example, some reports on elite tennis injury report males to sustain more injuries (9), whilst contrasting literature reports females to have higher injury occurrence (10). Additionally, body-region findings by sex report males and females to suffer more lower-limb and upper-limb injuries respectively, whereas other studies show no sex-differences in body-region injury incidence (16). Regardless of occurrence, limited analysis exists for 1) injury severity 2) environment of sustained injuries i.e. training or competition phases and 3) changes in injury incidence over time by region, sex or severity (11, 15). Such lack of literature exposes the superficial reporting of tennis injury incidence in elite tennis. Therefore, to further understand the injury epidemiology of elite junior and adult tennis, factors including the tournament and training period, the time-loss and year-on-year changes in injury incidence should be explored longitudinally with a specific focus on sex and body-region. This will extend the existing body of research profiling elite tennis injuries and have the ability to highlight risk groups of players to target for injury prevention. Additionally, it can provide guidance for medical resourcing in-event/program.

Beyond research examining the epidemiology of elite tennis injury, greater insight regarding the aetiology of injuries is needed to clarify and refine injury prevention. Injury risks in elite tennis can include a host of modifiable and non-modifiable intrinsic and extrinsic risk factors (7). Non-modifiable intrinsic risk factors can include age, sex, physical growth and previous injury history (17). Modifiable intrinsic risk factors can include musculoskeletal function,

physical capacity, playing standard and perceptual wellbeing (8). Additionally, extrinsic risk factors can include competition phase (training versus tournament), court surface, environment, equipment and training and matchplay loads (8, 17). In tennis, the relationship between these factors and injury remain poorly understood. For example, relationships exist between age, joint flexibility and strength, playing standard, tournament phases and court surface to subsequent injury in tennis (18-22). However, the findings are limited by their univariate approach which fails to consider the impact of other risk factors, such as training loads or physical capacity, as well as the interrelationship between such factors to injury (23, 24). Therefore, investigation of these relationships can inform individual athlete preparation, training design, rehabilitation strategies and scheduling (7). This information and analysis is available in other elite sports which further highlights the need for this type of research in elite tennis (23, 25, 26).

The association of training loads to injury have been extensively examined in other sports. That is, both the assessment of external (the dose) and internal (the response) loads to injury have been explored in sports including cricket, Australian football and rugby league (27-29). However, neither load type has been investigated in tennis as they relate to injury. The studies in cricket, Australian football and rugby league explore the load-injury relationship with loads quantified over acute and chronic timeframes in an attempt to capture short-term fatigue and longer-term fitness responses (27, 28). Typically, acute load has been calculated as a rolling average of the previous 7-days load and is commonly assessed as a ratio to chronic load, as a rolling average of the previous 21 or 28-days load (27, 28). Findings highlight that spikes in acute load, as well as low chronic loads, are associated to injury in these sports (27, 28). However, recent criticisms of the modelling techniques and assumptions underlying the quantification of the load-injury relationship in sport have emerged (30-34). Specifically, questions regarding the selection of load metrics and timeframes as well as the statistical

analysis have been critiqued (30-34). Given that the training load and injury relationship in elite tennis is yet to be explored, these assessments and criticisms in other sports can assist in determining the study design, methodology and analysis to efficiently and scientifically investigate this relationship in elite tennis.

In addition to examining the univariate relationship between workload and injury in elite tennis, the multifactorial nature of injury emphasises that a multivariate approach to assessing and understanding the interaction between risk factors and injury is fundamental (7, 8). Findings in Australian football and multiple adolescent elite sports highlight that the interplay of multiple risk factors, including measures of workload, physical capacity and perceptual wellbeing are the most indicative of injury (23, 24). However, the multivariate assessment of risk factors and their relationship to injury in elite tennis remains unexplored. Undertaking this analysis in elite tennis would have practical implications for the selection and utility of risk monitoring tools and strategies to mitigate such risk.

Therefore, this body of works aims to expand on the available epidemiological profile of elite junior and adult tennis, as well as explore the aetiology of injuries via univariate and multivariate analyses of risk factors. The specific aims of the research are:

1. To profile injury incidence at the Australian Open Grand Slam over multiple years including an analysis by sex, body-region, in-event treatment costs and changes over time (Chapter 4, Study 1).
2. To longitudinally investigate the injury epidemiology of elite junior tennis players in national tennis program by age, sex, body-region, time-loss and changes over time (Chapter 5, Study 2).

3. To model numerous training load metrics and timeframes to determine which model and timeframe have the best injury prediction ability in elite junior tennis players (Chapter 6, Study 3).

4. To analyse the interaction of multiple intrinsic and extrinsic risk factors and their association to injury in elite junior tennis players (Chapter 7, Study 4).

A supplementary aim of this thesis, which arose from current challenges in the comparability and precision of reported injury rates in epidemiology studies, is to determine the most precise and relevant exposure measure to understand injury rates relative to training/match demands (Appendix 1).

2. CHAPTER 2: LITERATURE REVIEW

2.1. OVERVIEW

Elite tennis imposes high match, tournament and season-based demands on players, with injury risk an ever-present concern for aspiring and professional players (1, 2, 4). Injuries can hinder player progression due to missed training and matches, along with negative consequences to success and financial livelihood from the sport (35). Therefore, injuries in elite tennis warrant exploration and understanding to establish evidence-based risk mitigation strategies. However, limitations exist in the current availability, methodology and profiling of tennis injuries, particularly in elite players (9, 10, 15, 36). Additionally, there is a lack of evidence as to what extrinsic and intrinsic risk factors relate to tennis injuries, and further, the association or predictive ability of these factors is yet to be explored in tennis (12). Therefore, most injury surveillance strategies in tennis currently rely on findings from other sports or intuition of relevant professionals. Consequently, this literature review will systematically explore the knowledge-base of injury epidemiology in tennis with a focus on elite adult and junior players. Once established, the aetiology of elite tennis injuries will be described. In particular, an examination of intrinsic and extrinsic risk factors and the relationship with injury will be explored. This narrative will subsequently support the direction of the research studies undertaken in this thesis.

2.2. LITERATURE SEARCH METHODOLOGY

All studies in this thesis were identified via a computer-aided search of AMED, CINAHL Complete, Health Source, MEDLINE Complete, PsycARTICLES, PsycINFO and SPORTSDiscus until June 2018. The search was restricted to only including publications in

English and involving human subjects. The search strategy utilised Boolean operators ‘AND’ and ‘OR’. Specifically, (‘tennis’ OR ‘sport’) AND (‘injury’ OR ‘injuries’) AND (‘training’ OR ‘risk’ OR ‘training loads’ OR ‘musculoskeletal’ OR ‘fitness’ OR ‘capacity’ OR ‘wellbeing’ OR ‘soreness’ OR ‘skill’ OR ‘competition’ OR ‘matchplay’)). The articles were initially screened for duplication, then by title, abstract and full text. The exclusion criteria included:

- Investigated an intervention or treatment effect
- Full text not available
- Text not available in English
- Articles before 1980
- Magazine articles
- Articles not specifically related to sport (i.e. military)

The PRISMA flow diagram (Figure 1) outlines the selection of information through the review process.

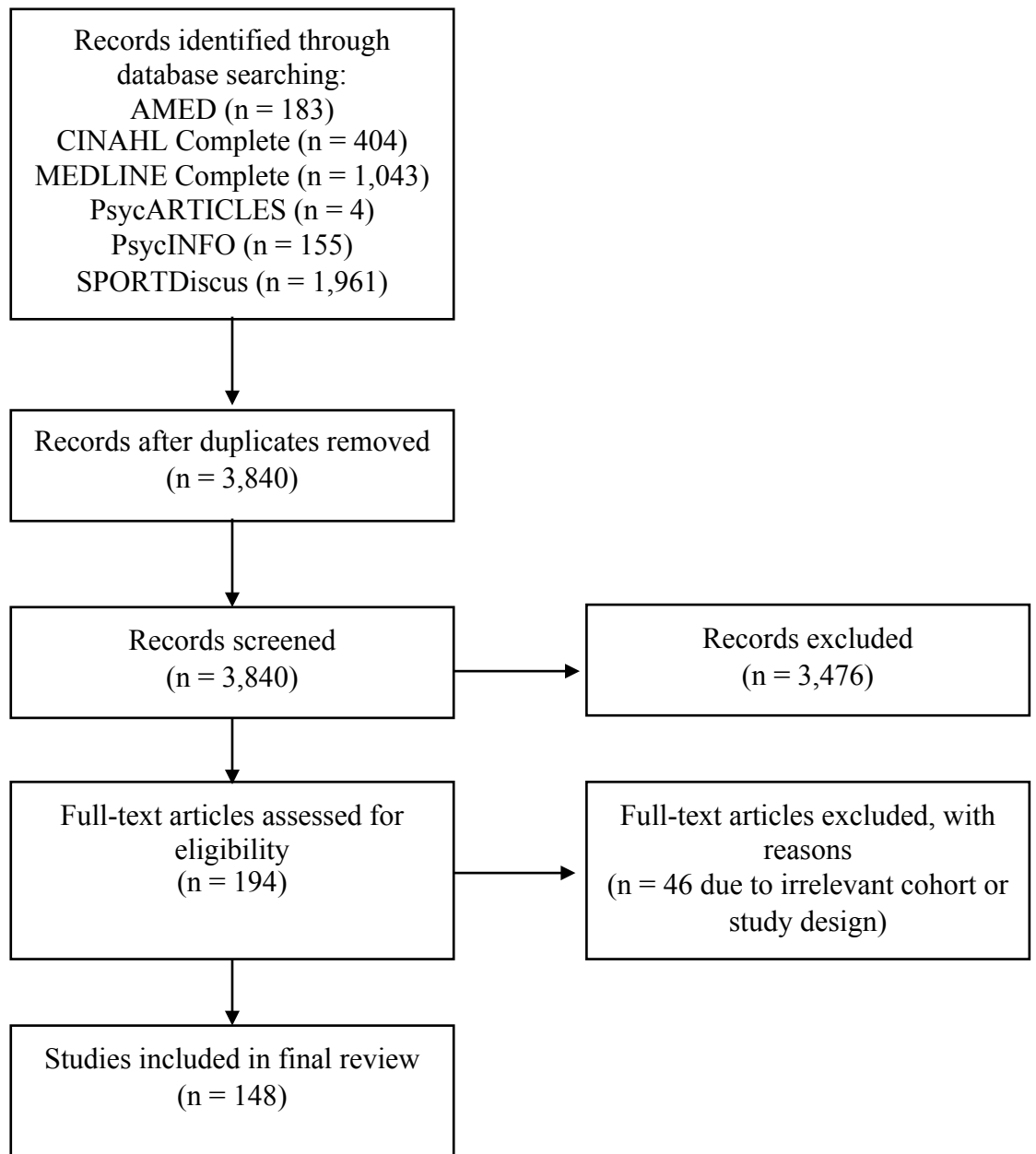


Figure 1: PRISMA flow diagram

2.3. THE DEMANDS OF ELITE TENNIS

To understand the unique and demanding landscape of elite tennis and the subsequent injury risk, the player pathway and activity profile of the sport needs to be discussed. There are close to 5,000 internationally ranked junior tennis players annually and another 5,000 professionally ranked tennis players (37). A typical annual playing calendar for an elite junior or adult tennis player involves 22-25 tournaments with demanding domestic and international travel schedules (1, 2). This is interspersed with training blocks and a short off-season of generally four-weeks (38). The average transition time between achieving an international junior ranking to achieving a professional ranking is four-years (37). Additionally, it takes approximately another four-years to reach a professional ranking where the sport may become a financially-viable career (37). Therefore, it is evident that the competition, training, travel and financial demands of elite tennis are high. This can consequently have ramifications for injury and ongoing performance throughout the pathway (35).

The load demands of elite tennis are also high within-matches. As tennis results are determined by score, the duration of matches are unrestricted with some Grand Slam matches exceeding five hours (6). Therefore, the load profile includes both external and internal components of elite tennis can quickly exacerbate in longer 3-5 set matches. External load describes the dose of work completed irrespective of the physical characteristics of the player (39). In tennis, this can include match duration, number of balls hit and distance covered (6, 40-44). Internal load describes the physiological and/or psychological stress response to the external load including responses such as heart rate, energy expenditure and RPE (39). The explicit external and internal load profiles of tennis matchplay have been well documented and are summarised in Tables 1 and 2. These ranges and values are obtained from both junior and adult elite tennis populations within-competition.

Table 1: External load profile of tennis matchplay

External load metric	Range
Point duration	3.0 – 14.9s
Match duration	1 - >5h
Effective playing time	16 - 26%
Total balls hit per match	<727
Total serves hit per match	85 - 157
Distance covered per set	553 - 572m
Changes of direction per point	1 - 8
Mean first serve speed	155 - 184km.hr ⁻¹
Mean groundstroke speed	106 - 111km.hr ⁻¹

(6, 40-44)

Table 2: Internal load profile of tennis matchplay

Internal load metric	Range
% of maximal heart rate	60 - 80%
% of maximal oxygen consumption	54 - 70%
Rating of perceived exertion (Borg 6-20 Scale)	11 - 15
Energy expenditure	213.7 - 343.1kcal.min ⁻¹
Blood lactate	<5mmol/L

(5, 6, 41, 45-47)

The within-match demands of elite tennis are typically greater than those reported in other overhead and racquet sports largely owing to the profiling of serve load, changes of direction (COD) demands, ball speeds and internal responses (48, 49). Additionally, the dose and response profile of competitive tennis matchplay has continued to increase with advancements in racquet, string and ball technology (50, 51) resulting in faster ball, and subsequent player speeds (50, 51). Therefore, the fast accelerations and decelerations, numerous COD and large rotational forces required to be successful in the modern game of tennis places even larger physical strain on elite players (5).

Moreover, the within-tournament demands of elite tennis are also challenging as most tournaments offer doubles and potentially consolation draws (52). Therefore, players are generally required to play multiple matches in a day and/or over consecutive days (6, 52). The technical and physical characteristics of repeated bouts of tennis matchplay highlight declines in external load with increases in internal load (6, 52, 53). Specifically, ratings of perceived exertion (RPE)(47) and biochemical and perceptual markers of muscle damage increase, coupled with a reduction in effective playing time over repeated matches within a day and over consecutive days (6, 52, 53). Additionally, multiple matches within and between days result in reductions in serve and groundstroke speed and accuracy, as well as decreased running ability which highlights the physical demands and subsequent decrements from participating in tournament tennis (6, 52, 53).

Evidently, elite tennis is challenging both within acute match-settings and chronic tournament and annual calendar settings (6, 35, 52). Therefore, these short and long-term demands pose injury risk which can hinder player development and progression in the sport (35). As such, an exploration of the injury epidemiology of elite tennis is important to determine the cohort

of players, as well as body-regions, that are most impacted by injury. This can provide initial insights for the development and targeting of injury prevention strategies.

2.4. INJURIES IN TENNIS

The epidemiological profile of injuries in tennis has been examined in both elite junior and adult tennis populations (9-11, 15). Specifically, injury incidence has been reported between 4.9 and 55.6 injuries per 1,000 athletic exposures or between 0.6 and 6.1 when expressed per 1,000 exposure hours (9, 11, 14, 15). However, these reported injury incidence profiles are limited and inconsistent in their methodological approaches and findings (9, 11, 14, 15). The discrepancies are largely owing to variations in cohort, timeframe and competition phases examined (9, 11, 14, 15). Regardless, these rates are generally higher than other sports such as swimming, cricket, and golf that have reported injury rates of 2.6 and 3.3 injuries per 1,000 exposure hours and 9.8 per 1,000 athletic exposures respectively (49, 54, 55). Similarly, a comparative study found elite junior tennis players reported a higher injury incidence than gymnasts, swimmers and soccer players of the same standard and age (56). Conversely, contact team sports generally exhibit higher injury rates with reports of 29.1, 65.8 and 160.6 injuries per 1,000 hours of field hockey, Australian Football and rugby league respectively (57-59). Whilst comparison of injury rates in tennis to other sports is contextual, they are of limited use to understand the specificity of tennis injuries given the differences in activity profiles across sports. As such, comparisons within tennis, including differences in injury incidence by playing standard, sex and age provide more contextual understanding of injuries in elite tennis.

The prevalence of lower-extremity injuries (31-67%) is commonly reported to be greater than upper-limb (20-49%) and trunk (3-21%) injuries in tennis (9, 60, 61). However, this trend can vary depending on the cohort of players analysed (15, 16). Specifically, upper-limb injuries have been reported to be the most common in national male and female players within competition environments (16); yet back injuries have been found to be the most common in elite, junior male players within-event (15). Regardless, it has been consistently reported that lower-extremity injuries in tennis players are generally acute in nature, whereas the upper-extremities are classically affected by chronic injuries (61). The acute nature of lower-limb injuries can be attributed to the fast accelerations, decelerations and changes of direction demands placing high (eccentric) loads through the lower-extremities (61). Of note, most acute tennis injuries occur during competition as compared to training, which may be a result of the addition of an opponent which can lead to more reactive and less controlled movements (14, 62, 63). Additionally, the chronic nature of upper-extremity injuries in tennis is typically associated with the repetitive movement demands of these limbs during overhead, groundstroke and volley actions (61). The most common types of tennis injuries, regardless of their onset, are often reported to be muscle sprains and strains (9, 10, 15). Although a general overview of tennis injury provides some insight, it fails to consider the nuances of specific age categories and skill levels which can impact on the injury incidence (12, 21). Additionally, targeted injury profiles are more informative for stakeholders involved in the development of elite tennis players across different stages of the player pathway.

2.4.1. INJURIES IN ELITE ADULT TENNIS PLAYERS

The tennis player pathway ultimately strives to develop professional players. Therefore, exploring the injury epidemiology of elite adult tennis players initially provides a top-down approach for the comparison and prevention of injury incidence throughout a player's developmental journey. The primary reporting of elite tennis injury profiles has emanated

from literature on the Grand Slams (9, 10). The four Grand Slams are the pinnacle events in the professional tennis calendar including the Australian Open, Roland Garros, Wimbledon and the US Open; with injury epidemiological profiles of the US Open and Wimbledon already existing (9, 10). Assessment of US Open injuries was over a 16-year period and reported a mean injury rate of 48.1 injuries per 1,000 match exposures per tournament (9). Males had a higher injury incidence than females (44.0 vs 32.2 injuries per 1,000 match exposures), which is in direct contrast to findings from Wimbledon (9, 10). The injury profile of Wimbledon highlighted that female players, between 2003-2012, incurred a mean injury incidence of 23.4 injuries per 1,000 set exposures compared to 17.7 injuries per 1,000 set exposures for the male players (10).

Of note, the relative exposure measure selected by each research team was different (1,000 match versus set exposures) which makes comparison difficult. More so, 1,000 match exposures, as utilised in the US Open study (9), fail to differentiate between male and female set demands in Grand Slam tennis, whereby males play the best of five-set singles matches and females the best of three-sets. Additionally, both exposure measures overlook the difference between competitive (i.e. 7-6) and non-competitive sets (i.e. 6-0), where the activity profiles vary and, potentially, so does the injury risk. The utilisation of an exposure measure more targeted to the demands of the competition could provide more precise findings. As such, the consensus statement on epidemiological studies of medical conditions in tennis recommends that injuries be reported per 1,000 playing hours (64). However, this metric does not capture the load profile imbedded within the duration. Given that injuries sustained in tennis are a direct result of mechanical loads imposed on the musculoskeletal system (65), exposure measures such as distance covered or number of balls hit may be more descriptive and definitive. Although not the primary focus of this thesis, further exploration of the relevance and precision of exposure measure selection in all epidemiological studies is needed

(Appendix I).

Even with the challenges of different exposure measures, the findings from Wimbledon and the US Open highlight that variations in injury profiles by sex exist between Grand Slam events (9, 10). However, the body-region analysis of both Grand Slams suggests similarities with the lumbar spine, shoulder, knee, groin and ankle featuring as the most common sites of injuries at both events (9, 10). Given the varying levels of consistency between Wimbledon and US Open injury profiles, an understanding of the injury epidemiology of other Grand Slams has merit. Particularly given they are scheduled at a different time of year, on a different court surface and in different climates.

Additionally, given all the Grand Slams are required to provide medical staff to treat all participating players, insight into the severity of injuries, as well as how injury incidence changes year-on-year, can contribute to the justification of medical resourcing in-event. However, this has not been explored (9, 10). Specifically, it can assist in the decision-making around Grand Slam staffing, supplies and budgetary consideration. Therefore, the need for further investigation into elite Grand Slam tennis injuries is critical from an injury profiling, athlete preparation and event-impact perspective.

Evidently, the profile of injuries in professional tennis players is currently confounded by the limited ability to compare findings due to differences in exposure measure selection and the unavailability of key insights such as the severity of injuries, resource burden or changes in year-on-year injury incidence within-event (9, 10). This can have repercussions for elite junior tennis players, and their support networks, whose long-term aspiration is to compete at

these events without the interference of injury. This resulted in the first aim of the thesis which was to explore the injury epidemiology of the Australian Open Grand Slam over multiple years. The sex, body-region, treatment cost and year-on-year changes in injury incidence were analysed to garner a more robust profile of elite adult tennis injuries.

2.4.2. INJURIES IN ELITE JUNIOR TENNIS PLAYERS

Whilst profiling Grand Slam tennis injuries is valuable for understanding the injury incidence at the top tier of elite tennis, it is equally as important to profile injuries in elite junior tennis whereby injuries can have an impact on their long-term athletic development and subsequent playing careers (65). As the injury reports in elite adult tennis are limited, it is challenging to establish early intervention strategies throughout the pathway. To supplement this, an understanding of the injury epidemiology of elite junior tennis players can mitigate the shorter-term risk.

However, the available literature on elite junior tennis injury epidemiology highlights discrepancy in the current knowledge-base. For example, sex-based reports have found junior males to incur more injuries than females in competition (12), whereas others have found elite junior females to sustain more injuries than their male counterparts (19, 66). These differences in injury profiles by sex are consistent with the findings in elite adult tennis players (9, 10). This may suggest that sex is not a moderating factor for elite tennis injury as both sexes are exposed the same amount of risk. Alternatively, it may highlight that injury incidence is affected by factors other than sex, such as the competition phase (training versus competition), age, physical capacity or physical maturation (4, 23, 67, 68). However, further research is needed to explore this.

There is also discrepancy regarding the specific body-region of injury incidence in junior tennis players (15, 63, 69). A study from the 1980's suggests that lower limb injuries were the most common region of injury in elite junior tennis players in a national program (69). Contrastingly, studies from the 1990's (15, 63) reported back injuries to be the most common in elite juniors during national competition (15); or that injuries were evenly distributed around the body with a slight weighting towards ankle and foot injuries (63). These findings highlight the lack of evidence and, subsequently, developing region-specific injury prevention strategies for elite junior tennis players is currently difficult. This is contrary to professional tennis whereby the existing literature displays consistency in the injury incidence by body-region between sexes (9, 10). Therefore, the body-region analysis of injuries in elite junior tennis needs further exploration to establish evidence-based justification for targeted injury mitigation strategies. Coupled with the professional tennis body-region injury findings, further investigation can provide clarity on the body-region injury trends throughout the entire elite tennis pathway.

To bolster the profiling of elite junior tennis injury incidence by sex and body-region, an understanding of the severity of injuries is important. As the fundamental goal of elite junior tennis players is to transition and achieve a professional ranking, quantifying the time-cost of injuries can reveal ramifications to athletic development. However, the severity of junior tennis injuries has been the subject of limited examination (11). For example, player recall was used to collect injury severity data from junior tennis players over a two-year period with almost half the reported injuries resulting in a time-loss of more than four-weeks (11). Additionally, it was reported that junior males incurred more injuries with a time-loss of greater than four-weeks as compared to females (11). However, the use of recall is commonly criticized for being bias and inaccurate (70). Furthermore, no study has observed the severity

of junior tennis injuries by body-region. Reports in elite junior rowers found lower back injuries to be the most severe followed by knee injuries (71). This level of information in tennis would provide guidance for region-specific injury prevention and rehabilitation programs to mitigate the developmental and potentially financial burden of severe injuries.

A consistent finding in the elite junior injury epidemiology profile of tennis, and other sports, is the relationship between age and injury. It is commonly found that injury incidence increases with age in elite junior athletes (12, 19, 72). With regards to tennis, this has been reported in studies within national competition (12, 19). However, the junior age-injury trend in longitudinal, tennis training settings remains unexplored yet has been found in elite junior rugby league players (72). Specifically, it was reported that an elite under 19-year-old team had the highest injury incidence, as well as injury severity, as compared to five younger aged teams in the same rugby league club over a season (72). Similarly, elite tennis players usually spend their entire junior journey in a nationally-supported program with prescribed training and tournament scheduling. Therefore, understanding the relationship between age and injury by players and staff in these programs can assist in providing evidence-based adaptations to training prescription and tournament scheduling to reduce the risk of injury at different ages.

It is clear that the injury profiling of elite adult and junior tennis players is scant and incongruent. Specifically, the limitations appear in the availability, uniformity of study design, timing of data collection and discrepancy in findings (10, 11, 15, 69). This has implication for the understanding and strategy to mitigate the risk of injuries in elite tennis populations. It also highlights that current injury prevention strategies across the entire elite player pathway are largely uninformed. Consequently, such lack of research also led to the

second aim of the thesis which was to comprehensively and longitudinally profile injuries in an elite junior national program. The emphasis, as per aim 1, was on exploring the sex, region and severity injury incidences and differences as well as investigating the longitudinal changes. This methodology assists in providing comparative insight into the injury epidemiology of elite junior and adult tennis players.

2.5. EXTRINSIC AND INTRINSIC RISK FACTORS

Elite tennis injuries are a result of a players biological and physical profile, paired with the demands of the sport (6). As depicted in Figure 2, injuries occur from of an aggregation of risk factors that can be considered intrinsic (internal) and extrinsic (external) to a player, coupled with an acute inciting event (7). Intrinsic risk factors can be non-modifiable factors such as age and sex, or modifiable, such as physical capacity (8). Extrinsic risk factors include those such as court surface, environmental factors and prescribed training volumes and match demands (8). Exploring the host of risk factors present in elite tennis and its players is meaningful for two main reasons. Firstly, it provides context to tennis injury epidemiology reports and, secondly, it can direct training, physician-intervention and scheduling strategies to abate the level of risk.

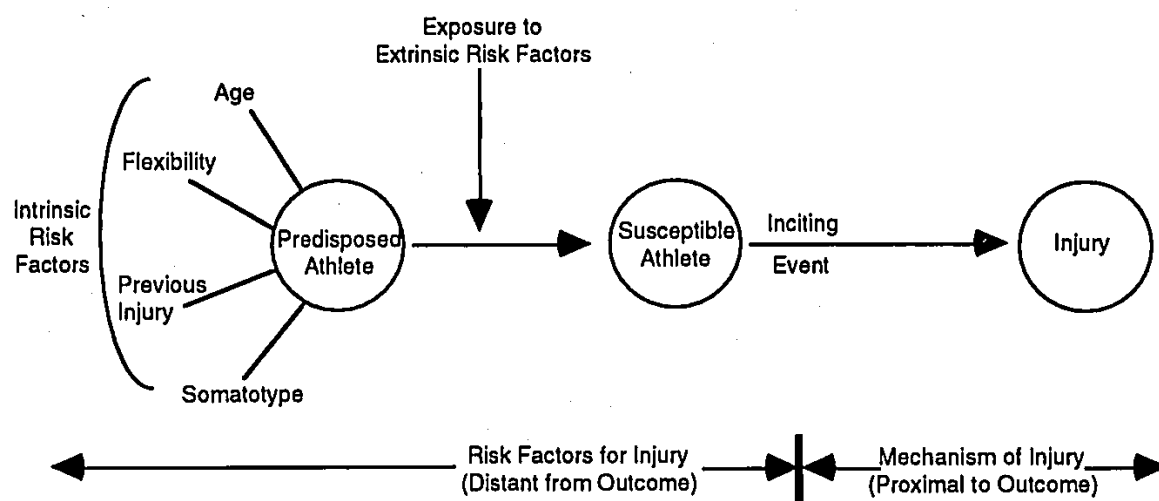


Figure 2: Multifactorial model of athletic injury aetiology (7)

The understanding of how these intrinsic and extrinsic risk factors relate to injury in tennis is still in its infancy. However, these insights are essential for tennis coaches and sports medicine staff to assess, monitor and develop strategies to prevent injuries and therefore represents a key area of focus of this literature review.

2.6. NON-MODIFIABLE INTRINSIC RISK FACTORS

Non-modifiable intrinsic risk factors are fixed internal characteristics such as age, physical maturation, injury history and sex (7, 8). They predispose a player to injury risk and are accepted as being unavoidable (7, 8). However, in understanding their relationship to injury in elite tennis, can determine strategies to reduce their impact. Although some of these non-modifiable factors have been mentioned previously as they relate to the profiling of tennis injuries, their association to injury will now be explored. However, the relationship between age, physical maturation, injury history and sex to subsequent injury is either scarce or inconclusive in the existing body of literature on elite tennis.

2.6.1. AGE

As has already been mentioned, it is common for age to be reported as associated with injury in athletic populations (59, 73, 74). Specifically, reports in tennis as well as ice-hockey, rugby league, soccer and squash highlight that older athletes, both in junior and senior competition, are more likely to incur an injury (19, 21, 59, 73, 74). Despite these associations, it remains unknown why injuries generally increase with age. It has been hypothesised that an increase in training volume and intensity with age results in a greater risk of injury (75, 76). However, the relationship of training loads to injury in tennis has not been explored. This forms a large focus of this thesis and will be elaborated on further in the literature review. Further,

degeneration in muscle strength and change of direction speed has also be attribute to the increase in injury incidence in adult ages (77, 78). These deficiencies may heighten injury risk due to the declined ability to tolerate the load and movement demands of elite tennis (35, 41). Additionally, in junior athletes, the rise in injuries may be as a result of physical maturation with age (79).

2.6.2. PHYSICAL MATURATION

Adolescent growth has been shown to have a clear association with injury risk (68).

Particularly, the period around peak height velocity has been suggested to be of heightened injury risk in junior athletes (79). For example, it has been reported that junior soccer players incurred more traumatic injuries during peak height velocity as well as a rise in overuse injuries shortly after peak height velocity (79). Additionally, fractures were reported as most common in junior athletes just before and during peak height velocity (80, 81). The reason for the rise in injuries around peak height velocity has been attributed to changes in bone density, joint stiffness, proprioception and movement mechanics (79, 82). Specifically, the adaptations in bone density and joint stiffness cause skeletal fragility (79). This may directly link to the rise in fractures commonly found during this period (79-81). Additionally, changes in proprioception and movement mechanics may result in impairments to task performance which may lead to acute injury incidence (82). However, how maturation impacts on elite junior tennis injuries, remains unexplored. Given it is a non-modifiable risk associated with all adolescent development, the monitoring of growth in junior tennis players is likely to be important for injury prevention. Regardless, specific understanding of the maturation-injury relationship in tennis can inform modifications to training and competition schedules to reduce the risk of injury around periods of growth and should be explored further.

2.6.3. INJURY HISTORY

In addition to age and physical maturation, injury history has commonly been reported as a key risk factor in athletes, explicitly for injury recurrence (83, 84). Injury recurrence is defined as an injury of the same type to the same body-region after returning to full training from the initial injury (64). It has been found that players who had an injury in one season of professional soccer were 2.7 times more likely to have an injury in the subsequent season (85). Similar findings of injury recurrence have been reported in junior soccer players as well as Australian footballers and cricketers (84, 86). In tennis, previous injury is a prominent risk factor for subsequent injuries in junior, club-level tennis players (13). The causal mechanism behind recurrent injuries has been attributed to the inadequate healing of tissue, a decline in load tolerance during rehabilitation, and/or coupled with a spike in loads when the athlete returns to competition (87, 88). Evidently, injury recurrence is common in many sports (83, 84). Therefore, the return to play after an initial injury should be closely monitored in order to reduce the likelihood of re-injury.

Interestingly, it has been reported that a higher training age can be protective against injury recurrence which may be an artefact of enhanced physical development and resilience (83). However, muscle degeneration and subsequent strength declines with older adult ages may suggest that training age is only protective against injury up to certain point (78). Beyond this, its protective nature may potentially be mitigated or actually reversed (78). Despite the large body of evidence relating injury history to recurrence, this association has not been specifically explored in elite tennis. Owing to the burden injuries can have on elite tennis player development, success and financial livelihood, there is an urgency for players to return to competition as soon as possible after injury (87). In turn, this may be the impetus for re-injury. Therefore, although further investigation into the specific relationship between injury

history and injury recurrence in elite tennis is desirable, there is enough evidence to suggest that the monitoring of injury history is crucial for reducing the risk of subsequent injuries.

2.6.4. *SEX*

As already discussed, there is conjecture in the literature relating sex to injury incidence, region or type. Tennis injury epidemiology studies highlight no sex difference in injury incidence whereas others suggest that males are more injurious, and others that female tennis players are more injurious (9, 10, 36). When deeper exploration of injury incidence by body-regions is undertaken, tennis injury findings by sex become more congruent, particularly in elite adult tennis players (9, 10). It is commonly reported that male professional tennis players are more prone to lower-limb injuries, whereas female injuries are spread evenly across all body-regions (9-11). This has been attributed to differences in playing styles and intensity, as well as biological differences (44, 89). Specifically, males have been found to have faster ball speeds and are able to win more points off their serve, whereas females have greater hitting and movement loads (44, 89). Additionally, sex differences in bilateral and unilateral movement and strength have been associated with sex and limb-specific injuries (90). Seemingly, the sex-injury relationship in tennis is currently more informative as it relates to region-specific injury incidence, particularly in elite adult players. Yet, further research is needed to understand the global and junior body-region sex-differences in elite tennis injury to determine relevant risk mitigation strategies.

Overall, age, maturation, injury history and sex are seemingly all important non-modifiable risk factors to consider and monitor by elite tennis players and support staff. The evidence of their relationship to injury is bolstered by findings in other sports (74, 79, 83). Although a starting point, further insights into the association of these unavoidable risk factors with injury

in elite tennis populations is needed to provide more targeted strategies to reduce their hindrance.

2.7. MODIFIABLE INTRINSIC RISK FACTORS

In addition to non-modifiable risk factors, there are numerous modifiable intrinsic risk factors that can also predispose a tennis player to injury risk (7, 8). Modifiable risk factors are also internal to an athlete, however unlike non-modifiable risk factors, they are not fixed and can subsequently be altered (7, 8). Therefore, the importance of understanding how these factors relate to injury lies in their ability to be adjusted to reduce the risk of injury. Modifiable risk factors in elite tennis can include physical capacity, musculoskeletal function, playing standard and wellbeing (7, 8). However, the understanding of each of these risk factors as they relate to injury in tennis is currently limited.

2.7.1. PHYSICAL CAPACITY

The demands of elite tennis, specifically the repeated multiple changes of direction, fast accelerations and decelerations, and large rotational and ground reaction forces places large amounts of strain on the musculoskeletal and cardiorespiratory systems (5, 46). Therefore, an established and robust physical foundation is important for the successful performance of these required repetitive movements (35). Conversely, a poor physical base may limit a player's ability to tolerate these loads and can predispose them to injury risk (35). The assessment of physical capacities is commonly measured via a battery of fitness tests which are usually completed at the start and end of a season or training block (91, 92). This timing limits the impact other variables, such as fatigue and soreness, on the test outcomes (91, 92). It also allows for the tracking of progress (91, 92). A suite of tests has been specifically recommended for the assessment of physical capacities in tennis players (91, 92) (Table 3).

However, the assessment of these physical capacity tests has only been reported as they relate to playing standard and performance, rather than injury. Nevertheless, it has been found that aerobic capacity was able to discriminate between national and international level male tennis players (93). Additionally, findings that elite junior tennis players had greater lower- and upper-body power, strength and flexibility compared to their recreational counterparts have been reported (76).

Table 3: Fitness testing measures utilised in tennis populations

Fitness Testing Measure	Tests
Strength	Grip strength test Push up test Sit up test
Speed	5m, 10m and 20m sprints Tennis specific sprint test
Change of direction speed	505 agility test Illinois agility test Tennis-specific agility test
Jumping ability (lower body power)	Countermovement jump Repetition jumps
Upper body power	Medicine ball throws Serve velocity
Aerobic capacity	Tennis-specific Hit & Turn Test Maximal multistage 20m shuttle run test

(91, 92, 94, 95)

Unlike other sports, there is no literature in elite tennis suggesting that underdeveloped physical capacities create a heightened injury risk (96-98). Low aerobic capacity has been associated with greater lower-limb injuries in elite junior Australian football players (97), elite adult Australian footballers (96) as well as global injury incidence in elite ballet students (98). Additionally, faster acceleration and slower change of direction speed were also found to be associated with greater lower-limb injuries in junior Australian football players (97). A poor aerobic capacity and slow change of direction ability may be associated with injury because they limit the ability for an athlete to tolerate the load and movement demands of the sport, as reported respectively in Australian football and ballet (96-98). Conversely, faster accelerations in Australian football may exacerbate the physical demands due to greater eccentric loads (97, 99). Alternatively, faster accelerations may result in an injury-inciting event such as a hamstring strain from biomechanical failure (8). As it relates to tennis, prolonged matchplay over consecutive days has shown to reduce sprinting ability in sub-elite tennis players (6). Aligning this to the heightened injury risk with faster accelerations in Australian football, may suggest that tennis players are more at risk when their acceleration and speed are impaired. However, this suggestion fails to consider whether tennis players with superior speed and acceleration are at less risk of injury. Evidently, research is needed to determine what and how physical capacity measures are associated with injury risk in elite tennis players so they can be tested and monitored appropriately as well as inform training prescription.

2.7.2. MUSCULOSKELETAL FUNCTION

Coupled with the understanding of the relationship between a player's physical capacity and injury, it is important to understand how limitations or deficiencies in a player's musculoskeletal function are associated with injury (100). Specifically, assessing the flexibility, strength and pain profile of player joints can potentially highlight injury risks (100,

101). Accordingly, musculoskeletal screenings are commonly used to assess musculoskeletal function (100, 101). Although no extensive list of musculoskeletal screening measures is available, particularly in tennis, the battery of tests utilised at Tennis Australia are listed in Table 4. Globally, musculoskeletal screenings are commonly completed pre-participation (baseline) or at the start of a training block to identify characteristics of the musculoskeletal system which may predispose an athlete to injury risk, without other confounding factors such as muscle soreness or fatigue (100, 101). They look to determine any structural or muscular weaknesses, dysfunction and/or imbalance that may limit the potential performance of athletes and/or be indicative of future injury risk (100, 101). They are also generally reviewed at the end of a season and/or training block to determine any adaptation to training as well as the effectiveness of injury prevention programs and physiotherapy intervention (100).

Table 4: Musculoskeletal screening test battery utilised at Tennis Australia

Musculoskeletal screening test	Description	Unit of measure
Dominant single leg squat	Unilateral lower limb mobility and strength	1: good, 2: fair, 3: poor
Thoracic overhead extension	Thoracic flexibility	1: within normal limits, 2: stiff, 3: hypermobile
Scapula dyskinesis	Scapula function in flexion	1: normal, 2: abnormal
Glenohumeral internal rotation deficit	Difference in shoulder range of motions	Degrees difference
Dominant supine hip internal rotation	Hip internal rotation	1: within normal limits, 2: stiff, 3: hypermobile
Dominant supine hip external rotation	Hip external rotation	1: within normal limits, 2: stiff, 3: hypermobile
Squeeze test	Hip adduction	1: good, 2: fair, 3: poor
Dominant Thomas test	Hip extension	1: above horizontal, 2: horizontal, 3: below horizontal

(102)

However, ambiguity exists in the standardisation of screening tests as well as the efficacy of these protocols (100, 103). A review on the inter and intra-rater reliability of musculoskeletal screening measures in sport found most studies did not undertake reliability testing as part of their research (103). This casts some doubt on interpretation of the screening results and subsequent relationship to injury. Additionally, Bahr (2016) highlighted that screenings are unable to determine injury outcomes without adequate testing of their validity, which has failed to be achieved in the current body of research. This may explain why the findings of many musculoskeletal screening and injury studies remain equivocal (100, 105-107). Some studies suggest that there is a correlation between certain adverse screening outcomes and injury incidence (100, 105-107), whereas others suggest no such relationship (108, 109). In tennis, the research into screening reliability, as well as the relationship to injury, is sparse. For example, differences in dominant and non-dominant shoulder internal and external strength may be indicative of injury (110). Additionally, an association between hip range of motion and injury in professional female tennis players has been reported (20). However, the findings were retrospective in nature with an athlete-reporting of injury history being the outcome measure. As such, the capability of existing screening protocols to assess injury risk in tennis and other sports is somewhat unclear, yet continue to be routinely performed. As a starting point, better quality methodological approaches to musculoskeletal screenings is needed, including reliability and validity testing. Additionally, further exploration of their relationship to injuries in tennis with a longitudinal and prospective approach may provide more useful findings.

2.7.3. PLAYING STANDARD

Although the focus of the thesis is on elite tennis players, the standard of play may predispose players to a greater exposure to injury risk. It has been found that injuries in international competition of gymnastics, swimming, soccer and tennis were far higher than in national

competition (111). Additionally, injuries in elite gymnasts were higher than sub-elite gymnasts over an 18-month training and competition period (112). Specifically, when comparing between tennis injury epidemiology studies, the injury profile varies across the standard of tennis players with higher reports in elite populations as compared to college/sub-elite and recreational populations (9, 10, 12, 62, 66). However, the reason for the variations in injury incidence with playing standard is not clearly defined. It has been suggested that the differences in injury incidences may be due to heightened training and match activity profiles as the standard of play improves (75). For example, professional tennis players perform more serves during matchplay compared to junior players, with the serve thought to be a mechanical injury precursor (42). Additionally, the serve speeds and aerobic demands of elite tennis matchplay have been found to be higher as compared to sub-elite matchplay (6, 44, 45). The duration of male Grand Slam tennis is also higher than lower-tiered tournaments owing to the fact that they are competed over the best of five-set matches (43). Although it is clear that the demands increase with playing standard, the explicit relationship between these heightened loads and injury remains speculative in tennis and warrants further exploration. As mentioned, this will form a large section of the body of research in this thesis and will be elaborated on further in the literature review.

2.7.4. WELLBEING

Of wide interest in elite sport globally, is the surveillance of wellbeing to monitor the condition of athletes (113, 114). The condition of an athlete can include their readiness to compete, fatigue, mood, training distress as well as psychological stress (113, 114).

Wellbeing is typically monitored and quantified via select psychometric assessments such as the Athlete Distress Questionnaire (115), Recovery-Stress Questionnaire (116) and Profile of Mood States (117) or customised wellness questionnaires (113, 114). These assessments are generally administered as athlete questionnaires which are then reviewed and actioned upon

by relevant practitioners and coaches. In addition to determining an athlete's psychological state, wellbeing monitoring tools are also utilised to determine the potential impact on athletic performance as well as injury risk (23, 118-120). Numerous studies, including those in soccer, Australian football and rugby league have found an association between athlete ratings of fatigue and stress, and an increase in injury risk (23, 118-120). Specifically, it was found that elite junior soccer players with higher ratings of general and sport-specific stress were more likely to incur a traumatic or overuse injury (118). Additionally, perceptual ratings of anxiety, negative life stresses and daily hassle were all shown to be predictors of injury in professional soccer players (119). Sleep quality, mood, perceived performance, and perceived health and fitness have all been associated with heightened injury risk in other sports (121-123). Of interest, perceived ratings of muscle soreness have also been found to be associated with heightened injury risk in elite sports (124). For example, higher ratings of lower-limb discomfort in rugby league, rugby union and Australian football players resulted in a greater incidence of subsequent injury (124). Overall, it is evident that numerous measures of athletic wellbeing are related to injury risk in respective sports. The specific mechanism for how wellbeing measures impact on injury is said to be caused by a psychological stress response (119). This can manifest in physical changes such as fatigue and muscle tension, as well as emotional responses such as a distraction which ultimately expose athletes to greater injury risk (119, 123).

However, the association between perceptual wellbeing measures and injury has not been explored in elite tennis. As tennis is an individual sport and termed a 'lonely' sport by many players, it can result in perceptual stresses which may ensue in injury risk (125). Additionally, the large competition and travel demands of elite tennis may also impact on a player's psychological state and subsequent injury risk (1, 4, 35). Therefore, further research is needed

to support these statements. Owing to the established link between reductions in wellbeing and injury in other elite sports, there is a clear need to explore this in elite tennis.

Summary of intrinsic risk factors in tennis

The specific relationships of modifiable risk factors including physical capacity, musculoskeletal function, playing standard and wellbeing to injury in elite tennis is unclear. The findings from other sports suggest some associations, however, they should be adopted with caution in tennis due to limitations in the generalisability of the practical outcomes (97, 101, 111, 114, 119). As a result, these intrinsic risk factors and how they related to injury in elite tennis deserves further investigation. Coupled with this, the extrinsic risk factors, which expose these players to further risk, needs to be considered.

2.8. EXTRINSIC RISK FACTORS

The environment in which elite tennis players operate results in an accepted exposure to numerous risk factors (17, 126). These risks can include court surface, climate and equipment as well as the type, volume and intensity of training and matchplay (17, 126). Coupled with an understanding of intrinsic risks, the exploration of how these extrinsic risk factors relate to injury in elite tennis is fundamental for the informed development of risk mitigation strategies. These strategies may be adopted by tournament organisers and the governing bodies of tennis, including the International Tennis Federation (ITF), Association of Tennis Professionals (ATP) and the Women's Tennis Association (WTA), to ensure events and annual tournament calendars are considerate of the extrinsic risks imposed on its players. Additionally, it can assist players and their support teams in the creation of evidence-based training and injury prevention programs. It must be noted that owing to data availability and

priorities of this thesis, court surface, climate and equipment will be explored in the literature review but not in the ensuing body of research.

2.8.1. COMPETITION PHASE

The demands of tournament matchplay, as compared to tennis training, are relatively different with greater serve loads, perceived intensity and distances covered reported during matchplay (75, 127). Owing to the congested tournament schedules of elite tennis, players typically compete in an average of three tournaments in a row. These consecutively competed tournaments are referred to as tournament swings (37). These tournament swings are interspersed with travel as well as time-restricted training. Therefore, although the activity profile of competition tennis is generally higher than training, as training blocks are short there is an urgency to maximise the training dose within the given timeframe (127). Therefore, the relationship between both tournament and training phases, and subsequent injury, may vary.

Variations in the injury profile of different competition phases have been highlighted previously (14, 62, 63). Specifically, it is often found that injuries during tennis competition are more frequent as compared to training in both sub-elite and elite tennis cohorts across both sexes (14, 62, 63). This is consistent with findings in elite soccer whereby the severity of within-event injuries were greater than those incurred during training (85). The explanation for the higher injury incidence in-event can be attributed to both additional extrinsic and intrinsic risk factors present in competition. Particularly, competitive matchplay exposes elite tennis players to unique risks including opponent-dictated loads and movement demands as well as the pressures of the score, media, crowd, ranking points and prizemoney (128). These risks are not present in training whereby the loads and movement demands are typically

controlled and the external pressures are either limited or non-existent. Additionally, as the external and internal load demands of competition tennis have been found to be greater than during training (4), the higher cumulative loads over the length of a tournament and/or tournament swing may heighten the injury risk in-competition. This suggested rise in injury incidence with higher cumulative loads has been found in other elite sports such as Australian football and rugby league (28, 29). The higher within-event demands in elite tennis may also exploit or exacerbate intrinsic risk including a player's physical capacity, age and musculoskeletal function. Although these mechanisms can explain the higher injury incidence within-competition, there is not existing elite tennis literature to support these explanations. Therefore, further research is needed to justify these statements. Regardless, the greater injury risk in competition has implications for players and tournament organisers alike. Players need to consider the load profile of matchplay and ensure training is specific to these demands so they are best prepared for competition. Additionally, tournament organisers can use this information in the consideration of match scheduling and player health and safety within-event.

However, the injury incidence during training also deserves exploration given their finite timeframes. Additionally, it is particularly important to understand why injuries occur in elite junior training given it is the key period of athletic, technical and tactical development prior to their transition and competition on the professional tour (2). It is commonly found that individual training durations are greater than individual match durations in elite tennis which may in itself heighten injury risk (75). Additionally, it has been reported that players experience declines in physical capacities during tournament swings (127). Specifically, declines in speed, change of direction ability and aerobic capacity have been reported post-tournament swing in elite junior tennis players (127). Therefore, this can limit a player's ability to tolerate the demands of training post-competition which can exacerbate injury risk.

However, like the competition load-injury relationship, the explicit relationship between the loads experienced during training and injury has not been explored in elite tennis. An understanding of the aetiology of injury incidence in tournament and training phases is seemingly important for their monitoring and management and warrants further investigation.

2.8.2. COURT SURFACE

Tennis is generally played on clay, grass and variations of hard court surfaces (50) with injuries reported to be more prominent on hard courts compared to clay and grass surfaces (22, 129). For example, a study on the injury-enforced retirement in male professional competition showed a greater incidence on hard court as compared to clay and grass (22). Similarly, it has been found that injuries on hard court were higher than clay in recreational tennis players of both sexes (130). However, another study observing retirements in professional tennis matches found no difference in male injury incidence by court surface but found women to incur more injuries on hard court as compared to clay (129). Comparing Grand Slams, injuries at the US Open, played on hard court, were more common than at Wimbledon which is played on grass (9, 10). It must be noted that the comparison between Grand Slams is limited by the difference in exposure measures selected (1,000 match versus set exposures; (9, 10)). Overall, the greater prominence of hard court injuries in tennis is relatively consistent across all playing standards and sexes.

Interestingly, the mechanism behind the higher incidence of tennis injuries on hard court, as compared to clay and grass, is inconclusive. Greater eccentric and concentric forces have been reported on hard court as compared to other surfaces (131). Additionally, larger loading through the foot has been found on hard versus clay court which may heighten the injury risk (132). However, point durations are generally longer in clay court competition (133) and ball

speeds faster in grass court competition (89) which may suggest that the physical demands, and subsequent injury risk, of clay and grass court tennis can also be high. However, interestingly, a physiological comparison of hard and clay matchplay found no differences in the profile of the matches by court surface (134). Although there is consistency in the injury incidence by court surface, the mechanisms behind the risk are still relatively unclear and require further investigation. Further research in this area may assist in specific risk management strategies for training and competition on different court surfaces. Additionally, it may inform consideration of tournament participation by court surface as a way to reduce the injury risk throughout the demanding elite tennis tournament season.

2.8.3. HEAT

Tennis is generally played outdoors, and during specific periods in the annual calendar, elite tournaments are contested in hot environmental conditions (135). Participation in tennis competition in hot climates has been commonly associated with heat illness (136). However, in relative terms, the incidence of heat illness is substantially lower than injury incidence in event (136). Additionally, if and how playing in hot climates is associated to tennis injury, in addition to illness, is largely unknown. Exercising in the heat has been known to increase the physiological and perceptual load on the body, increase central fatigue and reduce muscle function (135, 137, 138). Specifically, tennis matchplay in the heat has been found to reduce knee extensor strength which compromises the neuromuscular integrity of the lower-limb (139) and a theoretical injury risk. However, another tennis study reported no difference in the physical decrements of competition tennis in hot, as compared to cold environments, suggesting it is the match external load, not environment, that affects performance and injury risk (140, 141). Evidently, there is conjecture in the limited research exploring the impact of hot climates on performance and subsequent injury risk in tennis. Therefore, further

understanding of the heat-injury relationship in elite tennis is needed, particularly given the fact that many elite tournaments are competed in hot climates (135, 136).

2.8.4. EQUIPMENT

In addition to court surface and climate, equipment is another factor that can influence injury in elite tennis. Modern tennis has seen large technological advancements in the equipment used including racquets, balls and string (50, 51). Contemporary tennis racquets are generally constructed from a composite of materials including, but not limited to, graphite, carbon and fibre-glass (50). This has made them lighter and stiffer as compared to historic, wooden racquets (50), resulting in faster swing speeds and subsequently faster ball speeds (50).

However, the change from wood to new composite racquets has also seen a rise in tennis injuries (50, 51). The reason for this is unclear but may be due to greater vibrations and torque as well as a general increase in the pace of matchplay (50, 51). Correspondingly, although the composition of the tennis ball has not changed much with time, it has been found that modern balls are slightly harder compared to previous (50). Therefore, in combination with stiffer racquets and faster ball speeds, has been linked to injury (50). Conversely, no literature is currently available on the association between strings and injury. This may be as a result of limitations in the ability to quantify the effects of string technology *per se*. Yet, with Hawkeye technology now available (142), the ability to assess string performance and the subsequent association to injury risk is now possible. Coupled with the numerous types and combinations of string on the market, as well as variations in string tension selection, it seems crucial to explore from both an injury and performance perspective. The advent of Hawkeye technology can also provide more insight on racquet and ball performance and their subsequent risk for injury. Therefore, this requires further research attention.

2.8.5. TRAINING LOADS

Training loads are a critical part of modern-day sports science and have become ubiquitous in the preparation of professional athletes. As a starting point, it is important to define training load. The IOC consensus statement on load and injury states load as:

*'The sport and non-sport burden (single or multiple physiological, psychological or mechanical stressors) as a stimulus that is applied to a human biological system (including subcellular elements, a single cell, tissues, one or multiple organ systems, or the individual)'.
(143)*

Training load can be classified as external or internal. External load describes the amount of work completed irrespective of an athlete's physical characteristics (39). It is the dose of training or matchplay. Alternatively, internal load describes the physiological and psychological stress response to the dose of training (39). Quantifying, monitoring and understanding the external and internal loads of elite tennis is integral to the daily development of elite tennis players. It provides objective aid to coaches and medical staff to optimise player performance within competition. On the contrary, when not managed correctly, training loads are a risk factor for injury. Therefore, it is important to contextualise training loads and their relationship to injury so that athletes and staff are better informed in their strategies to minimise injury risk and maximise performance.

2.8.5.1. EXTERNAL LOADS IN TENNIS AND THE RELATIONSHIP TO INJURY

Understanding of the external load-injury relationship in tennis is extremely scant with the only findings suggesting that the volume of practice and matchplay per day and week are positively associated with injury (12, 60). Alternatively, the external load-injury relationship

has been heavily researched in other elite sports including cricket, rugby league and Australian football (25, 26, 29). The findings from these studies highlight varying levels of association between particular external workload profiles and injury. Specifically, findings in elite cricket highlights that either a low or high bowling load increase injury risk (25). Additionally, cumulative weekly distance covered and greater volumes of high speed running have been associated with heightened injury risk in Australian footballers and rugby league players respectively (26, 29). Similarly, a high number of accelerations, as well as large acute high-speed distances coupled with low chronic high-speed distances were also found to increase injury risk in elite junior football (soccer) players (144). These suggest specific external load measures should be monitored to determine injury risk in these select sports. However, some of these external loads metrics may not be applicable to tennis. Additionally, the external load profile of elite tennis is unique and may therefore result in different associations to injury compared to what has been found in other sports.

The lack of external load-injury research in tennis is largely owing to previous difficulties in the quantification of tennis-specific external load measures both within competition and training (145). To date, external loads in tennis have been limited to fairly global measures including number of balls hit, matches played, match duration and distance covered (6, 41, 43, 44). As reference, the external load profile of tennis has been categorised and described in Table 1 (page 35). Until recently, the capturing of these measures have generally involved human notational analysis via live or video feedback (145). This is time-consuming and limits the practicality of collecting this data on a regular basis, both within matchplay and training. However, with the modern advent of Hawkeye and inertial sensor technology this process is becoming automated and timely and can allow for more in-depth external load measures to be collected (44, 142, 145). For example, distances covered in different speed bands were able to be quantified during Grand Slam tennis matches via Hawkeye technology (44). Similarly, the

automatic capture of groundstrokes defined by spin type, i.e. backhand topspin compared to backhand slice, using an inertial sensor fixed to the dominant wrist has recently been validated (145). Subsequently, the growing ease of quantifying external loads in tennis can allow for a more robust examination of their relationship to injury in the near future.

However, in the absence of established external load and injury relationships, perhaps tennis can lean on findings from other sports with an overhead component. Specifically, cricket and baseball research highlight that balls bowled and pitches thrown, respectively, have been shown to be related to injury risk (25, 146). Therefore, extrapolating to tennis environments where there is an absence of data, it can be suggested that serve loads be monitored and assessed for its association to injury. Additionally, as competitive tennis matchplay is not defined by duration but rather score (45), as per cricket and baseball, variability in match duration, hitting volume and, speed and distance variables within a match may have some association to injury and should be explored further. In addition to the exploration of the external load-injury relationship in tennis, the response to such loads and the association to injury also needs to be considered.

2.8.5.2. INTERNAL LOADS IN TENNIS AND THE RELATIONSHIP TO INJURY

Internal loads quantify the physical, physiological and psychological stress response to a bout of training or matchplay (39). These include, but are not limited to, heart rate, oxygen consumption, RPE (47) and perceptual wellbeing (39). These responses have been found to be associated with injury risk in other sports, however, there has been no exploration of this relationship in tennis. Specifically, the internal load-injury relationship has been examined in Australian football, rugby league and cricket with disparate findings (29, 147-149). As case in point, studies have observed higher internal loads, quantified via sRPE (3), resulted in an

increased risk of injury in cricketers and rugby league players (28, 147, 148). However, other reports suggest there is no relationship between sRPE (3) and injury occurrence also in rugby league as well as Australian football players (30, 150). Although speculative, the differences in load profile of the sports and athletic cohorts, as well as differences in the load and timeframe calculations may have resulted in the confounding findings. Consistently though, numerous studies including those in professional soccer, Australian football and rugby league have reported relationships between perceptual wellbeing ratings and injury (23, 118, 119). Specifically, it was found the lower ratings of perceptual wellbeing were associated with injury in elite junior and adult soccer players (118, 119). Additionally, it has been reported that perceptual wellbeing measures are reduced post-Australian football and rugby league games which do not recover for 2-3 days (114, 120). Although no link to injury was explored in these studies, the findings suggest that there are complex interactions between external and internal loads which may collectively have an association to injury risk. The collation of findings in other elite sports highlights the need to understand the internal load-injury relationship in elite tennis, particularly given the fact that the internal load profile of elite tennis differs substantially. As reference, the internal load profile of tennis has already been categorised and described in Table 2 (page 35). Owing to the large volume of research exploring the relationship of sRPE (3) and wellbeing with injury in elite sport, the exploration of these internal loads may be the best place to start for uncovering the internal load-injury relationship in tennis. Yet, as an understanding of both the dose and response to training/matchplay are the most informative for injury management, the exploration of both external and internal loads collectively to injury is also needed.

2.8.5.3. THE MODELLING OF EXTERNAL AND INTERNAL LOADS TO INJURY IN SPORT

Conceptually, the genesis of the recent external and internal load and injury relationship research can be traced back to the fitness-fatigue model of Banister et al. (1975) (Figure 3).

This model describes the dose-response relationship to training whereby after a training stimulus an athlete has both an acute fatigue and chronic fitness response (151). The difference between these two variables results in a performance outcome. The outcome is positive if an athlete's fitness outweighs fatigue, and the contrary if not (151).

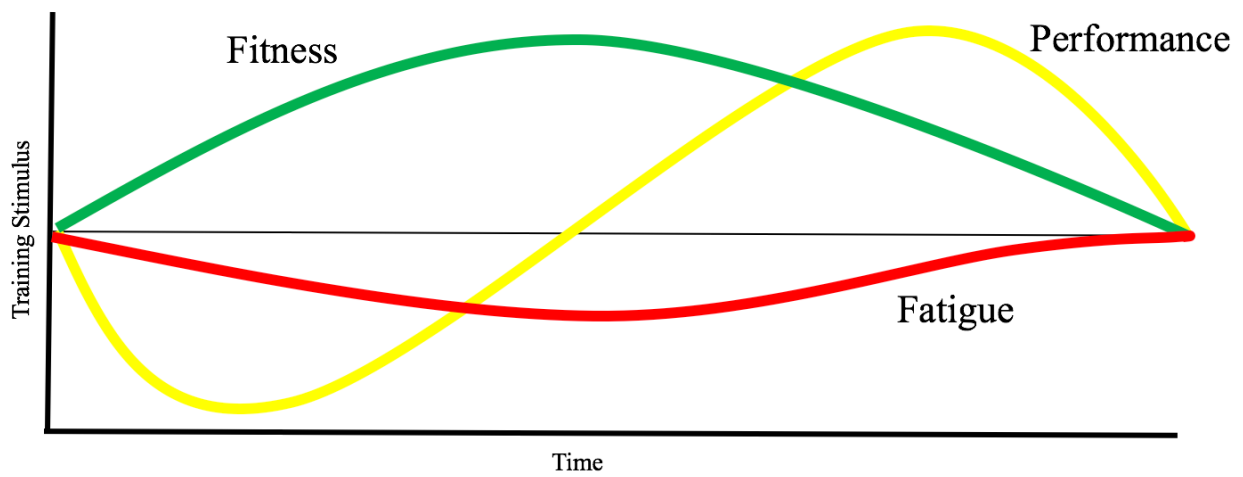


Figure 3: The fitness-fatigue model as proposed by Banister et al. (1975)

Similarly, the ACWR, which is commonly used to quantify training loads, is an adapted representation of the negative fatigue (acute load) and positive fitness (chronic load) response to training (25). Specifically, acute and chronic workloads are calculated via the rolling average of loads experiences in selected timeframes, usually 7 and 28-days respectively (30). These timeframes are arbitrarily assigned to the fatigue and fitness response but have been justified as aligning to typical micro- and mesocycles of training and competition (152, 153). It is the ratio of these two; the difference between the fatigue and fitness response, that is commonly assessed for its association to injury (25, 27). For example, findings in cricket suggest that a spike in the ACWR, quantified by distance covered, of greater than 1.5 in a given week results in heightened injury risk (25). This is consistent with findings in Australian football and rugby league (27). However, in these cases, the fitness-fatigue model (151) has been adapted to feature injury, rather than performance, as the outcome measure. This has consequently raised speculation over the relevant application of the Banister fitness-fatigue model to such contexts. Additionally, the selected timeframes of acute (1-week) and chronic (4-weeks) loads commonly used have also been criticised as being subjectively allocated to the training response timeframes of fatigue and fitness respectively (30).

Given these queries and critiques, recent variations in the timeframes and calculations of daily load metrics have been suggested as better indicators of injury risk than the commonly calculated ACWR over 7 and 28-days (30, 31, 33, 34). Different acute and chronic timeframes have been found to perform better in understanding the association to injury in elite Australian football (30). Specifically, acute timeframes of three or 6-days, coupled with a chronic timeframe of 3-weeks outperformed all other modelled timeframes including the traditional 1 and 4-week periods (30). An alternative load model has also been suggested compared to the ACWR which incorporates a decay factor to loads over time (154). The EWMA model provides greater weighting to loads experienced more recently with the theory

that they are likely to be more impactful on injury compared to loads experienced further in the past (33, 154). When the EWMA was compared to the ACWR in elite Australian footballers, it was found that EWMA was a more sensitive indicator of subsequent injury (33). Although an isolated study, the findings promote the need for further exploration. Additionally, a mathematical limitation in the ACWR calculation has been highlighted (34). Using the traditional 7 and 28-day acute and chronic timeframes as an example; the 7-day acute period is also included within the 28-day chronic calculation. Therefore, when the ratio is calculated, the acute load features in both the numerator and denominator resulting in mathematical coupling (34). Therefore, the removal of the acute load timeframe from the chronic load calculation, i.e. the calculation of chronic load from day 8 to 28, has also been recommended (34). Other alternatives to the ACWR have also been suggested, including the utilisation of monotony and strain calculations to account for variability in training loads and training stress (31, 155). However, to date, the findings have been limited (31, 155).

Given that not even the ACWR ratio has been explored in tennis, these alternative approaches can provide direction for the quantification and assessment of the load-injury relationship in elite tennis. Furthermore, future exploration of the load-injury paradigm in elite tennis and other sports may choose to assess the relationship differently as it has recently been suggested that the predictive ability of loads to injury should be explored, rather than the association (31, 32).

2.8.5.4. A MATHEMATICAL UNDERSTANDING OF THE LOAD-INJURY RELATIONSHIP IN SPORT: ASSOCIATION VERSUS PREDICTION

As highlighted above, most injury aetiology studies assess risk factors and their *association* to injury and thus lack exploration of *prediction*. However, it is common for these terms to be

used interchangeably (156). For example, Hulin et al. (2016) highlighted that training loads can predict injury but actually used injury risk as an association. It is important to understand the difference between these two terms in order to select the appropriate statistical methodology and subsequent interpretation of the findings. Association models, also called explanatory models, refer to the testing of casual explanations with specific statistical methods (156). Whereas prediction is the application of a statistical model on a dataset to predict future outcomes (156). Namely, understanding the sensitivity and specificity of a model being the ability of the model to detect true positives (injuries) and true negatives (non-injuries)(8). Although association and prediction outcomes can be related, a model with strong association may not necessarily be able to predict (157). As it relates to the ACWR, the ability to predict injury, rather than determine the association, has be explored in elite Australian football and soccer with limited results (31, 32). The injury predictive ability of ACWR in both were found to be similar to chance (31, 32). However, neither the predictive or associative ability has been explored in tennis. Owing to the differences in load profiles across sports, there is merit in investigating the injury prediction ability of workloads in elite tennis. The findings are important for the evidence-based guidance of load monitoring and manipulation in tennis to reduce injury risk.

Evidently, there is a lack of understanding of the load-injury relationship in tennis owing to scares research attempts. Additionally, the outcomes from load-injury research available in other sports highlights a lack of clarity in the methodology justification and findings. These limitations lead to the third aim of this thesis. Conceptually, the aim was to determine which load metrics and timeframes are the best predictors of injuries in elite tennis.

2.9. A MULTIFACTORIAL APPROACH TO EXPLAINING INJURY RISK

Although the exploration of each intrinsic and extrinsic risk factor in isolation is common and provides potential mechanisms for injury, it fails to consider the multifactorial nature of injury occurrence (7, 17). As Meeuwisse's injury aetiology model describes (Figure 2, page 45), injury occurs based on a collection of intrinsic and extrinsic risks coupled with an inciting event (7). To elaborate on the detailed context of these relationships, the injury aetiology model developed by Meeuwisse (1994) has been adapted in recent times by both Meeuwisse et al. (2007) as well as more recent adaptations by another research group (153).

The first adaptation includes the provision of a more cyclical approach to risk and injury (158) (Figure 4). This iteration highlights that some predisposed and susceptible athletes do not actually suffer an injury. This may be a result of the correct monitoring and management of such risk factors or the development of an athlete's tolerance to the present risks.

Alternatively, it may be due to attempts to avoid injury by reducing exposure to risks such as lowering training loads or not competing in hard-court tournaments. However, this avoidance can also result in a decline in performance (28). Regardless, the model highlights that, due to non-injury, athletes continue to participate which may likely expose them to new intrinsic and extrinsic risks which subsequently recommences the cyclical model (158).

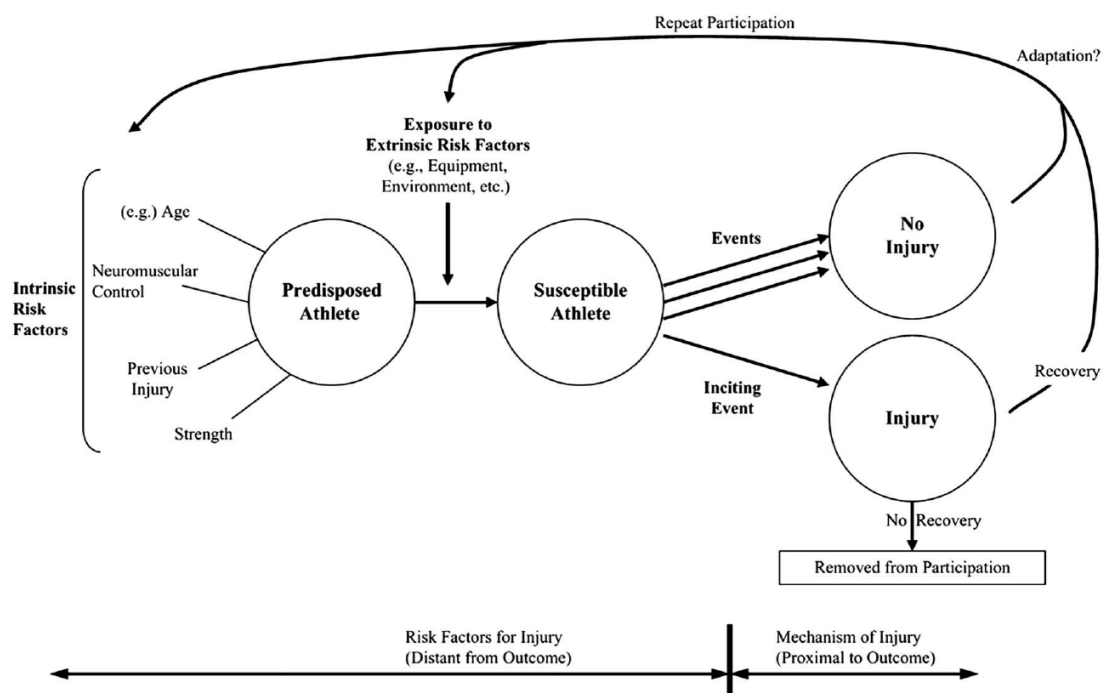


Figure 4: Dynamic, recursive athletic injury aetiology model (158)

Additionally, a more modern iteration of the model includes workload as a standalone risk factor, which, itself impacts on other intrinsic and extrinsic risk factors (153) (Figure 5). For example, a prolonged competitive tennis match has a high workload profile. This can exacerbate extrinsic risk factors such as the court surface, climate and equipment as well as amplify intrinsic risk factors such as age or perceptual wellbeing. Additionally, the workload may also heighten the risk of an inciting event occurring. Therefore, this model highlights that workload is integral to the risk of injury in sport.

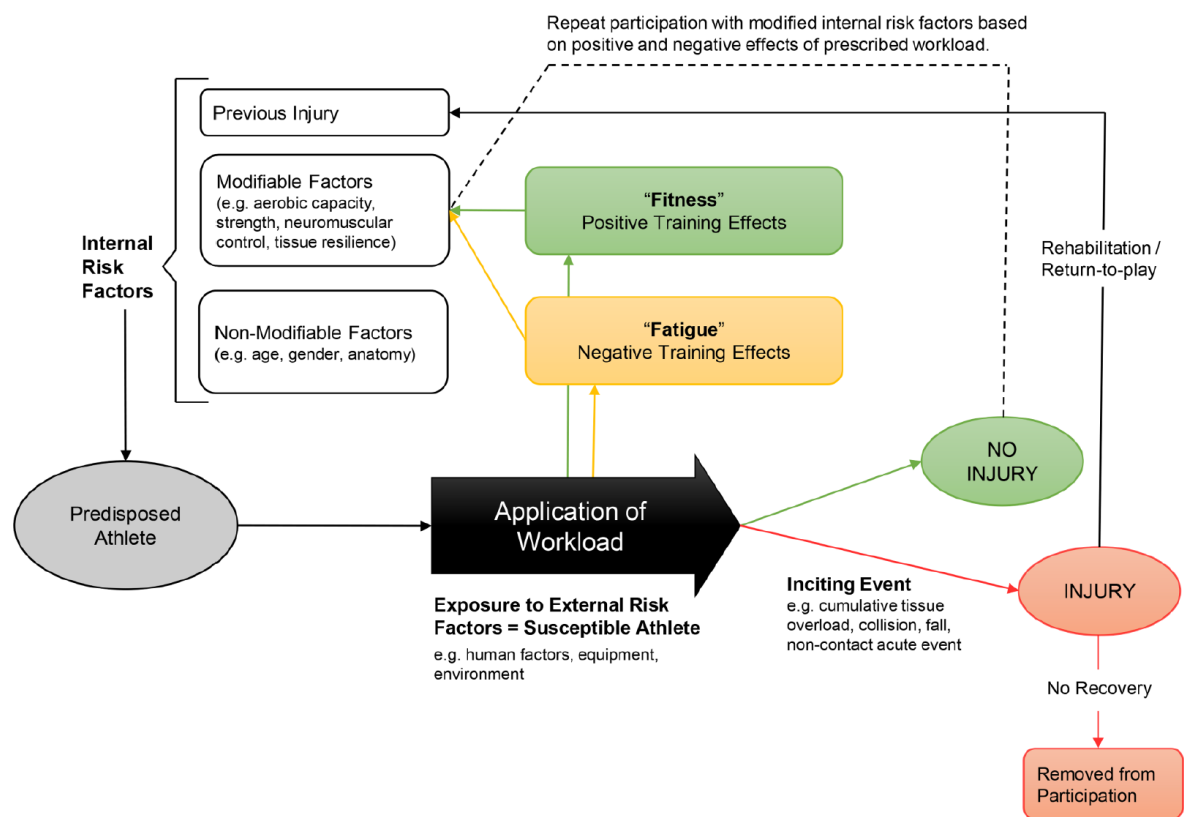


Figure 5: The workload-injury aetiology model (153)

These injury aetiology model iterations highlight the need to investigate how risk factors and inciting events interact with one another to resultant injury outcomes. These outcomes can shape decision-making around the collective monitoring of risk factors for the prevention of injury.

Multifactorial approaches to assessing injuries in other sports are common (23, 24, 85, 148), yet remain absent in tennis. Specifically, it has been found that the aggregation of both intrinsic and extrinsic risk factors in other sports are best at informing injury outcomes (23, 24, 85, 148). For example, a rise in training volume and intensity coupled with a decrease in sleep duration resulted in a higher injury risk in elite youth athletes across 16 other sports (24). Other reports show that low chronic loads, as measured by sRPE (3), coupled with high running distances to be associated with an increase in injury risk in elite Australian footballers (23). Correspondingly, sub-elite rugby league players with slower running speeds, lower aerobic capacity and less pre-season training weeks were at greatest risk of injury (148). Additionally, older soccer players with a previous injury history were also found to be at greater risk of incurring a hamstring injury, whereas taller soccer players in the same cohort with a previous injury history were at greater risk of incurring a knee injury (85). These findings highlight the multifactorial development of injuries and potential risk factors to monitor for injury mitigation strategies in the respective sports. As an aside, as most elite sports monitor multiple risk factors in an attempt to reduce injury incidence, a multifactorial analysis can also shed light on the prioritisation and/or necessity of some commonly monitored risk factors. This can have further implication for the resourcing of staff, time, systems and budget needed to monitor these factors.

Although the same methodological approaches can be adopted for tennis research, the findings cannot necessarily be applied, owing to the differing profiles of the sport and the

associated risk factors. Within elite tennis, the exploration, study design and findings of multifactorial assessments of injury are extremely limited. It was found that older, elite junior male tennis players who played a greater number of matches incurred more injuries in national competition (12). However, the interaction of each of these variables to one another was not assessed. Rather, they were all determined to be associated to the same injury outcome in isolation. Therefore, it is unknown whether the combination of age and match demands would result in a better understanding of injury risk rather than each in isolation.

As the multifactorial analysis of elite tennis injuries is in its infancy and fundamentally important for a more holistic understanding of injury aetiology, the fourth and final study of this thesis emerged. Specifically, the aim was to determine which collection of commonly measured intrinsic and extrinsic risk factors are best associated with subsequent injuries in elite tennis. The findings can have practical implications for the selection and monitoring of risk factors and strategies to mitigate their influence on injury.

2.10. STATE OF THE LITERATURE

It is evident that limitations exist in the current body of literature describing the incidence, precursors and relationships to injury in elite tennis players. There is an incomplete epidemiological profile of injuries in elite junior and professional tennis as well as a lack of definitive and empirical insight into the association and predictive ability of individual and multiple risk factors to injury (9-12, 15, 36).

The injury epidemiology of professional tennis has previously been explored, particularly within the Wimbledon and US Open Grand Slam events (9, 10). However, owing to

differences in exposure measure selection as well as the absence of severity and year-and-year changes in incidence, further profiling is needed (9, 10). Additionally, given each of the Grand Slams have different court surface, climate and temporal (time of year) profiles, the subsequent injury profiles may differ. Therefore, the first study in this thesis will explore the epidemiological injury profile of the Australian Open Grand Slam longitudinally. The aim is to provide further understanding of the sex and region-based differences in injuries within a professional tennis tournament as well as establish novel insight into the treatment cost and changes from year-to-year associated with in-event injuries. The findings can provide practical insight for medical-resourcing in-event as well as add to the profile of injuries that occur at the pinnacle tier of the elite tennis pathway.

In addition to the incomplete injury epidemiology of professional tennis, the elite junior tennis injury profile is also limited in the current literature (11, 15, 36). The limitations include scarcity or absence of select injury incidence variables including severity and changes over time, as well as discrepancy in the findings. Subsequently, a longitudinal epidemiological profile of elite junior tennis players in a national program will be undertaken. The aim is to explore the injury incidence by age, sex, body region, severity and time. These findings, coupled with the findings from the Australian Open study, can assist in clarifying and broadening the injury profile of the elite tennis pathway.

This literature review has also detailed that the aetiology of elite tennis injuries is scant in the current body of research (12). This is owing to limitations in the quantification of external load measures in tennis, uncertainty in the current relationship between load and injury in elite sport, as well as a lack of exploration into the multifactorial nature of tennis injuries. Therefore, this thesis also aims to understand the load-injury relationship in elite tennis.

Specifically, to determine which load metric and timeframe is the best at predicting elite tennis injuries. Consequently, a multivariate analysis of intrinsic and extrinsic risk factors in elite tennis will also be undertaken with the aim to determine the aggregate of risk factors with the strongest association with subsequent injury. The outcomes of these two studies aims to provide evidence-based selection of risk factors to be captured and monitored, as well as the development of practical and targeted approaches to mitigate their risk. Overall, this body of research aims to expand both the descriptive and detailed understanding of injury epidemiology and aetiology in elite tennis players to ultimately reduce their burden on player development and success in the sport.

Supplementary to this body of research, the review of literature highlighted limitations in the comparison and precision of exposure measures selected in the reporting of injury rates in epidemiology studies. Therefore, an ancillary objective of this thesis will explore external workload metrics to determine their ability to specifically describe the demands of training/matchplay as it relates to injury rates. This features in Appendix 1.

3. CHAPTER 3: METHODOLOGY AND DESIGN

3.1. STUDY 1 – INJURY EPIDEMIOLOGY OF TENNIS PLAYERS AT THE 2011 TO 2016 AUSTRALIAN OPEN GRAND SLAM

3.1.1. METHODS

Injury data from the 2011 to 2016 Australian Open Grand Slams were used for the analysis. A total of 1,170 unique injuries incurred across the men's and women's qualifying and main draw singles, doubles and mixed doubles events and all were included for analysis. There were a total of 3,120 players competing in these events across the six years. The mean male and female professional singles ranking of the singles cohorts were 84 ± 71 and 81 ± 76 respectively. Junior and wheelchair tennis player injuries were excluded to ensure homogeneity in the cohort as well as to allow for comparison to previous Grand Slam injury literature (9, 10). All consultations were entered and stored on secure, digital repositories. Consent for the use of data for research purposes was collected from all Australian Open players upon entry to the tournament, assuming player anonymity was maintained. The study was approved by the Australian Catholic University Human Ethics Committee (reference number 2015-200N).

3.1.2. INJURY DEFINITION AND CLASSIFICATION

Injury incidence was defined as an injury that occurred during the Australian Open requiring a medical consultation by a tournament-appointed physician. The number of tournament-appointment physicians was six per year over the 6-year collection period. Injury data was classified by region and type as per the Orchard Sports Injury Classification System (OSICS)(159) and was obtained by exporting the relevant consultations. The OSICS is a hierarchical four-character injury coding system. The first character refers to the body-region

of injury, the second to the injury type and the third and fourth character provide a broader description of the diagnosis (159). Injury type was limited to musculoskeletal injuries and therefore illnesses and other consultations not related to musculoskeletal injuries were omitted. These included lacerations/abrasions and bruising/haematomas consultations. The reason for such was to ensure that the results provide insight for tennis players and their stakeholders into the musculoskeletal injuries that occur in elite tennis without being confounded by acute, dermal injuries. This helps to inform training monitoring and periodization as well as physical injury prevention strategies.

3.1.3. IN-EVENT TREATMENT FREQUENCY DEFINITION

The in-event treatment frequency of each injury region was defined as the mean number of initial and follow-up medical and physiotherapy consultations per injury. The in-event treatment frequency dataset contained injury consultation information from 2013-2016 as previous WTA and ATP consultation data was not available. Physiotherapy consultations were performed by Tennis Australia-appointed physiotherapists as well as physiotherapists from the ATP and WTA.

De-identified, consultation frequency per injury data was obtained from the ATP and WTA repositories and migrated with the same data from the Tennis Australia repository. The physiotherapy injury coding system varied with Tennis Australia physiotherapists utilising the OSICS, whereas the ATP and WTA physiotherapists used the Sports Medicine Diagnostic Coding System (SMDCS)(160). Given these disparate diagnostic-coding indices, a sports physiotherapist with more than 10-years experience in delivering and recording Grand Slam tennis physiotherapy treatments, qualitatively transformed the SMDCS codes into their

equivalent OSICS code for the purposes of analysis. Again, only musculoskeletal consultations were included in the dataset.

3.1.4. CHOICE OF EXPOSURE

Although 1,000 match hours has been recommended as the preferred injury frequency (64), match durations were not readily available for all matches in the current study. In order to retain all available match data, an exposure measure that was strongly and positively correlated with match duration was sought. In tennis, games are nested within sets and sets are nested within a match. Under a standard best of three-set format, the number of games in a set can range from six to 13, while the number of sets can range from two to three. This would suggest that the number of games would be the most precise measure of match duration among these choices being the smallest common unit available. Therefore, it provides a more standardised and accessible approach to quantifying exposure. To confirm this supposition an empirical correlation analysis was undertaken. Publicly available data on minutes played for 52,948 ATP and 4,625 WTA matches of all professional event types played between 2011 and 2016 was obtained. The Pearson correlation coefficient and 95% CI between minutes and games played and minutes and sets played was evaluated. As minutes played are nested within match, the correlation with matches played is necessarily zero. The findings from this analysis are featured in Table 5 and highlight that games played was the most strongly related to minutes played.

Table 5: Correlation between minutes played and games versus sets played by gender in 52,948 ATP and 4,625 WTA matches respectively (Pearson's correlation coefficient $\pm$ 95% confidence interval)

	Games	Sets
Male	0.87 $\pm$ 0.00	0.77 $\pm$ 0.00
Female	0.73 $\pm$ 0.01	0.61 $\pm$ 0.02

Therefore, game exposures (GE) were used rather than the 1,000 set or match exposures as reported in the Wimbledon and US Open injury profiles (9, 10) as it provides a more accurate account of the exposure of matchplay (161).

Data were collated based on sex and year and reported as an injury frequency per 10,000 GE. Each singles game equated to two GEs as both players were exposed to the same game. Doubles and mixed doubles equated to four GE per game. As mixed doubles concluded with a third-set super-tiebreak (first to ten points) the total points were summed and divided by the mean number of points per game (six)(162) to quantify the GE. The total game exposures for each sex and year are listed in Table 6:

Table 6: Total number of game exposures including all singles, doubles and mixed-doubles games by sex and year

Year	Total Male Game Exposures	Total Female Game Exposure
2011	20,380	15,288
2012	21,098	15,132
2013	21,598	15,902
2014	21,296	15,748
2015	21,788	16,112
2016	21,566	15,374

3.1.5. STATISTICAL ANALYSIS

Statistical programming (R Core Team, 2012) was used for the all statistical analyses.

The ‘metafor’ package was used to implement the fixed-effects meta-regression analysis of incidence rates $\pm$ 95% CI with precision weights. Incidence rates represent the year-on-year change in injury counts by region and type. The base year for injury incidence rates was 2011, and the base years for in-event treatment frequency was 2013 due to the unavailable of data before this time. The magnitude of change is inferred by rate ratios (RR) whereby a ratio of greater than 1 is considered to be an increase, and less than 1, a decrease. An example of the R code used to calculate the incidence rates $\pm$ 95% CI and RR by body-region and sex is shown below. An adaptation of this script was used to quantify overall injury incidence as well as injury incidence by injury type and in-event treatment frequency.

Example of R code to calculate incidence rates $\pm$ 95% CI and RR:

```
library(metafor)

rr.se <- function(model, years){
  coef <- model$b
  coef.dot <- c(-1 * (coef[2] * years) / coef[1]^2, (years/coef[1]))
  se <- t(coef.dot) %*% vcov(model) %*% coef.dot
  sqrt(se)
}

malelumbar <- data.frame(event = c(3, 5, 3, 6, 2, 3), exposure = c(20380, 21098, 21598,
  21296, 21788, 21566), year = 2011:2016)

malelumbar <- transform(malelumbar, IR = (event/exposure)*1000)

malelumbar <- escalc(xi = event, ti = exposure, measure = "IR", data = malelumbar,
  append = TRUE)

fit <- rma(yi = yi, vi = vi, data = malelumbar, mods = ~ I(year - 2011), method = "FE")
summary(fit)

malelumbartable <- coef(summary(fit))

rr.se(fit, years = 5)
```

3.2. STUDY 2 – A MULTI-YEAR INJURY EPIDEMIOLOGY ANALYSIS OF AN ELITE NATIONAL JUNIOR TENNIS PROGRAM

3.2.1. METHODS

3.2.2. PARTICIPANTS

A total of fifty-eight male and forty-three female Australian junior tennis players were included in the study and all were aged 18 or under at the time of each injury. All players were full-time scholarship-holders for at least a year between 2012 and 2016 in a national tennis academy governed by Tennis Australia and had mean peak national male and female rankings of 117 ± 139 and, 57 ± 48 respectively. The number of players in the national tennis academies fluctuated each year resulting in changes in the participant numbers year-on-year. The number of players in each year of the study are listed in Table 7:

Table 7: Number of males and females in a national tennis academy each year between 2012 and 2016

Year	Junior Males	Junior Females
2012	40	29
2013	44	31
2014	39	25
2015	35	25
2016	30	26

No players in the study participated in other sports competitively over the time period. Given the lack of data prior to 2012, this year was used as the base year for ensuing analysis. Data was collected and stored in a secure, Tennis Australia managed data repository (Athlete Management System). This study received human ethics committee approval from Australian

Catholic University (reference number 2015-196N) with informed consent obtained from all players and player parents if the players were underage.

3.2.3. MEASUREMENTS: INJURY AND SEVERITY

An injury was diagnosed by Tennis Australia's physiotherapists and doctors and defined as a physical complaint from training/matchplay resulting in interrupted training or matchplay (163). Interrupted training was defined as any restrictions to tennis and off-court training resulting in an athlete unable to take a part in the full session (163). Injuries were calculated as injury incidence, which describes the number of new injuries within the population over the period of time (163). Severity was defined as the mean number of days since injury onset to a particular region, to the day that the player returned to full on and off court training (163). Injury data was classified by region as per the OSICS (159). Only musculoskeletal injuries were included with lacerations/abrasions and bruising/haematomas were omitted from the dataset. The reason for such was to ensure that the results provided insight for junior tennis players and their stakeholders into the musculoskeletal injuries that occur in elite junior tennis without being confounded by acute, dermal injuries. The injury data was also entered and stored on the Athlete Management System by the designated Tennis Australia treating physiotherapist ($n = 32$, mean 2.3 ± 1.3 years treating Tennis Australia athletes) and doctors ($n = 14$, mean 3.1 ± 2.0 years). Injury severity was also entered and stored in the repository via athlete self-reporting. Athlete self-reporting was used to quantify severity (time-loss) as the Tennis Australian physiotherapists were not on-site every day to log return to play timelines. Injury data, including injury region obtained from the OSICS, year of injury, age at time of injury and injury severity on the studied population between 2012-2016 were exported for analysis.

3.2.4. MEASUREMENT: EXPOSURE HOURS

Injury incidence was reported per 1,000 exposure hours. This exposure measure was selected as it is consistent with the recommendation for injury in the consensus statement on epidemiological studies of medical conditions in tennis (64). It was also selected due to limitations with the data availability of more detailed external load measures. Exposure hours include the durations of both on- and off-court training and matchplay and was recorded via athlete daily self-reporting. The total exposure hours captured the total exposure time for all athletes in each given year which allowed for a relative comparison year-on-year. The exposure hours equated to a mean $\pm$ SD of 648.8 ± 108.6 and 661.8 ± 112.6 training hours per year for male and female players respectively. Tables 8 and 9 highlight the average exposure hours per person per year for sex and age respectively. All players trained and competed on multiple court surfaces throughout the data collection period however this was not captured due to the epidemiology, not aetiology, focus of the study.

Table 8: Average number of exposure hours per person, per sex, per year (2012-2016)

Year	Males	Females
2012	612.3	662.4
2013	688.3	790.0
2014	675.2	728.3
2015	566.2	723.6
2016	591.2	587.8

Table 9: Average number of exposure hours per person, per birth year, per year (2012-2016)

Year	13th Birth Year	14th Birth Year	15th Birth Year	16th Birth Year	17th Birth Year	18th Birth Year
2012	631.7	626.5	691.8	689.1	698.7	594.5
2013	698.4	609.4	735.3	731.1	749.6	753.6
2014	685.7	722.0	697.7	606.4	657.2	749.1
2015	645.4	600.9	706.1	658.5	650.1	634.4
2016	631.0	660.9	586.2	735.3	632.8	628.8

3.2.5. STATISTICAL ANALYSIS

Statistical programming (R Core Team, 2012) was used for all analyses. The ‘metafor’ package was used to implement the fixed-effects meta-regression analysis of incidence rates $\pm$ 95% CI with precision weights. Incidence rates represent the year-on-year change in injury counts by region and severity, where 2012 was the base year. The magnitude of change over time is inferred by RR whereby a ratio of greater than 1 is considered to be an increase, and less than 1, a decrease. Results are reported as mean $\pm$ SD, incidence rates $\pm$ 95% CI, and RR. An example of the R code used to calculate the incidence rates $\pm$ 95% CI and RR by body-region and sex is shown below. An adaptation of this script was used to quantify overall injury incidence as well as injury incidence by injury type, age and severity.

R code example used to calculate the incidence rates $\pm$ 95% CI and RR:

```
library(metafor)

rr.se <- function(model, years){
  coef <- model$b
  coef.dot <- c(-1 * (coef[2] * years) / coef[1]^2, (years/coef[1]))
  se <- t(coef.dot) %*% vcov(model) %*% coef.dot
  sqrt(se)
}

femaleankle <- data.frame(event = c(10, 3, 2, 3, 4), exposure = c(19211, 24491, 18208,
  18089, 15282), year = 2012:2016)

femaleankle <- transform(femaleankle, IR = (event/exposure)*1000)

femaleankle <- escalc(xi = event, ti = exposure, measure = "IR", data = femaleankle,
  append = TRUE)

fit <- rma(yi = yi, vi = vi, data = femaleankle, mods =~ I(year - 2012), method = "FE")

summary(fit)

femaleankletable <- coef(summary(fit))

rr.se(fit, years = 4)
```

3.3. STUDY 3 – PREDICTIVE MODELLING OF INJURY IN TENNIS: DETERMINING THE BEST INTERNAL WORKLOAD CALCULATION AND TIMEFRAME

3.3.1. METHODS

3.3.2. PARTICIPANTS

The study was conducted as part of Tennis Australia's injury surveillance program and included 101 players; 58 males and 43 females with a mean ($\pm$ SD) age of 19.1 ($\pm$ 2.8) years. Players were ranked domestically with mean $\pm$ SD peak rankings of 91 $\pm$ 112. All players also held international junior ($n = 97$; 499 $\pm$ 577) and/or senior ($n = 59$; 583 $\pm$ 537) rankings. Players were in the Tennis Australia nationally-supported program for a mean ($\pm$ SD) duration of 3.2 ($\pm$ 1.2) years. The following proportion of participants competed in the five individual competitive seasons: all ($n = 27$), four ($n = 11$), three ($n = 23$) and two ($n = 40$). Given the year-round but highly individualised nature of tournament tennis, systematic control of the competition and training schedules was not possible (35). Age-appropriate informed consent, from each participant or guardian, was obtained and ethics were approved by Australian Catholic University human ethics committee (reference number 2015-198N).

3.3.3. DEFINING INJURY

Injuries were medically diagnosed and defined as sport incapacity, whereby a player was sidelined or restricted due to the inability to perform planned training or matchplay based on loss or abnormality of bodily structure or functioning (164). Recurrent injuries, also coded in the dataset, were defined as an injury to the same region and linked to an initial injury which occurred after a player's full return to participation from the initial injury (163). The current study used OSICS to classify injuries (159). Tennis injury records were maintained by Tennis Australia physiotherapists and medical doctors. As the relationship between injury region/type and workload was not the focus of the current study, all injuries were aggregated in the same way.

3.3.4. INTERNAL WORKLOAD AND INJURY DATA COLLATION AND MODELLING

Internal workload was defined as sRPE (3) with RPE obtained from the Borg CR10 scale (47) 30-minutes post-session utilising a mobile phone application accessible to all players (Figure 6).



Figure 6: Screenshots of mobile phone application and Borg CR10 scale used to collect internal load data

All workload and injury data on each player over the five-year period was compiled. Daily workload values were then utilised to test the injury prediction performance of the seven workload metrics. The metrics were (a) rolling average of daily loads, (b) ACWR, (c) ACWR with the acute load omitted from the chronic load calculation, (d) EWMA, e) EWMA with the acute load omitted from the chronic load calculation, (f) monotony, g) strain. Both (c) and (e) were tested due to the existence of mathematical coupling (34) in metrics (b) and (d) as the acute timeframe is included in both the numerator and denominator. The load calculation and selected timeframes for each model are featured in Table 10.

Table 10: Load metrics and timeframes modelled to determine the injury prediction accuracy

Model	Acute timeframes (days)	Chronic timeframes (days)	Formula
a) Rolling averages of daily load	1, 3, 5, 7, 14, 21, 28, 60	NA	Rolling average of total daily load for each timeframe (W1)
b) Acute to chronic workload ratios using rolling averages	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$W1/0.25 \times (W1 + W2 + W3 + W4)$
c) Acute to chronic workload ratios with the acute load omitted from the chronic load calculation (34)	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$ACWR = W1/0.25 \times (W2 + W3 + W4 - W1)$
d) Exponentially weighted moving averages (154)	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$ $\lambda_a = 2/(N+1)$ $EWMA \text{ ACWR} = EWMA_{acute}/EWMA_{chronic}$
e) Exponentially weighted moving averages with the acute load omitted from the chronic load calculation (34, 154)	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$ $\lambda_a = 2/(N+1)$ $EWMA \text{ ACWR} = EWMA_{acute}/EWMA_{(chronic - acute)}$
f) Monotony	1, 3, 5, 7, 14, 21, 28, 60	NA	$W1/\text{Standard Deviation of } W1$
g) Strain	1, 3, 5, 7, 14, 21, 28, 60	NA	$(W1/\text{Standard Deviation of } W1) \times \text{Load}$

3.3.5. *MISSING DATA*

The retrospective and applied setting for which the data was obtained resulted in missing data (53%). To increase the power and accuracy of the study analysis in the presence of missingness, multiple imputations for training load were conducted, which is appropriate and justified for longitudinal data (165). To strengthen the imputation procedure, the available training loads for each subject were assessed for normality prior to imputation. The variability in each subject's available training loads was replicated within the imputations. Five imputations were undertaken, as recommended by Allison (2000), and were developed in R Statistics using the 'Amelia' package (165). The mean value of the five imputations for each data point was included in the final dataset for analysis. Sex (male or female), state of training (Australian states), ranking (national), tournament or training week, tournament/training location (home state or away) as well as loads experienced pre and post the missing days were factored into the imputation calculations to assign the most appropriate load values.

3.3.6. *STATISTICAL ANALYSES*

All modelling was conducted in R Statistics (R Core Team, 2012) using the dplyr, lme4, zoo, pROC, ROCR and caret packages. For each workload method, a logistic regression model was fit relating the workload method to injury. In order to test the predictive performance, sequential training and testing of the models was performed. This involved fitting the logistic model for every month of the last two years of data, using the most recent three years of training in each case. The assessment of loads in the lead up to a recurrent injury were omitted to assess the performance of each load metric and timeframe to initial injury outcomes. To evaluate the overall performance of each model, area under the curve (AUC) of receiver operator characteristic (ROC) curves were utilised, including all two years of test outcomes obtained from the sequential training and testing approach. The AUC summarises the discriminative ability of each model across a full range of sensitivity and specificity cut-offs

(167) which refer to the detection of true positives and true negative respectively (167).

Therefore, the $AUC \pm 95\% \text{ CI}$ determined the predictive ability of each model, with a perfect predictive model equating to an $AUC = 1$, and a model performing the equivalent of chance corresponding to an $AUC = 0.5$ (167). The sensitivity and specificity values for each of the model and timeframe outcomes were utilised to assess the performance of each model in detecting injuries (true positives) and non-cases (true negatives)(167). To determine the comparative predictive strength of the model outcomes, the AUC CIs were assessed. If there was no overlap between models or timeframes, then a difference was established (168).

However, if the CIs between models and timeframes overlapped, the difference between models was not considered to be practically important (168). To determine the direction of each models relationship to injury, the training load dataset was split into deciles. The models and timeframes were then rerun only including the top (highest) and bottom (lowest) deciles individually. The change in the model outcomes, compared to the global model outcome, determined the direction of each model and timeframe to injury. Specifically, the changes in the sensitivity and specificity value alongside the AUC changes. An example of the R code used to incorporate one of the imputed dataset, obtain each models AUC, sensitivity and specificity values is shown below. All timeframes assessed are included in the output.

R code example to incorporate one of the imputed datasets and obtain the AUC, sensitivity and specificity values for each model and all timeframes:

```
load("imputed2.RData")
dataset1 <- fit$imputations[[1]]
dataset1 <- dataset1[order(dataset1$Name, dataset1$session_date),]
start <- min(dataset1$session_date) + months(1:23)
end <- start + years(3)
training_data <- mapply(
  function(x, y){
    subset(dataset1, session_date >= x & session_date < y)
  },
  x = start,
  y = end,
  SIMPLIFY = FALSE)

one.load.injury <- function(data, acute = 7, chronic = 28){
  print(c(acute, chronic))
  data$Name <- as.character(data$Name)

  data <- data %>%
    group_by(Name) %>%
    dplyr::mutate(
      n = n()
    ) %>%
    filter(n > 1) %>%
    dplyr::mutate(
      Total.Load = ifelse(Total.Load == 0, 1, Total.Load),
      Acute = rollmean(Total.Load, k = min(c(acute, n()) - 1)), fill = NA, align = "right"),
      Chronic = rollmean(Total.Load, k = min(c((chronic), n()) - 1)), fill = NA, align =
"right"))
```

```

data <- data[!is.na(data$Chronic) & !is.na(data$Acute),]
max.date <- max(data$session_date)

test <- subset(data, session_date >= max.date - month(1))

data <- subset(data, session_date < max.date - month(1))


fit <- glm(injury ~ I(Acute / Chronic),

          data = data,

          family = binomial)

test$prediction <- predict(fit, new = test, type = "response")

test[,c("prediction", "injury")]

}


load.injury <- function(data, acute, chronic){

  do.call("rbind", lapply(data, one.load.injury, acute = acute, chronic = chronic))

}

params <- expand.grid(chronic = c(7, 14, 21, 28, 60), acute = c(1, 3, 5, 7, 14))

params <- params %>% filter(chronic > acute)

```

```

models <- mapply(
  load.injury,
  acute = params$acute,
  chronic = params$chronic,
  MoreArgs = list(data = training_data),
  SIMPLIFY = FALSE
)

get_metrics <- function(test){

  AUC <- ci.auc(response = test$injury, predict = test$prediction,
partial.auc.focus=c("specificity", "sensitivity"), partial.auc.correct=FALSE)

  precision <- sum(test$injury * test$prediction) / sum(test$prediction)

  recall <- sum(test$injury * test$prediction) / sum(test$injury)

  data.frame(
    auc = as.numeric(AUC)[2],
    lower = as.numeric(AUC)[1],
    upper =as.numeric(AUC)[3],
    specificity =as.numeric(AUC),
    precision = precision,
    recall = recall,
    f1score = 2 * (recall * precision) / (recall + precision)
  )
}

aucs <- lapply(models, get_metrics)

```

3.4. STUDY 4 – MULTIVARIATE MODELLING OF INTRINSIC AND EXTRINSIC RISK FACTORS TO INJURY IN ELITE JUNIOR TENNIS PLAYERS

3.4.1. METHODS

3.4.2. PARTICIPANTS

Twenty-six male (15.5 ± 1.6 y) and 23 female (15.6 ± 2.3 y) nationally-supported junior tennis players with mean peak national rankings of 173 ± 140 and 112 ± 115 respectively, participated in the study. The study period included a 500-day period from the start of 2017 through to mid-2018 when all players were actively part of the national program. The systematic control of player competition and training schedules was not possible due to the applied setting of the study. Informed consent was obtained from all participant guardians as all players were under the age of 18. The Australian Catholic University's human ethics committee approved the study (2015-192E).

3.4.3. RISK FACTORS

Both extrinsic and intrinsic risk factors were collected during the study period for all participants. Extrinsic risk factors included external and internal training loads quantified via serve counts and sRPE (3) respectively. These were collected via athlete self-reporting in a custom built mobile phone application after the final training session/match of each day (Figure 7). Athlete self-reported serve load was selected owing to resource burden of manual notation and the scarcity of validated tennis-specific inertial technologies (145) limiting the capture of other external load measures. Yet, athlete self-reporting of daily external loads are routinely performed in other sports and show appropriate validity as a count of actions in tennis (169). Internal sRPE loads were classified as on-court or off-court (i.e. gym, conditioning) loads; with on-court loads categorised as training or competitive matchplay load. Both internal and external loads were quantified as raw total daily values on the day of

injury as well as the rolling average of the previous 21-days in the lead up to injury (Table 11). The rolling average of the previous 21-days was selected based on unpublished observations suggesting this load metric and timeframe has some injury prediction ability in a similar cohort of tennis players (Study 3).

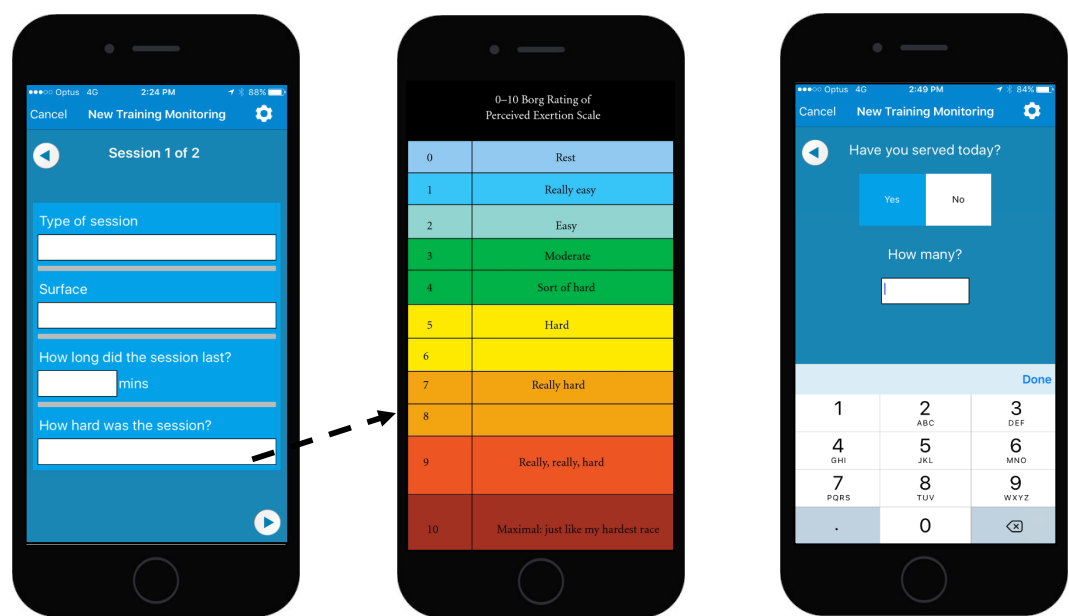


Figure 7: Screenshots of mobile phone application used to collect internal and external load data

Non-modifiable intrinsic risk factors included sex, and age calculated at the start of the data collection period. Modifiable intrinsic risk factors comprised daily wellbeing ratings, baseline physical capacity and musculoskeletal function measures and playing standard assessed via peak national ranking during the study period. Daily wellbeing included each player's self-reported assessment of sleep quality, mood, worry, fatigue and appetite (114), as well as perceived body region soreness and corresponding magnitude. These measures were entered in the same mobile phone application as the reported training loads 30 min post-waking on a 0-10 Likert scale, where 10 was the best score and 0 the worst (170). Sleep duration was obtained in the same way and reported to the nearest 30 min (Figure 8).

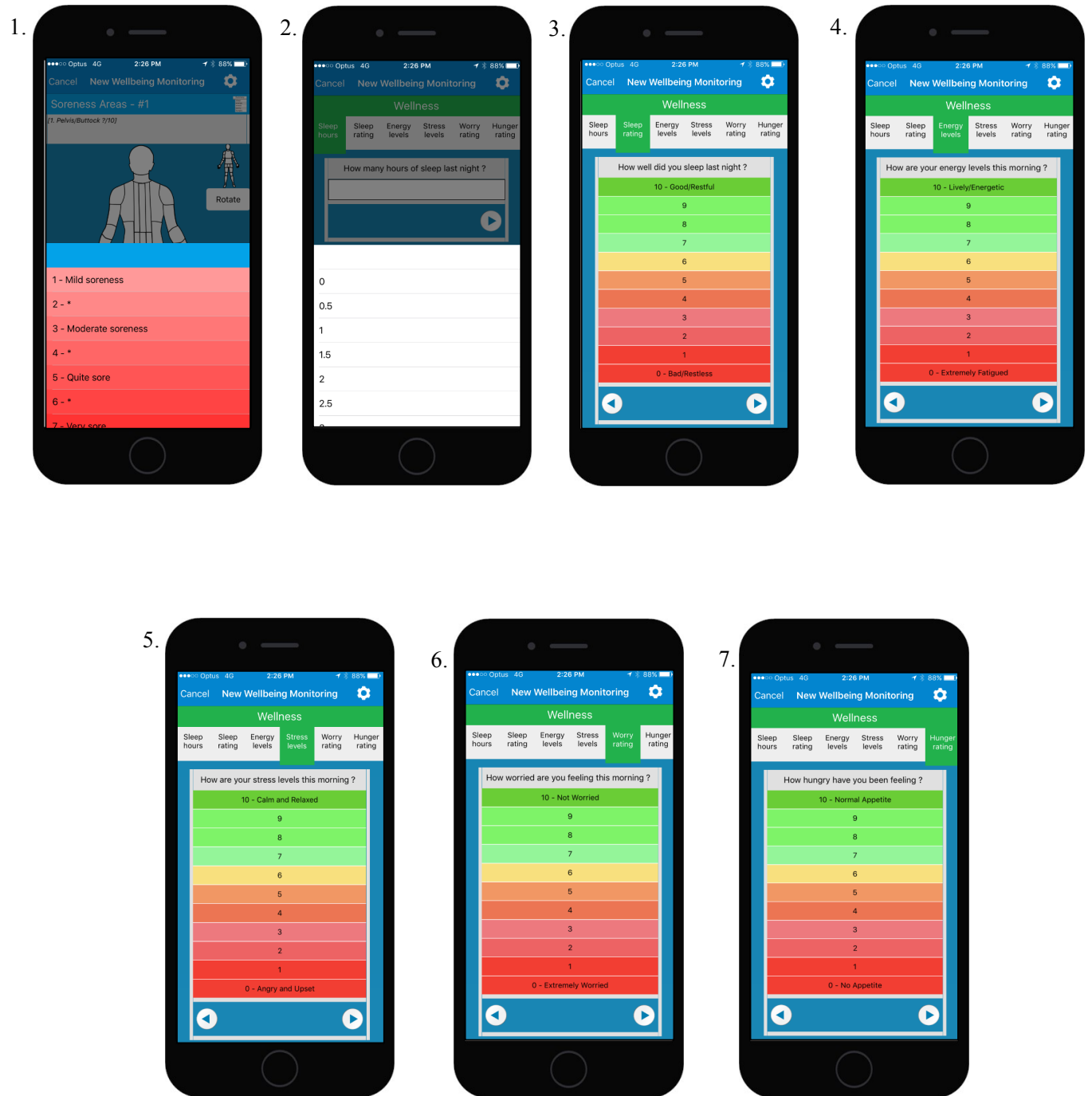


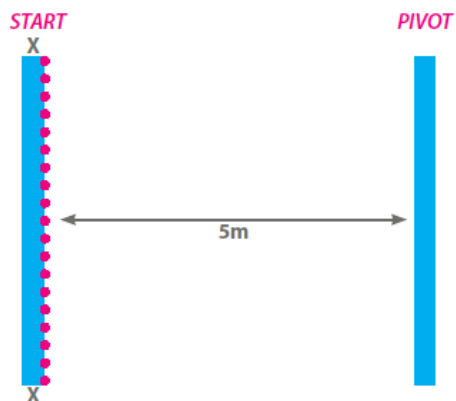
Figure 8: Screenshots of mobile phone application used to collect wellbeing data

Physical capacity measures included a 5m and 20m sprint test, modified 505 COD speed test (94) (Figure 9), vertical jump and maximal multistage 20m shuttle run test (95) (Table 11). Only single time point physical capacity measures existed and are treated as baseline measures recorded at the start of the data collection period. Similarly, baseline musculoskeletal screening measures including assessments of joint pain, strength and flexibility, were obtained for each player by a qualified physiotherapist (Table 11). The same physiotherapist undertook all musculoskeletal screenings to ensure intra-rater reliability (ICC >0.83, CV% <8.6).

505 agility test (right and left) cont.

Test procedure:

- The course and electronic timing gates (X) are set up as in the figure below.



- The player starts in a two-point stance with the front foot up to the start line with no part of the body crossing the line.
- The player can start when ready.
- The player will sprint from the start line, breaking the beam of the gates (set up at X), to the pivot line (five m from the start line), where the player is to turn on either his/her right or left foot, ensuring part of the foot crosses the line, and then sprint back through the gates (X, five m from the pivot line).
- A minimum of two trials (interspersed with two minutes rest) need to be completed for both right and left foot pivots.
- The best 505 times (i.e. for the right and left foot pivots) should be recorded. These times will also be

Figure 9: Modified 505 change of direction speed test diagram and protocol

Table 11: Musculoskeletal screening, fitness testing and training load measures and frequency of capture

Risk factor	Description	Unit of measure	Frequency of data capture
Musculoskeletal screening battery			
Dominant single leg squat	Unilateral lower limb mobility and strength	1: good, 2: fair, 3: poor	At baseline
Thoracic overhead extension	Thoracic flexibility	1: within normal limits, 2: stiff, 3: hypermobile	At baseline
Scapula dyskinesis	Scapula function in flexion	1: normal, 2: abnormal	At baseline
Glenohumeral internal rotation deficit	Difference in shoulder range of motions	degrees difference	At baseline
Dominant supine hip internal rotation	Hip internal rotation	1: within normal limits, 2: stiff, 3: hypermobile	At baseline
Dominant supine hip external rotation	Hip external rotation	1: within normal limits, 2: stiff, 3: hypermobile	At baseline
Squeeze test	Hip adduction	1: good, 2: fair, 3: poor	At baseline
Dominant Thomas test	Hip extension	1: above horizontal, 2: horizontal, 3: below horizontal	At baseline
Fitness testing battery			
5m sprint	Acceleration	seconds	At baseline
20m sprint	Speed	seconds	At baseline
Dominant side modified 505 change of direction speed test (94)	Change of direction speed test from stationary start	seconds	At baseline
Double leg vertical jump height	Leg power	cm	At baseline
Maximal multistage 20m shuttle run test score (95)	Aerobic capacity	decimal score	At baseline
Load measures			
Total Load	Internal load	sRPE	Daily
On-court load	Tennis internal load	sRPE	Daily
Off-court load	Gym internal load	sRPE	Daily
21 day rolling average total load	Internal load	sRPE	Daily
21 day rolling average on-court load	Tennis internal load	sRPE	Daily
21 day rolling average off-court load	Gym internal load	sRPE	Daily
Serve count	Number of serves hit	count	Daily
21 day rolling average serve count	Number of serves hit	sRPE	Daily

3.4.4. INJURY DEFINITION

Injuries were defined as sport incapacity, whereby a player was sidelined or restricted due to the inability to perform planned training or matchplay based on loss or abnormality of bodily structure or functioning (164). Recurrent injuries were recorded as injuries of the same type and to the same region as a preceding initial injury. However, recurrent injuries were not included in the analysis due to potential training load and tournament scheduling adaptations as a result of an initial injury which may have impacted the assessment of these variables in the modelling (64). Additionally, only musculoskeletal injuries were included in the dataset (lacerations/abrasions, bruising/haematomas and illnesses were omitted) to ensure that the injuries were more directly attributable to risk factors. All injuries were treated equally in the analysis. The time to injury was counted as the number of days to injury from the start of the assessment period. The survival curve is shown in Figure 10 which displays the time to injury.

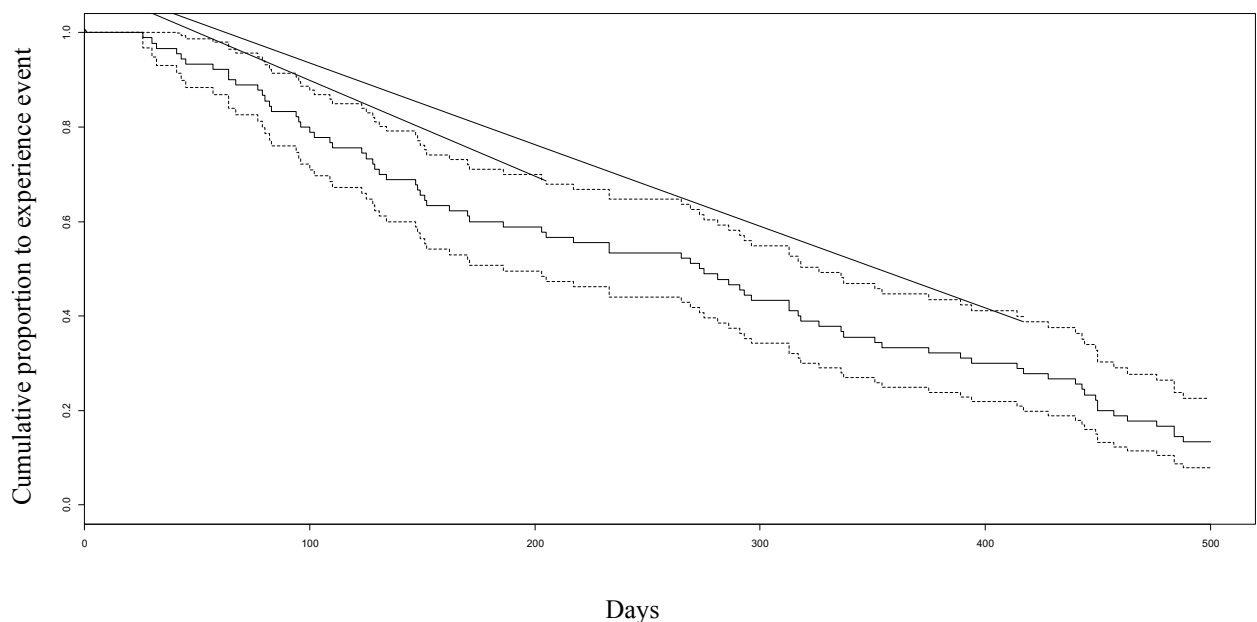


Figure 10: Survival chart of days to injury

3.4.5. DATA PRE-PROCESSING

Multiple steps were needed to prepare the data for analysis. As is common in applied elite sport research, the training load and wellbeing data were incomplete. To enhance the accuracy and power of the modelling, multiple ($n = 5$)(166) imputations were utilized to combat the missingness which is appropriate for longitudinal data (165). The imputations were developed using the ‘Amelia’ package (165) in R Statistics (R Core Team, 2012). An example of the R code used to calculate the imputations is shown below. The normality of distribution of the observed data for each imputed training load and wellbeing variable was initially examined, with all variables being normally distributed. Sex, peak national ranking, competition phase (tournament or training day) as well as each preceding variable with imputed data were utilised in the subsequent imputation to best determine each assigned imputed value. The mean of the five imputations for each missing data point was adopted in the complete dataset for analysis.

Example of R code to develop the imputations:

```
X <- model.matrix( ~ Schedule.Mode + Ranking.Group + meansleephours + meanappetite +
  meanworry + meanmood + meansleepquality + meanfatigue + meanscload + meantennisload
  + meanservecount + meansorenessareas, data = fulldataset2)

X <- X[,-1]

model.frame(~ Schedule.Mode + Ranking.Group + meansleephours + meanappetite +
  meanworry + meanmood + meansleepquality + meanfatigue + meanscload + meantennisload
  + meanservecount + meansorenessareas, data = fulldataset2, na.action=NULL)

data <- cbind(X, fulldataset2[,c("Name", "Date", "Injury", "Total.Load",
  "Averagesoreness")])

data$Date <- (as.Date(data$Date))

fit <- amelia(data,
  ts = "Date",
  m = 5,
  cs = "Name",
  lags = "Averagesoreness",
  leads = "Averagesoreness",
  sqrts = "Averagesoreness",
  spline = 6
)
```

3.4.6. COLLINEARITY

Highly correlated risk factors can violate the multivariate model outcomes (171). Therefore, the collinearity of each variable to each other was assessed via Pearson's correlations and Chi-Square analysis in R statistics (R Core Team, 2012). Examples of the R code used to calculate the Pearson's correlations and Chi-Square analysis are shown below. Interestingly, all fitness testing and musculoskeletal screening measure outcomes which were tested on both the dominant and non-dominant side of the athlete had very strong collinear relationships ($r > 0.80$)(172). Additionally, 5m and 10m sprint outcomes were strongly correlated ($r = 0.91$). Subsequently, one variable in each collinear pair was omitted from the dataset. The dominant side measure was retained for all collinear pairs tested on each side of the body, as well as the 5m sprint time due to this distance being more specific to the sprint distance demands in tennis matchplay as compared to 10m (173).

R code example of collinearity assessment:

```
fitnesscorrelations <- cor(fitness_data, method = "pearson", use = "complete.obs")
round(fitnesscorrelations, 2)
write.table(fitnesscorrelations, file = "fitnesscorrelations.csv", row.names = FALSE, sep =
",")

table(screenings$sls.left.rating, screenings$sls.right.rating)
chisq.test(table(screenings$sls.left.rating, screenings$sls.right.rating))
```

3.4.7. STATISTICAL ANALYSES

All statistical analyses were conducted in R statistics (R Core Team, 2012) using the dplyr and survival packages. Cox Proportional Hazards models was used to investigate the association between the injury outcome and one or more of the predictor variables, namely the risk factors, via a forward step selection process (171). A univariate Cox analysis of each risk factor was conducted initially to determine the first factor in forward step selection process for the multivariate analysis, with the most statistically significant variable selected ($p < 0.05$ in Wald test)(171). The corresponding effect was added to the multivariate model and the process repeated until none of the remaining variables met the significance level in association to both injury and the other significant effects (171). Results are reported at Hazard Ratios $\pm$ 95% CI.

4. CHAPTER 4: STUDY 1 - INJURY EPIDEMIOLOGY OF TENNIS PLAYERS AT THE 2011 TO 2016 AUSTRALIAN OPEN GRAND SLAM

Publication statement:

This chapter is comprised of the following paper published in the *British Journal of Sports Medicine*.

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Wood TO, Omizzolo M, Reid M. Injury epidemiology of tennis players at the 2011–2016 Australian Open Grand Slam. *Br J Sports Med* 2017;51(17):1289-1294. doi: <http://dx.doi.org/10.1136/bjsports-2016-097283>.

4.1. LINKING PARAGRAPH

The literature describing the injury epidemiology of professional tennis players is sparse (9, 10), which is surprising given the sport's popularity, extent of yearly competitive calendars and long-term professionalism. The research that is available primarily focuses on profiling injuries at the Grand Slams, specifically Wimbledon and the US Open (9, 10). However, owing to methodological differences, comparison between these Grand Slams is difficult. Indeed, the findings are further confounded by the court surface, climate and time of year of these events being substantially different, all of which may impact on the injury incidence in-event. Previous empirical efforts have also failed to explore the treatment cost of injuries or the changes in injury incidence over time, which provide important additional context for tennis stakeholders. Therefore, Study 1 aimed to explore the injury epidemiology at the Australian Open Grand Slam, which is played on a different court surface, a different time of year and in a different climate to the other Grand Slams. Specifically, the aim was to profile injuries in-event by sex, body-region, injury type, treatment cost as well as changes in injury incidence over time.

4.2. ABSTRACT

Aim: To examine the epidemiology and in-event treatment frequency of injury at the 2011-2016 Australian Open tournaments. **Methods:** Injury incidence was defined as a medical consultation by a tournament physician, and in-event treatment frequency as the mean total number of follow-up medical/physiotherapy consultations (2013-2016 tournaments only). Data were collated by sex, injury region and type and reported as frequencies per 10,000 game exposures. Incidence rates $\pm$ 95% confidence intervals and rate ratios were used to test effects for injury, sex and year. **Results:** Female players experienced more injuries than male players over the 6-years (201.7 vs 148.6). The shoulder (5.1 ± 1.1 injuries per year), foot (3.2 ± 1.1), wrist (3.1 ± 1.5) and knee (3.1 ± 1.1) were the most commonly injured regions among females. Knee (3.5 ± 1.6), ankle (2.3 ± 1.3) and thigh (2.3 ± 1.5) were the most prevalent male injuries. Upper-arm injuries and in-event treatment frequency increased by ≥ 2.4 times in both sexes over the 6-year period. Muscle injuries were most frequent. There was a >2.0 -fold increase in men and women with stress fractures over the 6-year period. The torso region, including the neck, thoracic spine, trunk and abdominal, lumbar spine, hip and groin, pelvis/buttock, attracted high in-event treatment frequencies in both sexes. **Conclusion:** Investigation of injury at the Australian Open suggests that females are more commonly injured than males. Upper and lower-extremity injuries affected females while lower-limb injuries were more prominent in males. There was an increasing rate of in-event treatments of upper-limb and torso injuries as well as stress fractures during the observation period.

4.3. INTRODUCTION

The Australian Open is one of four Grand Slam events in professional tennis. Epidemiological profiles of injuries at the Wimbledon and US Open Grand Slams have been conducted (9, 10), though as yet, the Australian Open profile remains to be reported. As the Australian Open is scheduled at a different time of year, on a different court surface (Plexcushion) and in a different climate to the other Grand Slams, its injury profile may differ.

The injury profiles of the Wimbledon and US Open Grand Slams suggest that elite tennis is highly injurious compared to other sports (9, 10). As context, sports like rugby and basketball have reported means of 10.5 (147) and 8.5 (14) injuries per 1,000 training hours and athletic exposures, respectively. Injuries at Wimbledon between 2003-2012 resulted in a mean injury rate of 20.7 injuries per 1,000 set exposures (which typically last for less than one hour)(10). Within the Wimbledon injury rate, female players were more frequently injured than their male counterparts (23.4 vs 17.7 injuries per 1,000 set exposures). Acute injuries were more prominent than chronic injuries, with the shoulder, knee and lumbar spine the most commonly injured regions (10). At the US Open between 1994 to 2009, the mean injury rate was 48.1 injuries per 1,000 match exposures (9). Within this tournament, a higher injury incidence existed among male than female players (44.0 vs 32.2 per 1,000 match exposures), which directly contrasts with Wimbledon's sex-based injury profile (9, 10). Further, lower-limb injuries were three and 1.3 times more prominent than trunk injuries and upper-limb injuries respectively, despite similar prevalence of acute injuries as reported at Wimbledon (10). Collectively, these data highlight the variation in the injury profile of respective Grand Slam tennis events.

Injury incidence in tennis has been described in the context of match exposures (9), tennis hours (11, 16) and per 100 tennis players (15). These disparate methods complicate the comparison of injury rates between tennis events. Given reporting differences, a standard method of comparison would be useful. This would also assist with comparisons between sexes given that males play the best of five-set Grand Slam singles tennis and females, the best of three-sets (6). For example, as described above, the mean women's and men's injuries at the US open were 32.2 and 44.0 per 1,000 match exposures respectively. However, if normalised to sets, games or duration played, the sex comparison may present different conclusions, and suggest alternate practical outcomes.

While the incidence of injury at tennis tournaments has been widely investigated, the in-event treatment frequency of injuries, through the number of practitioner consultations, has seldom been examined (19). This type of information may provide insight into the in-event medical resource burden of different types of injuries, and inform tournament physician and physiotherapist resourcing. Therefore, the aim of this study was to examine the epidemiology of injury at the Australian Open from 2011-2016 relative to sex, injury type and in-event treatment frequency.

4.4. METHODS

Injury data from the 2011 to 2016 Australian Open Grand Slams were used for the analysis. A total of 1,170 unique injuries across the men's and women's qualifying and main draw singles, doubles and mixed doubles were included with a total of 3,120 players competing in these events across the six years. The mean male and female professional singles ranking of the singles cohorts were 84 ± 71 and 81 ± 76 respectively. Junior and wheelchair tennis player

injuries were excluded (9). All consultations were entered and stored on secure, digital repositories. Consent for the use of data for research purposes was collected from all Australian Open players upon entry to the tournament, assuming player anonymity was maintained. The study was approved by the Australian Catholic University Human Ethics Committee.

4.4.1. INJURY DEFINITION AND CLASSIFICATION

Injury incidence was defined as an injury that occurred during the Australian Open requiring a medical consultation by a tournament-appointed physician (omitting consultations not related to injuries)(9). The number of tournament-appointment physicians was six per year over the six-year collection period. Injury data, classified by region and type as per the OSICS (159), was obtained by exporting the relevant consultations. Injury type was limited to musculoskeletal injuries (omitting lacerations/abrasions and bruising/haematomas).

4.4.2. IN-EVENT TREATMENT FREQUENCY DEFINITION

The in-event treatment frequency dataset contained injury information from 2013-2016 as previous WTA and ATP consultation data was not available. The in-event treatment frequency of each injury region was defined as the mean number of initial and follow-up medical and physiotherapy consultations per injury. Physiotherapy consultations were performed by Tennis Australia-appointed physiotherapists, and physiotherapists from the ATP and WTA.

De-identified, consultation frequency per injury from the ATP and WTA repositories were then migrated with the same data from the Tennis Australia repository. The physiotherapy

classification system used by Tennis Australia physiotherapists was the OSICS, whereas the ATP and WTA physiotherapists used the SMDCS (160). Given these disparate diagnostic-coding indices, a sports physiotherapist, with more than 10 years' experience in delivering and recording Grand Slam tennis physiotherapy treatments, qualitatively transformed the SMDCS codes into their equivalent OSICS code for the purposes of analysis.

4.4.3. CHOICE OF EXPOSURE

Although 1,000 match hours has been recommended as the preferred injury frequency (64), match durations were not readily available for all matches in the current study. In order to retain all available match data, an exposure measure that was strongly and positively correlated with match duration was sought. In tennis, games are nested within sets and sets are nested within a match. Under a standard best of three-set format, the number of games in a set can range from six to 13, while the number of sets can range from two to three. This would suggest that the number of games would be the most precise measure of duration of play among these choices. In other words, being the smallest common unit of match play available, it provides a more standardised and accessible approach to quantifying exposure. An empirical correlation analysis confirmed this supposition. Using publicly available data on minutes played for 52,948 ATP and 4,625 WTA matches of all professional event types played between 2011 and 2016, the Pearson correlation coefficient and 95% CI between minutes and games played and minutes and sets played was evaluated. As minutes played are nested within match, the correlation with matches played is necessarily zero. Both games (male: $r = 0.87 \pm 0.00$, female: $r = 0.73 \pm 0.01$) and sets (male: $r = 0.77 \pm 0.00$, female: $r = 0.61 \pm 0.02$) played were positively correlated with match duration, yet games played was the most strongly related to minutes played. Therefore, game exposures were used rather than the 1,000 set or match exposures as reported in the Wimbledon and US Open injury profiles (9, 10) as it provides a more accurate account of the exposure of matchplay (161).

Data were collated based on sex and year, and reported as an injury frequency per 10,000-GE. Each singles game equated to two GEs as both players were exposed to the same game. Doubles and mixed doubles equated to four GE per game. As mixed doubles concluded with a third-set super-tiebreak (first to ten points) the total points were summed and divided by the mean number of points per game (six)(162) to quantify the GE.

4.4.4. STATISTICAL ANALYSIS

Results are reported as mean $\pm$ SD, incidence rates $\pm$ 95% CI, and rate ratios. Statistical programming (R Core Team, 2012) was used for the all statistical analyses. The ‘metafor’ package was used to implement the fixed-effects meta-regression analysis of incidence rates $\pm$ 95% CI with precision weights. Incidence rates represent the year-on-year change in injury counts by region and type, where 2011 and 2013 were the base years for injury incidence and in-event treatment frequency respectively. The magnitude of change is inferred by RR whereby a ratio of greater than 1 is considered to be an increase, and less than 1, a decrease.

4.5. RESULTS

4.5.1. TOTAL INJURIES

Over the six-years of Australian Opens, 2011-2016, female players had more injuries, per 10,000 GE than their male counterparts (201.7 vs 148.6). Females also experienced more injuries than males per individual Australian Open in all years bar 2011 (33.6 ± 1.6 versus 24.8 ± 1.2 per year). However, there was no change in injury risk by sex over time (Figure 11).

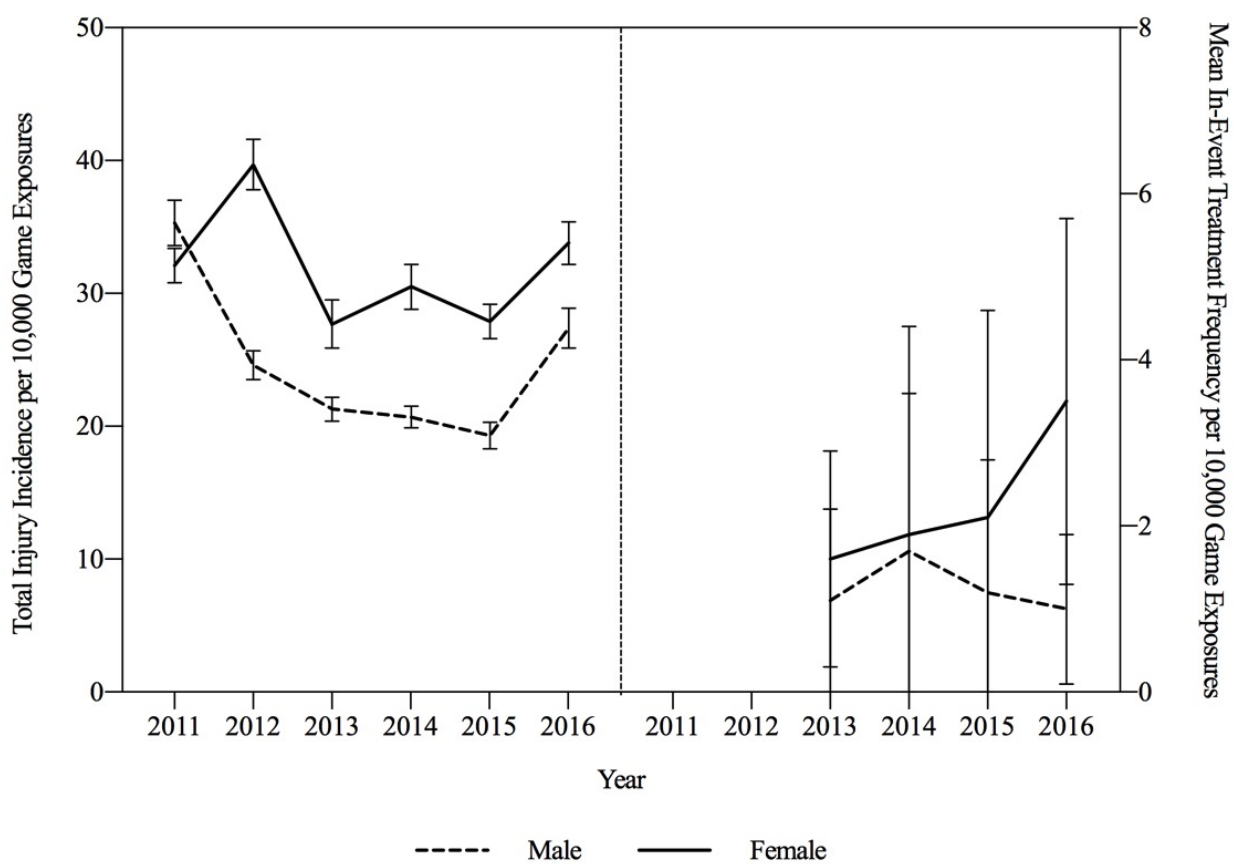


Figure 11: Total male and female injury incidence ($\pm$ SD) and mean in-event treatment frequency ($\pm$ SD), per 10,000 game exposures, at the 2011–2016 Australian Open (2013–2016 for mean in-event treatment frequency)

4.5.2. INJURY REGION

The most common male injury region over the six-year period was the knee, followed by the ankle and thigh (3.5 ± 1.6 , 2.3 ± 1.3 and 2.3 ± 1.5 injuries per year; Figure 12). The shoulder (5.1 ± 1.1 injuries per year) was the most common injury region in females followed by the foot (3.2 ± 1.1), wrist (3.1 ± 1.5) and knee (3.1 ± 1.1 ; Figure 12). There was a 2-fold or greater increase in the rate of male ankle and elbow (incidence rate $\pm$ 95% CI; 0.3 ± 0.5 and 0.3 ± 0.4) injuries over the 2011-2016 period (Table 12). The increased rate of female shoulder (2.0 times; 0.6 ± 0.7) and wrist injuries (2.2 times; 0.4 ± 0.7) was also pronounced. Additionally, the rate of upper-arm injuries increased by at least 2.4 times in male and female (0.1 ± 0.2 and 0.1 ± 0.3) players over the six Australian Opens (Table 12).

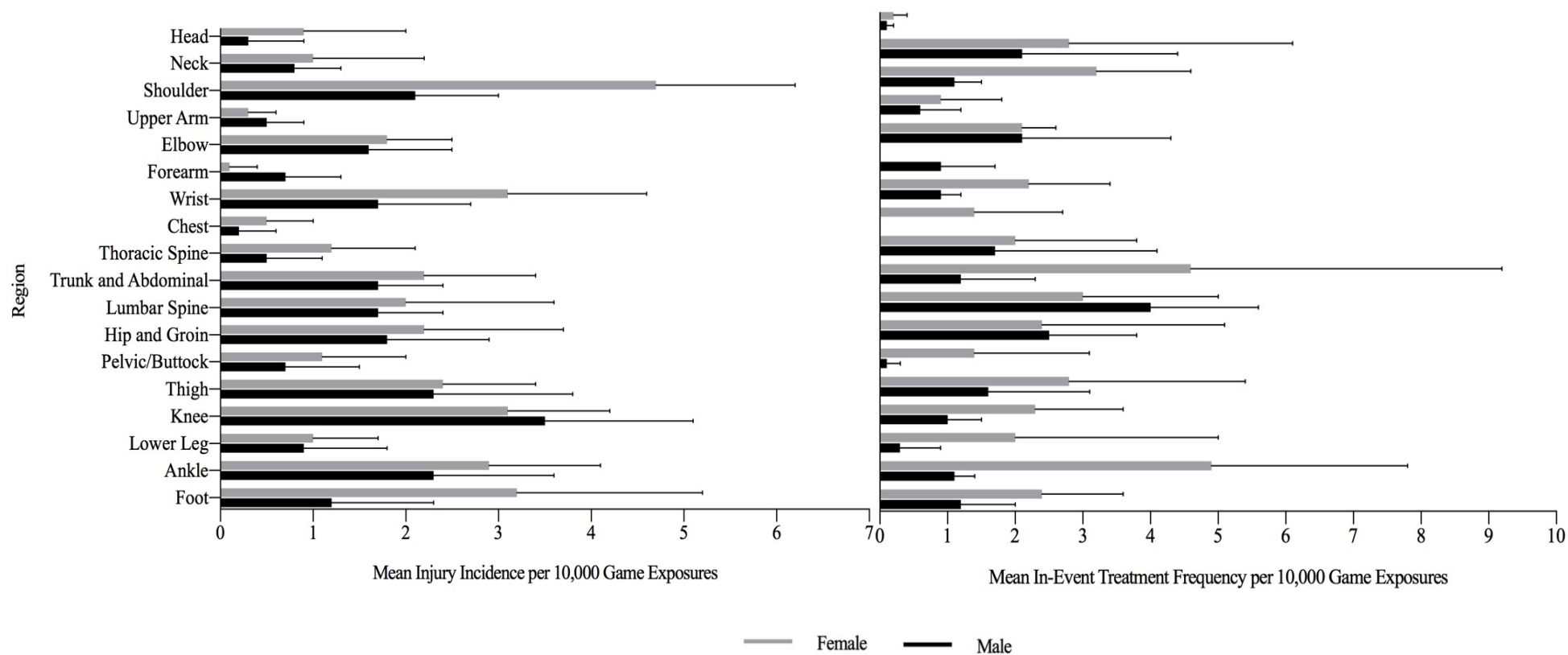


Figure 12: Mean ($\pm$ SD) male and female injury incidence and in-event treatment frequency, per 10,000 game exposures, by region over the 2011–2016 Australian Open (2013–2016 for in-event treatment frequency).

Table 12: Male and female injury incidence $\pm$ 95% confidence interval and rate ratio (RR), per 10,000 game exposures, and treatment cost by region at the 2011 to 2016 Australian Open.

Region	Male				Female			
	Injury Occurrence^		Treatment Cost*		Injury Occurrence^		Treatment Cost*	
	Incidence rate change $\pm$ 95% confidence interval	RR	Incidence rate change $\pm$ 95% confidence interval	RR	Incidence rate change $\pm$ 95% confidence interval	RR	Incidence rate change $\pm$ 95% confidence interval	RR
Head	0.00 $\pm$ 0.19	1.0	0.00 $\pm$ 0.29	1.0	-0.12 $\pm$ 0.28	0.3	0.04 $\pm$ 0.35	1.6
Neck	-0.12 $\pm$ 0.31	0.4	0.66 $\pm$ 0.79	150.9	-0.11 $\pm$ 0.26	0.4	1.19 $\pm$ 0.88	39.3
Shoulder	-0.11 $\pm$ 0.48	0.8	0.05 $\pm$ 0.56	1.0	0.57 $\pm$ 0.69	2.0	0.55 $\pm$ 1.28	1.8
Upper Arm	0.09 $\pm$ 0.24	3.1	0.30 $\pm$ 0.46	5.8	0.08 $\pm$ 0.26	2.4	0.41 $\pm$ 0.62	5.2
Elbow	0.26 $\pm$ 0.40	2.5	0.03 $\pm$ 0.59	1.1	-0.31 $\pm$ 0.51	0.4	0.17 $\pm$ 0.97	1.3
Forearm	-0.07 $\pm$ 0.28	0.5	-0.38 $\pm$ 0.56	0.1	-0.02 $\pm$ 0.22	0.8	0.00 $\pm$ 0.00	0.0
Wrist	0.08 $\pm$ 0.42	1.3	-0.09 $\pm$ 0.59	0.7	0.37 $\pm$ 0.66	2.2	0.79 $\pm$ 1.03	3.5
Chest	-0.01 $\pm$ 0.16	0.9	0.00 $\pm$ 0.00	0.0	-0.01 $\pm$ 0.24	0.9	-0.36 $\pm$ 0.60	0.3
Thoracic Spine	-0.04 $\pm$ 0.17	0.6	-0.49 $\pm$ 0.53	0.0	0.09 $\pm$ 0.29	1.8	0.24 $\pm$ 0.87	2.2
Trunk and Abdominal	-0.39 $\pm$ 0.41	0.2	-0.01 $\pm$ 0.52	1.0	-0.34 $\pm$ 0.56	0.3	-0.55 $\pm$ 1.09	0.2
Lumbar Spine	-0.09 $\pm$ 0.38	0.7	-0.68 $\pm$ 1.01	0.6	0.05 $\pm$ 0.49	1.3	1.07 $\pm$ 1.33	-18.0
Hip and Groin	-0.48 $\pm$ 0.38	0.2	0.90 $\pm$ 0.77	4.1	-0.33 $\pm$ 0.45	0.3	-0.29 $\pm$ 1.01	0.4
Pelvis/Buttock	-0.20 $\pm$ 0.29	0.1	0.04 $\pm$ 0.33	1.7	-0.12 $\pm$ 0.36	0.4	-0.01 $\pm$ 0.80	1.0
Thigh	0.17 $\pm$ 0.51	1.9	-0.41 $\pm$ 0.78	0.3	-0.09 $\pm$ 0.57	0.1	-0.12 $\pm$ 0.93	0.7
Knee	-0.46 $\pm$ 0.67	0.5	-0.11 $\pm$ 0.65	0.7	0.22 $\pm$ 0.65	1.5	-0.29 $\pm$ 1.05	0.6
Lower Leg	-0.20 $\pm$ 0.24	0.1	-0.02 $\pm$ 0.29	0.8	0.13 $\pm$ 0.43	2.6	0.70 $\pm$ 0.75	37.0
Ankle	0.25 $\pm$ 0.51	2.0	-0.09 $\pm$ 0.59	0.8	0.23 $\pm$ 0.55	1.6	1.11 $\pm$ 1.46	2.4
Foot	-0.12 $\pm$ 0.23	0.4	-0.54 $\pm$ 0.52	0.2	-0.15 $\pm$ 0.57	0.8	-0.73 $\pm$ 1.14	0.3

^ 2011 as base year; * 2013 base year

4.5.3. *INJURY TYPE*

Muscle injuries, in both sexes, were the most prominent type of injury with a total of 45.9 ± 3.3 and 56.5 ± 1.3 male and female muscle injuries respectively per 10,000 GE (Figure 13). From 2011 to 2016, there was a 2.1 fold (incidence rate $\pm$ 95% CI; 0.1 ± 0.3), and 2.4 fold (0.2 ± 0.5) increase in the rate of stress fractures among male and female players respectively (Table 13).

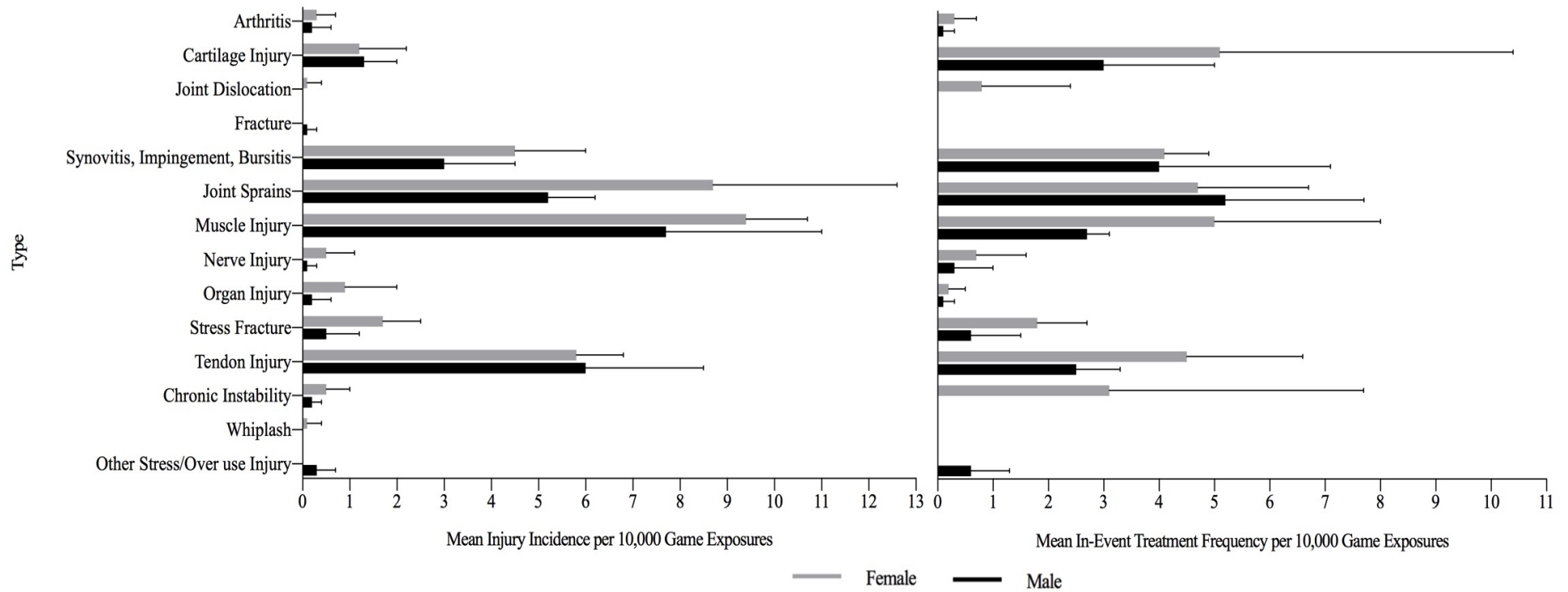


Figure 13: Mean ($\pm$ SD) male and female injury incidence and in-event treatment frequency, per 10,000 game exposures, by type over the 2011–2016 Australian Open (2013–2016 for in-event treatment frequency)

Table 13: Male and female injury incidence $\pm$ 95% confidence interval and rate ratio (RR), per 10,000 game exposures, and treatment cost by type at the 2011 to 2016 Australian Open

Type	Male				Female			
	Injury Occurrence [^]		Treatment Cost*		Injury Occurrence [^]		Treatment Cost*	
	Incidence Rate Change $\pm$ 95% confidence interval	RR	Incidence Rate Change $\pm$ 95% confidence interval	RR	Incidence Rate Change $\pm$ 95% confidence interval	RR	Incidence Rate Change $\pm$ 95% confidence interval	RR
Muscle Injury	-1.35 $\pm$ 0.91	0.4	0.19 $\pm$ 0.92	1.3	-0.64 $\pm$ 1.17	0.7	0.01 $\pm$ 1.56	1.0
Joint Sprains	0.26 $\pm$ 0.71	1.3	-0.14 $\pm$ 1.14	0.9	-0.23 $\pm$ 1.01	0.9	0.71 $\pm$ 1.07	0.4
Tendon Injury	-0.52 $\pm$ 0.80	0.6	-0.43 $\pm$ 0.94	0.6	-0.18 $\pm$ 0.89	0.9	0.43 $\pm$ 0.94	0.6
Synovitis, Impingement, Bursitis	-0.07 $\pm$ 0.61	0.9	-0.24 $\pm$ 0.98	0.8	0.44 $\pm$ 0.78	1.7	0.15 $\pm$ 1.42	1.1
Cartilage Injury	-0.00 $\pm$ 0.20	1.0	-0.93 $\pm$ 1.13	0.2	0.06 $\pm$ 0.29	1.6	-0.20 $\pm$ 2.00	-1.2
Stress Fracture	0.05 $\pm$ 0.27	2.1	0.69 $\pm$ 1.02	8.3	0.23 $\pm$ 0.49	2.4	0.70 $\pm$ 0.84	4.0
Organ Injury	-0.00 $\pm$ 0.18	0.9	0.00 $\pm$ 0.00	0.0	-0.12 $\pm$ 0.28	0.3	-0.32 $\pm$ 1.52	4.1
Chronic Instability	-0.00 $\pm$ 0.20	1.0	0.00 $\pm$ 0.00	0.0	-0.07 $\pm$ 0.31	0.5	3.61 $\pm$ 2.76	9.1
Nerve Injury	0.01 $\pm$ 0.16	1.2	0.00 $\pm$ 0.00	0.0	-0.02 $\pm$ 0.32	0.8	-0.30 $\pm$ 0.88	0.5
Arthritis	-0.02 $\pm$ 0.21	0.7	0.00 $\pm$ 0.00	0.0	-0.02 $\pm$ 0.22	0.8	-0.01 $\pm$ 1.75	1.0
Other Stress/Over use Injury	0.01 $\pm$ 0.17	1.2	0.44 $\pm$ 2.03	3.6	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0
Fracture	0.00 $\pm$ 0.16	1.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0
Joint Dislocation	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	0.02 $\pm$ 0.22	1.2	0.00 $\pm$ 0.00	0.0
Whiplash	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	-0.02 $\pm$ 0.22	0.8	0.00 $\pm$ 0.00	0.0

[^] 2011 as base year; * 2013 base year

4.5.4. IN-EVENT TREATMENT FREQUENCY BY INJURY REGION

The mean number of in-event treatments per injury did not differ between sex (females 3.5 ± 1.2 vs males 2.6 ± 0.7). The lumbar spine had the highest mean in-event treatments among male Australian Open competitors between 2013-2016 (4.0 ± 1.6 per year; Figure 12), while the ankle had the highest mean in-event treatments among female players (4.9 ± 2.9 per year; Figure 12). The rate of male and female upper-arm in-event treatments per injury increased by 5.8 (incidence rate $\pm$ 95% CI; 0.3 ± 0.5) and 5.2 (0.4 ± 0.6) over the four-year period (Table 12).

4.5.5. IN-EVENT TREATMENT FREQUENCY BY INJURY TYPE

The injury types with the highest in-event treatment frequency differed between sex, with joint sprains the most common among male players (5.2 ± 2.5 mean in-event treatment frequency $\pm$ SD per year) and cartilage injuries the most common amongst females (5.1 ± 5.3 ; Figure 13). Over the four years, there was a rate increase of 8.3 (incidence rate $\pm$ 95% CI; 0.8 ± 1.0) and 4.0 (0.7 ± 0.9) for stress fracture mean in-event treatments among males and females respectively (Table 13).

4.5.6. SET AND MATCH EXPOSURE RESULTS

Supplementary tables including the incidence rates $\pm$ 95% CI and rate ratios for injury region, type and in-event treatment frequency per 1,000 set and match exposure are available (Appendix V).

4.6. DISCUSSION

The aim of this study was to profile injuries at recent Australian Opens by sex, region, type, in-event treatment frequency and year. Female players sustained more injuries than male players over the tournaments except for 2011. Shoulder and wrist, as well as foot and knee injuries were most common among female players, while lower-limb injuries were the most prevalent among males. Over time, there were discernible increases in the rate of male upper arm, elbow and ankle injuries, and female upper-arm, shoulder, wrist and lower-leg injuries. In keeping with previous accounts of Grand Slam injuries (9, 10), muscle injuries were the most prominent injury type in both sexes. However, the rate of stress fractures noticeably increased over time. The torso region (neck, thoracic spine, trunk and abdominal, lumbar spine, hip and groin, pelvis/buttock) - and more particularly the neck and lumbar spine of male players and thoracic spine of female players - attracted high treatment frequencies. Joint sprains in male players and cartilage injuries in female players were the most frequently treated injury type.

4.6.1. SEX DIFFERENCES

Higher injury rates have been reported among male than female players competing at Grand Slam level (9). Conversely, accounting for injuries per 10,000 GE in the present study, women were found to have a higher injury rate compared to men. This is consistent with the higher incidence of injury in female professionals previously reported at Wimbledon, which utilised a set exposure injury rate to account for differences in sex set requirements (10). While the likely mechanisms of injury are multifactorial, it is likely that sex-based physical (43, 174), technical and tactical differences (43, 53) are contributors. For example, females have slower movement speeds (43), and lower absolute strength (174) compared to professional male tennis players. Therefore, they may have less time to set up for optimal

stroke execution resulting in compromised joint positioning (53). This could explain their high prevalence of injuries across both extremities. Additionally, males could be relatively more likely to sustain lower-limb injuries owing to the heightened absolute movement demands of the men's game (43). Indeed, the higher incidence of lower-limb injury as compared to upper-limb injury in male Australian Open players, is consistent with the earlier Wimbledon and US Open Grand Slam injury epidemiology research (9, 10).

4.6.2. INJURY BY TYPE

Muscle injuries were the most common across both sexes followed by tendon and joint sprains. This agrees with the injury reports at the US Open and Wimbledon Grand Slams (9, 10). This finding was anticipated given the dynamic, high-intensity and repetitive nature of tennis that places large strain on the muscles, tendons and joints (41, 174, 175). It is worth noting that whilst remaining the most prominent injury, a 13% reduction in muscle injuries in males existed over the six-year period, despite no reduction in total injuries. Additionally, the highest male and female injury type in-event treatment frequencies resulted from joint sprains and cartilage injuries respectively. The higher cost of such injuries suggests that these injury types require greater on-going consultation by tournament physicians and physiotherapists. Separately, stress fracture injury occurrence and in-event treatments in both sexes increased over this time-period. This is supported by findings highlighting the high risk of stress fractures in tennis players due the repetitive powerful movements demanded which could place heavy mechanical loads on athlete bone (176).

4.6.3. INJURY BY REGION: TORSO INJURIES AND IN-EVENT TREATMENT FREQUENCY

The incidence of female thoracic and lumbar spine injury incidence increased over time. However, the incidence rate of male torso injuries and other female torso regions - including

the neck, thoracic and lumbar spine, trunk and pelvis - decreased over the same time period. Despite this, the in-event treatments for torso injuries in both sexes was found to be among the Australian Open's highest. This trend may be attributable to the mechanical demands placed on this region during stroke production, changes in equipment (9) or cause players to seek further treatment. Given the literature that has highlighted the importance of trunk rotation to racquet speed - particularly in the serve (177) - it is unsurprising that the pelvis-spine-trunk receive considerable medical attention in-event. This heightened medical attention in-event, coupled with the general reduction in incidence rate, suggests that injury prevention and training programs could already be focused on the torso and should remain the ongoing target.

4.6.4. INJURY BY REGION: UPPER-LIMB INJURIES AND IN-EVENT TREATMENT FREQUENCY

The rate and in-event treatment frequency of upper-arm injuries in both sexes increased over time. This effect was also observed for the rate of male elbow and female shoulder injuries as well as the rate and in-event treatments of female wrist injuries. Although Sell et al. (2012), McCurdie et al. (2016) did not report in-event treatment frequencies, they highlighted a high occurrence of shoulder injuries in both sexes and wrist injuries in female players. The constantly evolving racquet, string and ball technology may be one reason for these changes (43, 50). Spikes in serve load, which are common during tournament play as compared to training, particularly at a Grand Slam at the start of the season (42), might also place relatively greater strain on the upper-limb joints (178, 179).

4.6.5. INJURY BY REGION: LOWER-LIMB INJURIES AND TREATMENT COST

There was a rate increase of ≥ 2.4 times in in-event treatments of female ankle and lower-leg injuries over the time-period. The prevalence of female lower-leg injuries and male ankle

injuries also increased, by ≥ 2 fold, between 2011-2016. Sell et al. (2012) reported the lower-limb as being more susceptible to injury than the upper extremity in both sexes but noted no change in the injury rate over time. This sex-independent increase in ankle pathologies would appear related to the repeated rapid changes in direction on a hard-court surface, which places high stress on the ankle joint and lower-leg (60, 175). Interestingly, the sex-specific growth observed in in-event treatments could imply that physiotherapists treating female players adopt a precautionary/hyper-vigilant, through taping, approach.

4.6.6. LIMITATIONS

It must be noted that this study is unable to draw conclusions regarding the causative mechanisms of injury. Additionally, as the WTA and ATP datasets were de-identified, in-event treatment frequencies are calculated as an average across all injuries of the same region and type rather than each injury in isolation. Finally, the dataset does not contain injury or treatment information on players whom sought treatment outside of the tournament's doctors and physiotherapists.

4.7. CONCLUSION

The injury epidemiology of the 2011-2016 Australian Open revealed that female players were more commonly injured than male players. Lower-limb injuries were more prominent in males whereas females were susceptible to injuries in both extremities, which is consistent with findings from Wimbledon and US Open Grand Slams (9, 10). Both sexes also presented with a high prevalence of muscle injuries, and, the high in-event treatment frequencies of the torso highlighted the demand on medical resources. Collectively, these findings demonstrate

the most common injuries and workload for the medical services at the Australian Open, which is informative for the injury prevention and treatment of elite tennis players.

4.8. NEW FINDINGS

- Using game exposures as a relative injury scale offers a more accurate measure of match volume or exposure than previously published methods. Correspondingly, this allows for more precise standardisation in epidemiological comparison between Grand Slams.
- Female players incurred more injuries than male players over the 2011 to 2016 Australian Opens per games played.
- Across both sexes, the torso region incurred high in-event treatment frequency highlighting their demand on medical resources during the Australian Open.
- In-event treatment frequency as a novel reporting of medical and physiotherapy consultations per injury, provides scope for the assessment of medical resource management at tennis events.

5. CHAPTER 5: STUDY 2 - A MULTI-YEAR INJURY EPIDEMIOLOGY ANALYSIS OF AN ELITE NATIONAL JUNIOR TENNIS PROGRAM.

Publication statement:

This chapter is comprised of the following paper published in the *Journal of Science and Medicine in Sport*.

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Wood TO, Omizzolo M, Reid M. A multi-year injury epidemiology analysis of an elite national junior tennis program. J Sci Med Sport 2018; In Press. doi: <https://doi.org/10.1016/j.jsams.2018.06.006>.

5.1. LINKING PARAGRAPH

Study 1 found that female Australian Open tennis players had a higher injury incidence (per 10,000 game exposures), compared to their male counterparts, even though in-event treatment frequency was the same across sexes. Additionally, torso injuries were the most severe in both sexes and increased over time. For elite junior tennis players aspiring to compete at the Grand Slam level, these findings offer guidance for targeted injury prevention strategies. However, the journey from junior through to professional tennis career is long, with average transition times of 4-years to a Top 100 ranking (37). Therefore, an understanding of the injury epidemiology of elite junior tennis players may highlight risks for long-term athlete development and subsequent professional tennis success. It also allows for contrast with the injury profile of professional Grand Slam tennis players to draw attention to differences with age and playing standard. Currently, the injury epidemiology literature on elite junior tennis players is sparse and has disparate findings. Additionally, the studies that are available fail to explore important factors such as injury severity and changes over time which are both critical for tennis stakeholders. Therefore, Study 2 aimed to profile injuries in elite junior tennis players in a national program by body region, and severity over time by both age and sex.

5.2. ABSTRACT

Objective: To profile multi-year injury incidence and severity trends in elite junior tennis players from a national program. **Design:** Prospective Cohort. **Methods:** Injury data was collated by sex, age and region for all nationally-supported Australian junior players (58 males, 43 females 13-18 y) between 2012-2016. Injury was defined as a physical complaint from training/matchplay interrupting training/matchplay determined by presiding physiotherapists and doctors. Severity represented the days of interrupted training/matchplay per injury. Injury incidence was reported per 1,000 exposure hours. Incidence rate change and $RR \pm 95\%$ CI were used to assess changes over time. **Results:** No difference in male and female injury incidence existed (2.7 ± 0.0 v 2.8 ± 0.0) yet male injuries were more severe (3.6 ± 0.6 v 1.1 ± 0.9 days). The lumbar spine was the most commonly and severely injured region in both sexes (4.3 ± 0.2 , 9.9 ± 1.4 days). Shoulder injuries were the second most common in both sexes (3.1 ± 0.2) and with the second highest severity in males (7.3 ± 1.4 days). Knee injuries were also common in males (2.3 ± 0.2) yet potentially reduced over time (0.4 ± 0.6 RR) as pelvis/buttock injuries increased (3.4 ± 14.0 RR). Females had high trunk and abdominal injury incidences (2.5 ± 0.3). Independent of sex, the injury incidence increased with age from 2.0 ± 0.1 (13 y) to 2.9 ± 0.1 (18 y). **Conclusion:** Despite no sex-based difference in injury incidence, male injuries resulted in more interrupted days of training/matchplay. The lumbar spine and shoulder were the most commonly injured body regions in both sexes. The number of injuries sustained by players also increased as they aged.

5.3. INTRODUCTION

Injuries in junior tennis players can disrupt their long-term athletic development(65). Therefore, an understanding of the injury epidemiology in junior tennis is important to assist medical, physiotherapy and strength and conditioning professionals to monitor and manage the musculoskeletal health of young elite tennis players. However, limited evidence describing the injury epidemiology of junior tennis players exists, and that which does is inconsistent in reporting of injury incidence by anatomical region or sex (11, 15, 19, 36). This makes for an incomplete view of tennis injuries in youth tennis and may inadvertently affect the treatment and care of players.

Of the sparse research that is present, a three-year analysis of 16 to 20-year-old players in a national program in the 1980's found that lower-limb injuries were the most common in both genders as compared to trunk and upper-limb injuries (69). These findings were reported as absolute values and not relative to training volume or other extrinsic risk factors. Conversely, back injuries were found to be the most common in national junior male tennis players over a six-year period in the 1980's and 1990's (15). Since then, the sport has observed dramatic changes in equipment and strategy (43, 50), likely influencing the sport's injury profile (50). More recently, junior male club tennis players aged between 12 and 18 were shown to be more prone to injury than girls over a 2-year period of training and matchplay (11). However, this contrasts with another study where girls of the same age bracket were reported as more susceptible to injury than boys during higher level national competitions (19). Although these studies provide some context to the injuries sustained by junior tennis players they are limited in their variation of study design, the age and standard of athletes, injury classification, period of data capture and relative exposure measure (11, 15, 19, 36, 69). Further, much of the research has focused on the epidemiology of junior injuries in-event rather than in training

settings(15, 19). In turn, this highlights the need to better understand whether sex and age-based differences exist in the injury patterns of a homogenous sample of elite junior tennis players(10).

An understanding of the severity of injury is important for determining the extent to which injuries impede training and potentially athletic development (65), yet this has also been poorly examined in the tennis injury literature. Particularly, previous studies are limited by definitional differences (11, 19) and methodological limitations in quantifying the severity of injury (11). For example, the severity of injuries in Swedish local junior tennis players was collected over a two-year period via player recall (11). However, the use of recall to quantify injury time-loss has been criticised for its bias and inaccuracy (70). Additionally, no tennis injury study has described injury severity by body region which would be a valuable addition to the knowledge base of the sport. The same applies to the lack of investigation into the change in injury profile over time which is especially important among adolescent cohorts where maturation and risk of injury have been linked (68).

Overall, the relevance of previous attempts to profile injuries in junior tennis has been limited by the timing (15, 69), tournament-only focus (15), length of data collection (15, 69) and lack of trend analysis (36, 69). Therefore, the aim of this study was to comprehensively examine the injury epidemiology of junior, elite tennis players of both sexes over a five-year time period. Specifically, the incidence, severity and changes over time in injuries of elite tennis players between the ages of 13 and 18 was assessed.

5.4. METHODS

A total of fifty-eight male and forty-three female Australian junior tennis players were included in the study and had mean peak national rankings of 117 ± 139 and, 57 ± 48 respectively. All players were aged 18 or under at the time of each injury and were full-time scholarship-holders for at least a year between 2012 and 2016 in a national tennis academy governed by Tennis Australia. The number of players in a national academy fluctuated each year resulting in changes in the participant numbers year on year. The number of unique players in each year of the study included 69 (40 males, 29 females) in 2012, 75 (44 males, 31 females) in 2013, 64 (39 males, 25 females) in 2014, 59 (34 males, 25 females) in 2015 and 56 (30 males, 26 females) in 2016. All players in the study did not participate in other sports. Given the lack of data prior to 2012, this year was used as the base year for ensuing analysis. Data was collected and stored in a secure, Tennis Australia managed data repository (Athlete Management System). This study received human ethics committee approval from Australian Catholic University (reference number 2015-196N) with informed consent obtained from players and player parents if those under the age of 18.

An injury was diagnosed by Tennis Australia's physiotherapists and doctors and defined as a physical complaint from training/matchplay resulting in interrupted training or matchplay (163). Interrupted training was defined as any restrictions to tennis and off-court training resulting in an athlete unable to take a part in the full session (163). Injuries were calculated as injury incidence, which describes the number of new injuries within the population over the period of time (180). Severity was defined as the mean number of days since injury onset to a particular region to the day that the player returned to full training (64) both on and off court. Injury data was classified by region as per the OSICS (159) with only musculoskeletal injuries included (lacerations/abrasions and bruising/haematomas were omitted). The injury

data was entered and stored on the Athlete Management System by the designated Tennis Australia treating physiotherapist ($n = 32$, mean 2.3 ± 1.3 years treating Tennis Australia athletes) and doctors ($n = 14$, mean 3.1 ± 2.0 years). Injury severity was also entered and stored in the repository via athlete self-reporting. Injury data, including OSICS-defined injury region, year of injury, age and injury severity on the studied population between 2012-2016 were exported for analysis.

Injury incidence was reported per 1,000 exposure hours which is consistent with recommendations in the consensus statement on epidemiological studies of medical conditions in tennis (64). Exposure hours included the durations of both on and off court training and matchplay and were recorded via athlete daily self-reporting. The total exposure hours were the total exposure hours for all athletes in each given year which allowed for a relative comparison year-on-year. All players trained and competed on multiple court surfaces throughout the data collection period however this was not captured due to the epidemiology, not aetiology, focus of the study.

Statistical programming (R Core Team, 2012) was used for all analyses. The ‘metafor’ package was used to implement the fixed-effects meta-regression analysis of incidence rates $\pm$ 95% CI with precision weights. Incidence rate changes represent the year-on-year change in injury counts by region and severity, where 2012 was the base year. The magnitude of change over time is inferred by $RR \pm 95\%$ CI whereby a ratio of greater than 1 is considered to be an increase, and less than 1, a decrease. Results are reported as mean injury incidence $\pm$ SD, incidence rate change $\pm$ 95% CI, and $RR \pm 95\%$ CI. The RR 95% CI values truncate at 0 when lower bound value is larger than the RR . Incidence rate changes $\pm$ 95% CI are reported to two decimal places due to the size of the values.

5.5. RESULTS

There were 327 male injuries and 258 female injuries during the time period. The exposure hours equated to a mean $\pm$ SD of 648.8 ± 108.6 and 661.8 ± 112.6 training hours per year for male and female players respectively. Injuries were comparable between sexes over the time period with 2.7 ± 0.0 and 2.8 ± 0.0 in female and males per 1,000 exposure hours respectively (Table 14).

Table 14: Male and female injury incidence (mean $\pm$ SD), incidence rate change ($\pm$ 95% confidence interval (CI)) and rate ratio (RR) ($\pm$ 95% CI), per 1,000 exposure hours, by region 2012-2016

Region	Males			Females		
	Injury incidence	Incidence rate change	RR	Injury incidence	Incidence rate change	RR
Head	0.1 $\pm$ 0.0	0.00 $\pm$ 0.02	1.2 $\pm$ 4.0	0.0 $\pm$ 0.0		
Neck	0.5 $\pm$ 0.1	0.00 $\pm$ 0.02	1.4 $\pm$ 2.9	0.5 $\pm$ 0.1	0.01 $\pm$ 0.03	2.3 $\pm$ 6.5
Shoulder	3.6 $\pm$ 0.2	-0.02 $\pm$ 0.08	0.8 $\pm$ 0.8	2.6 $\pm$ 0.2	0.07 $\pm$ 0.08	3.6 $\pm$ 5.8
Upper Arm	1.8 $\pm$ 0.2	0.01 $\pm$ 0.05	1.4 $\pm$ 1.9	0.7 $\pm$ 0.1	0.00 $\pm$ 0.04	0.7 $\pm$ 2.0
Elbow	1.8 $\pm$ 0.2	24.51 $\pm$ 51.66	1.7 $\pm$ 2.1	1.7 $\pm$ 0.3	0.04 $\pm$ 0.06	4.7 $\pm$ 14.4
Forearm	0.7 $\pm$ 0.1	0.00 $\pm$ 0.03	1.3 $\pm$ 2.5	0.2 $\pm$ 0.1	0.00 $\pm$ 0.03	1.3 $\pm$ 4.0
Wrist	3.0 $\pm$ 0.4	-0.07 $\pm$ 0.07	0.3 $\pm$ 0.5	2.4 $\pm$ 0.2	0.09 $\pm$ 0.06	5.8 $\pm$ 9.0
Chest	0.0 $\pm$ 0.0			0.2 $\pm$ 0.1	0.00 $\pm$ 0.03	1.3 $\pm$ 4.0
Thoracic Spine	1.0 $\pm$ 0.3	-0.03 $\pm$ 0.03	0.1 $\pm$ 0.5	1.3 $\pm$ 0.2	0.04 $\pm$ 0.04	6.1 $\pm$ 13.4
Trunk and Abdominal	1.2 $\pm$ 0.1	0.00 $\pm$ 0.05	0.9 $\pm$ 1.6	2.5 $\pm$ 0.3	0.09 $\pm$ 0.06	6.1 $\pm$ 9.9
Lumbar Spine	4.7 $\pm$ 0.2	0.02 $\pm$ 0.09	1.2 $\pm$ 0.9	3.9 $\pm$ 0.2	0.09 $\pm$ 0.10	3.0 $\pm$ 3.6
Hip and Groin	1.9 $\pm$ 0.1	0.03 $\pm$ 0.06	1.8 $\pm$ 2.5	1.4 $\pm$ 0.2	-0.03 $\pm$ 0.05	0.4 $\pm$ 0.7
Pelvis/Buttock	0.6 $\pm$ 0.1	0.01 $\pm$ 0.03	3.4 $\pm$ 14.0	0.6 $\pm$ 0.1	0.00 $\pm$ 0.04	1.2 $\pm$ 3.4
Thigh	1.4 $\pm$ 0.1	0.00 $\pm$ 0.05	1.1 $\pm$ 1.5	1.6 $\pm$ 0.1	0.01 $\pm$ 0.06	1.5 $\pm$ 2.5
Knee	2.3 $\pm$ 0.2	-0.04 $\pm$ 0.07	0.4 $\pm$ 0.6	2.0 $\pm$ 0.2	0.04 $\pm$ 0.05	3.2 $\pm$ 5.0
Lower Leg	1.0 $\pm$ 0.0	0.00 $\pm$ 0.05	0.9 $\pm$ 1.7	1.2 $\pm$ 0.2	-0.02 $\pm$ 0.05	0.4 $\pm$ 1.3
Ankle	1.4 $\pm$ 0.2	-0.03 $\pm$ 0.05	0.2 $\pm$ 0.7	2.3 $\pm$ 0.3	-0.01 $\pm$ 0.07	0.8 $\pm$ 1.5
Foot	0.7 $\pm$ 0.0	0.00 $\pm$ 0.04	0.9 $\pm$ 2.5	1.9 $\pm$ 0.4	0.05 $\pm$ 0.05	7.5 $\pm$ 10.8
Overall	2.7 $\pm$ 0.0	-0.11 $\pm$ 0.23	0.9 $\pm$ 1.3	2.8 $\pm$ 0.0	0.51 $\pm$ 0.25	2.1 $\pm$ 1.6

The lumbar spine, followed by the shoulder, had the highest incidence of injuries by region in both sexes over the observed time period (Table 14). Junior female tennis players experienced an increase in total injuries and particularly the upper-limb (shoulder, elbow, wrist), neck, thoracic spine, trunk and abdominal, knee and foot injury incidence over time ($RR \geq 2.1 \pm 5.0-14.4$). There was also a reduction in hip and groin and lower-leg injuries over time (0.4 ± 1.0 RR; Table 15). Males experienced an increase in pelvis/buttock injuries (3.4 ± 14.0 RR) over time, with a reduction in thoracic spine, knee, ankle and wrist injuries ($RR \leq 0.4 \pm 0.5-0.7$; Table 14).

Male injury severity was greater than females with 3.6 ± 0.6 days lost (Table 15), compared to a female injury severity of 1.1 ± 0.9 days lost. Male injury severity also increased over time (2.6 ± 2.5 RR). Lumbar spine injury severity was the highest in both sexes ($>4.6 \pm 0.6$ days lost). The shoulder, hip and groin and wrist also had high injury severity in male tennis players, with an increase in pelvis/buttock injury severity (3.4 ± 14.0 RR) and a reduction in trunk and abdominal severity (0.3 ± 0.4 RR) over time. Female tennis players experienced high elbow, ankle and knee injury severity with an increase in neck (2.3 ± 2.8 RR), elbow (2.5 ± 13.4 RR), thoracic spine (6.1 ± 13.4 RR) and foot (7.5 ± 12.8 RR) injury severity over time.

Table 15: Male and female mean injury severity ($\pm$ SD), incidence change ($\pm$ 95% confidence interval (CI)) and rate ratio (RR) ($\pm$ 95% CI), per 1,000 exposure hours, by region 2012-2016

Region	Males			Females		
	Mean Severity	Incidence rate change	RR	Mean Severity	Incidence rate change	RR
Head	0.4 $\pm$ 0.4	0.00 $\pm$ 0.02	1.2 $\pm$ 4.0	0.0 $\pm$ 0.0		
Neck	1.1 $\pm$ 0.3	0.00 $\pm$ 0.02	1.4 $\pm$ 2.9	0.3 $\pm$ 0.3	0.01 $\pm$ 0.03	2.3 $\pm$ 6.5
Shoulder	7.3 $\pm$ 1.4	0.11 $\pm$ 0.11	2.7 $\pm$ 3.1	1.4 $\pm$ 0.9	-0.21 $\pm$ 0.11	0.2 $\pm$ 0.2
Upper Arm	4.1 $\pm$ 0.0	0.04 $\pm$ 0.09	1.5 $\pm$ 1.4	0.6 $\pm$ 0.2	0.00 $\pm$ 0.04	0.7 $\pm$ 2.0
Elbow	4.8 $\pm$ 0.7	24.51 $\pm$ 51.66	1.7 $\pm$ 2.1	3.0 $\pm$ 2.4	0.13 $\pm$ 0.14	2.5 $\pm$ 2.8
Forearm	2.5 $\pm$ 0.7	0.00 $\pm$ 0.04	0.9 $\pm$ 1.3	0.5 $\pm$ 0.4	0.00 $\pm$ 0.03	1.3 $\pm$ 4.0
Wrist	5.3 $\pm$ 0.6	0.06 $\pm$ 0.11	1.9 $\pm$ 2.1	1.2 $\pm$ 0.7	-0.02 $\pm$ 0.10	0.9 $\pm$ 0.6
Chest	0.0 $\pm$ 0.0			0.2 $\pm$ 0.1	0.00 $\pm$ 0.03	1.3 $\pm$ 4.0
Thoracic Spine	1.9 $\pm$ 0.4	-0.03 $\pm$ 0.03	0.1 $\pm$ 0.5	0.5 $\pm$ 0.5	0.04 $\pm$ 0.04	6.1 $\pm$ 13.4
Trunk and Abdominal	4.7 $\pm$ 0.9	-0.09 $\pm$ 0.07	0.3 $\pm$ 0.4	1.3 $\pm$ 1.0	-0.04 $\pm$ 0.09	0.7 $\pm$ 0.5
Lumbar Spine	15.2 $\pm$ 1.4	0.02 $\pm$ 0.09	1.2 $\pm$ 0.9	4.6 $\pm$ 0.6	0.12 $\pm$ 0.14	1.9 $\pm$ 1.6
Hip and Groin	6.2 $\pm$ 1.7	0.05 $\pm$ 0.08	2.3 $\pm$ 3.3	0.8 $\pm$ 0.8	-0.08 $\pm$ 0.07	0.1 $\pm$ 0.4
Pelvis/Buttock	1.4 $\pm$ 0.2	0.01 $\pm$ 0.03	3.4 $\pm$ 14.0	1.2 $\pm$ 1.2	0.00 $\pm$ 0.04	1.2 $\pm$ 3.4
Thigh	1.7 $\pm$ 0.2	0.03 $\pm$ 0.04	2.7 $\pm$ 3.5	0.3 $\pm$ 0.2	-0.01 $\pm$ 0.05	0.7 $\pm$ 1.1
Knee	2.7 $\pm$ 0.5	-0.07 $\pm$ 0.07	0.1 $\pm$ 0.5	2.1 $\pm$ 1.6	-0.03 $\pm$ 0.12	0.8 $\pm$ 0.8
Lower Leg	3.9 $\pm$ 0.9	0.04 $\pm$ 0.06	5.4 $\pm$ 11.6	1.6 $\pm$ 2.0	-0.03 $\pm$ 0.09	0.6 $\pm$ 1.0
Ankle	1.7 $\pm$ 0.2	-0.03 $\pm$ 0.05	0.2 $\pm$ 0.7	2.4 $\pm$ 2.7	0.05 $\pm$ 0.13	1.4 $\pm$ 1.2
Foot	2.6 $\pm$ 0.4	0.00 $\pm$ 0.04	0.9 $\pm$ 2.5	1.5 $\pm$ 0.7	0.05 $\pm$ 0.05	7.5 $\pm$ 12.8
Overall	3.6 $\pm$ 0.6	0.10 $\pm$ 0.10	2.6 $\pm$ 2.5	1.1 $\pm$ 0.9	-0.01 $\pm$ 0.12	0.9 $\pm$ 1.6

Injury incidence increased with age with 13 through to 18 year-olds incurring 2.0 (± 0.1), 2.3 (± 0.1), 2.2 (± 0.1), 2.9 (± 0.1), 3.0 (± 0.1) and 2.9 (± 0.1) injuries per 1,000 exposure hours respectively. The lumbar spine featured as the most common injury region for 14 to 18 year olds, whereas the shoulder and hip and groin were the most common injury regions for 13-year-old players (Table 16). Changes over time highlighted an increase in wrist injuries in the 13th (9.2 ± 12.1 RR) and 18th birth years (3.4 ± 13.1 RR), pelvis/buttock injuries in the 14th (5.2 ± 13.9 RR) and 15th birth year (2.2 ± 9.9 RR), knee injuries in the 16th (3.0 ± 9.9 RR) birth year and shoulder injuries in the 17th (6.0 ± 11.1 RR) birth year (Table 16).

Table 16: Birth year injury incidence (mean $\pm$ SD), incidence rates change ($\pm$ 95% confidence interval (CI)) and rate ratio (RR) ($\pm$ 95% CI), per 1,000 exposure hours, by region 2012-2016

Region	13th Birth Year			14 th Birth Year			15 th Birth Year			16 th Birth Year			17 th Birth Year			18 th Birth Year		
	Injury incidence	Incidence rate change	RR	Injury incidence	Incidence rate change	RR	Injury incidence	Incidence rate change	RR	Injury incidence	Incidence rate change	RR	Injury incidence	Incidence rate change	RR	Injury incidence	Incidence rate change	RR
Head																0.1 $\pm$ 0.1	-0.03 $\pm$ 0.11	0.4 $\pm$ 1.3
Neck				0.1 $\pm$ 0.0	0.03 $\pm$ 0.10	2.9 $\pm$ 10.1	0.1 $\pm$ 0.0	0.00 $\pm$ 0.10	0.9 $\pm$ 3.3	0.1 $\pm$ 0.0	-0.02 $\pm$ 0.08	0.5 $\pm$ 1.7	0.1 $\pm$ 0.0	-0.02 $\pm$ 0.08	0.5 $\pm$ 1.7			
Shoulder	0.3 $\pm$ 0.1	0.05 $\pm$ 0.27	2.6 $\pm$ 11.2	0.3 $\pm$ 0.1	-0.01 $\pm$ 0.18	0.8 $\pm$ 3.0	0.2 $\pm$ 0.1	-0.05 $\pm$ 0.11	0.0 $\pm$ 1.1	0.3 $\pm$ 0.1	0.03 $\pm$ 0.10	1.6 $\pm$ 3.2	0.3 $\pm$ 0.1	0.06 $\pm$ 0.14	6.0 $\pm$ 11.1	0.3 $\pm$ 0.1	-0.02 $\pm$ 0.17	0.7 $\pm$ 1.6
Upper Arm	0.2 $\pm$ 0.0	0.09 $\pm$ 0.23	5.7 $\pm$ 12.3	0.1 $\pm$ 0.0	0.04 $\pm$ 0.13	2.9 $\pm$ 8.7	0.1 $\pm$ 0.0	0.00 $\pm$ 0.09	1.0 $\pm$ 2.8	0.1 $\pm$ 0.0	0.00 $\pm$ 0.08	0.9 $\pm$ 3.0	0.2 $\pm$ 0.0	0.04 $\pm$ 0.14	3.4 $\pm$ 12.2	0.2 $\pm$ 0.1	-0.09 $\pm$ 0.14	0.2 $\pm$ 0.5
Elbow	0.2 $\pm$ 0.0	0.04 $\pm$ 0.25	1.9 $\pm$ 5.8	0.1 $\pm$ 0.0	-0.02 $\pm$ 0.13	0.5 $\pm$ 2.7	0.1 $\pm$ 0.0	-0.02 $\pm$ 0.11	0.5 $\pm$ 2.5	0.2 $\pm$ 0.0	0.03 $\pm$ 0.11	2.4 $\pm$ 7.4	0.2 $\pm$ 0.0	0.04 $\pm$ 0.11	2.4 $\pm$ 6.7	0.2 $\pm$ 0.0	0.03 $\pm$ 0.14	1.7 $\pm$ 5.0
Forearm				0.1 $\pm$ 0.0	0.01 $\pm$ 0.11	1.6 $\pm$ 7.2	0.1 $\pm$ 0.0	0.01 $\pm$ 0.08	1.4 $\pm$ 5.6				0.1 $\pm$ 0.0	-0.02 $\pm$ 0.08	0.5 $\pm$ 1.7			
Wrist	0.1 $\pm$ 0.0	0.12 $\pm$ 0.20	9.2 $\pm$ 12.1	0.2 $\pm$ 0.1	-0.10 $\pm$ 0.16	-0.1 $\pm$ 1.0	0.3 $\pm$ 0.1	-0.06 $\pm$ 0.12	0.2 $\pm$ 1.1	0.3 $\pm$ 0.1	-0.06 $\pm$ 0.11	0.4 $\pm$ 0.7	0.2 $\pm$ 0.0	0.01 $\pm$ 0.12	1.3 $\pm$ 2.8	0.3 $\pm$ 0.1	0.07 $\pm$ 0.17	3.4 $\pm$ 13.1
Chest							0.1 $\pm$ 0.0	0.01 $\pm$ 0.08	1.4 $\pm$ 5.6	0.1 $\pm$ 0.0	0.00 $\pm$ 0.08	1.3 $\pm$ 4.5						
Thoracic Spine	0.1 $\pm$ 0.0	0.05 $\pm$ 0.20	3.1 $\pm$ 13.2	0.1 $\pm$ 0.0	0.03 $\pm$ 0.10	2.9 $\pm$ 10.1	0.1 $\pm$ 0.0	0.00 $\pm$ 0.08	1.2 $\pm$ 4.6	0.2 $\pm$ 0.1	-0.04 $\pm$ 0.12	0.3 $\pm$ 1.2	0.1 $\pm$ 0.0	-0.03 $\pm$ 0.09	0.4 $\pm$ 0.9	0.1 $\pm$ 0.0	-0.03 $\pm$ 0.11	0.4 $\pm$ 1.3
Trunk and Abdominal	0.1 $\pm$ 0.0	0.04 $\pm$ 0.19	2.6 $\pm$ 11.4	0.2 $\pm$ 0.0	-0.02 $\pm$ 0.14	0.6 $\pm$ 2.3	0.1 $\pm$ 0.0	0.01 $\pm$ 0.08	1.9 $\pm$ 6.4	0.2 $\pm$ 0.0	0.01 $\pm$ 0.10	1.3 $\pm$ 3.1	0.3 $\pm$ 0.1	0.06 $\pm$ 0.14	4.0 $\pm$ 7.5	0.1 $\pm$ 0.0	0.00 $\pm$ 0.13	0.9 $\pm$ 2.9
Lumbar Spine	0.2 $\pm$ 0.0	0.08 $\pm$ 0.23	5.3 $\pm$ 11.5	0.4 $\pm$ 0.1	0.06 $\pm$ 0.20	1.9 $\pm$ 3.9	0.5 $\pm$ 0.1	-0.08 $\pm$ 0.20	0.2 $\pm$ 1.3	0.4 $\pm$ 0.1	0.08 $\pm$ 0.12	2.7 $\pm$ 4.5	0.5 $\pm$ 0.1	0.02 $\pm$ 0.16	1.2 $\pm$ 1.8	0.4 $\pm$ 0.1	-0.11 $\pm$ 0.17	0.3 $\pm$ 0.6
Hip and Groin	0.3 $\pm$ 0.1	0.15 $\pm$ 0.24	6.5 $\pm$ 18.2	0.1 $\pm$ 0.0	27.81 $\pm$ 83.20	4.1 $\pm$ 4.1	0.3 $\pm$ 0.1	-0.03 $\pm$ 0.13	0.5 $\pm$ 1.6	0.1 $\pm$ 0.0	0.02 $\pm$ 0.09	2.2 $\pm$ 8.0	0.2 $\pm$ 0.1	-0.02 $\pm$ 0.14	0.7 $\pm$ 1.9	0.1 $\pm$ 0.0	-0.01 $\pm$ 0.12	0.9 $\pm$ 2.3
Pelvis/ Buttock	0.1 $\pm$ 0.0	0.08 $\pm$ 0.18	6.1 $\pm$ 11.6	0.1 $\pm$ 0.0	0.04 $\pm$ 0.11	5.2 $\pm$ 13.9	0.1 $\pm$ 0.0	0.01 $\pm$ 0.08	2.2 $\pm$ 9.9	0.1 $\pm$ 0.0	0.01 $\pm$ 0.09	1.6 $\pm$ 5.2	0.1 $\pm$ 0.0	0.00 $\pm$ 0.09	1.0 $\pm$ 3.4	0.1 $\pm$ 0.0	0.01 $\pm$ 0.12	1.2 $\pm$ 4.0
Thigh	0.2 $\pm$ 0.0	0.07 $\pm$ 0.22	4.6 $\pm$ 18.7	0.1 $\pm$ 0.0	0.02 $\pm$ 0.15	1.9 $\pm$ 9.0	0.1 $\pm$ 0.0	0.01 $\pm$ 0.08	1.5 $\pm$ 4.4	0.1 $\pm$ 0.0	0.00 $\pm$ 0.07	0.8 $\pm$ 2.9	0.2 $\pm$ 0.1	-0.03 $\pm$ 0.14	0.6 $\pm$ 1.6	0.2 $\pm$ 0.0	-0.03 $\pm$ 0.14	0.6 $\pm$ 1.6
Knee	0.2 $\pm$ 0.0	0.04 $\pm$ 0.25	1.9 $\pm$ 5.8	0.1 $\pm$ 0.0	0.00 $\pm$ 0.11	1.1 $\pm$ 3.8	0.2 $\pm$ 0.1	-0.02 $\pm$ 0.09	0.7 $\pm$ 1.8	0.2 $\pm$ 0.0	0.05 $\pm$ 0.13	3.0 $\pm$ 9.9	0.1 $\pm$ 0.0	0.01 $\pm$ 0.11	1.1 $\pm$ 3.3	0.2 $\pm$ 0.1	-0.08 $\pm$ 0.13	0.2 $\pm$ 0.6
Lower Leg	0.1 $\pm$ 0.0	0.04 $\pm$ 0.19	2.6 $\pm$ 11.4	0.1 $\pm$ 0.0	0.01 $\pm$ 0.14	1.3 $\pm$ 6.5	0.1 $\pm$ 0.0	-0.02 $\pm$ 0.09	0.5 $\pm$ 2.3	0.2 $\pm$ 0.1	-0.02 $\pm$ 0.12	0.7 $\pm$ 1.7	0.1 $\pm$ 0.0	-0.01 $\pm$ 0.10	0.7 $\pm$ 2.0	0.1 $\pm$ 0.0	0.00 $\pm$ 0.13	0.9 $\pm$ 2.9
Ankle	0.2 $\pm$ 0.0	0.06 $\pm$ 0.20	3.1 $\pm$ 10.5	0.2 $\pm$ 0.1	-0.02 $\pm$ 0.14	0.4 $\pm$ 3.2	0.1 $\pm$ 0.0	-0.02 $\pm$ 0.11	0.5 $\pm$ 2.0	0.1 $\pm$ 0.0	0.01 $\pm$ 0.10	1.4 $\pm$ 5.4	0.2 $\pm$ 0.0	0.01 $\pm$ 0.11	1.2 $\pm$ 3.5	0.4 $\pm$ 0.1	0.01 $\pm$ 0.19	1.1 $\pm$ 2.3
Foot				0.2 $\pm$ 0.0	0.02 $\pm$ 0.12	1.7 $\pm$ 4.8				0.1 $\pm$ 0.0	0.00 $\pm$ 0.08	1.2 $\pm$ 3.7	0.2 $\pm$ 0.0	0.05 $\pm$ 0.13	4.3 $\pm$ 12.7	0.3 $\pm$ 0.1	0.06 $\pm$ 0.17	2.5 $\pm$ 7.3
Overall	2.0 $\pm$ 0.1	0.38 $\pm$ 0.67	2.0 $\pm$ 6.1	2.3 $\pm$ 0.1	-0.39 $\pm$ 0.48	0.4 $\pm$ 1.6	2.2 $\pm$ 0.1	-0.46 $\pm$ 0.37	0.3 $\pm$ 1.4	2.9 $\pm$ 0.1	0.2 $\pm$ 0.39	1.3 $\pm$ 4.2	3.0 $\pm$ 0.1	0.31 $\pm$ 0.46	1.6 $\pm$ 5.0	2.9 $\pm$ 0.1	-0.15 $\pm$ 0.54	0.8 $\pm$ 2.9

5.6. DISCUSSION

This study provides a comprehensive longitudinal examination of injury incidence and severity in elite junior tennis players by sex, region and age (injury incidence only). Injury incidence in junior male and female tennis players was comparable when expressed relative to exposure hours. This finding is novel in elite junior tennis, although it is consistent with reports in collegiate tennis (62). However, when all body regions were considered, male junior players experienced higher injury severity than female juniors. Further, and in line with previous research (15, 129, 181), the lumbar spine was the most commonly and severely injured region across both sexes.

In addition to the lumbar spine being the most common and severe injury region in both sexes, it was also the most common and severe across age groups (14-18 year olds). Previous research has identified the mechanical loading of serving, primarily through lateral flexion and extension, as a risk factor for the development of low back pain in adolescent tennis players (182). The performance of the kick serve is known to be particularly problematic in this regard with coaches generally introducing and then emphasising this type of serve to players between the ages of 12 to 15 (182). The combination of high joint loads, increased repetition of an unaccustomed skill and physical growth during this time may therefore contribute to the high incidence of lumbar region injuries (182). Interestingly, the high eccentric-concentric activation of the abdominals during the serve would also appear to be implicated in the high incidence of trunk and abdominal injuries sustained by junior female players (90). Further research is required to determine why this injury is less common among junior male players. Given trunk injuries are of concern in elite junior tennis players, careful monitoring of serve loads, technique via biomechanical analyses and targeted injury prevention programs may mitigate occurrence and severity.

The shoulder was found to be the second most common region of injury in both sexes and the second most severe in junior males. Consistently, the shoulder has been highlighted to be the most common upper-limb injury region in tennis irrespective of age and standard (10, 179, 181). Shoulder injuries in tennis are generally reported to be overuse injuries as opposed to acute (179). As the joint is utilized in all strokes in tennis, it is likely the repetitive strain on the shoulder results in the large injury incidence often observed (179). As context, profiling of junior tennis matchplay suggests that players hit 2.5 to 3 strokes per point (183) and in excess of 90 serves per tennis match (42). When extrapolated to include the potential multiple singles and doubles matches completed in a day (52) and then on repeated days (181), the escalation in shoulder joint loading from hitting volumes and intensity may be cause for concern (179). Similarly, these playing demands expose the wrist to large forces which may explain the high incidence and severity of wrist injuries in both sexes in this study. In turn, these ballistic and repetitive movements are performed with equipment that is selected with little systematic regard to the loading implications for the upper-limb (50). The adverse effects of the inappropriate selection of equipment are likely to be magnified by biomechanical limitations that may also be associated with injury (184). Consequently, when these factors are coupled with high or increasing hitting volumes and intensities, the high incidence of wrist and global upper limb injuries among juniors is explicable.

Junior males had a high incidence of knee and ankle injuries, yet both trended downwards and were highly variable (large CI bounds) over time. Nevertheless, with these injuries to the lower limb in mind, the court surface upon which players train may be worth considering. Australian tennis players have naturally trained on hard rather than clay tennis courts, yet almost the same amount of international junior tournaments are offered on clay as compared to hard (185). As a result, Australian junior tennis players have recently increased their clay-court training leading to some of the juniors sampled in the current study spending up to five

times more time training on clay over the time period than previous cohorts in this National program. The increase in time spent training on clay, as compared to hard, may play a role in the reduction in knee and ankle injuries over time, as clay courts transmit less force through the body and allows players to slide more freely (186). However, the potential rise in pelvis/buttock injuries over the time period may have been a by-product of this increased clay-based hitting, as the movement and sliding actions on clay courts result in greater strain on the gluteus muscles (132). In comparison, a reduction in pelvis/buttock injuries over time was found at the Australian Open which is competed on hard court (181). Court surface may impact on junior tennis injuries and should be considered by both athletes and performance staff during junior athletic development.

The age-based analysis of injury incidence in this study provides a novel insight into the increasing injury occurrence in a developing junior population. Peak height velocity is generally experienced between the ages of 13 to 15 years (68), whereby soon after, the risk of injury is suggested to be greatest (68). In addition to physical growth, training and matchplay volume and intensity rise as junior tennis players begin to specialise in the sport and compete more often. This increase in load has been linked to a rise in injury risk (42). The finding that lumbar spine injuries were the most common injury region for players aged 14 to 18 is consistent with what was observed with the cohort overall. Shoulder, hip and groin injuries were the most common in 13 year-olds. The age analysis of injuries over time highlights an upward trend, albeit subject to large RR CIs, in upper-limb injuries in early and late teen players (13, 17 and 18 year-olds) and lower-limb and trunk injuries in mid teen players. Changes in technique, tactical approach, physicality of the players and matchplay, as well as equipment selection may all contribute to the variations in anatomical injury incidence by age over time (43, 50, 90, 183).

It is important to recognise the large size of the RR 95% CIs as a limitation, interpreted as the lower bounds extending beyond the null value (<1.0). A primary explanation is the small and variable injury numbers from year-to-year in the dataset, which then limits the strength of our conclusions. Future research should explore changes in injury rates over time with a larger and less variable dataset to provide some more meaningful insights. Additionally, although reporting tennis injuries per 1,000 exposure hours has been recommended as the best exposure measure (64), recent findings suggest that training/match duration may not be the optimal denominator for reporting injuries (187). However, a more precise measure of training and matchplay, such as hitting volume and distance covered, was not available in the dataset. The court surface of each training session and match was not recorded, which may have added to the understanding of changes in injury incidence. Also, no gender and severity analysis by age was undertaken due to limitations with sample size dilution (188). Furthermore, there was a lack of control in the injury prevention and interventions implemented during the time period. This may have impacted injury incidence by region, gender and age over time.

5.7. CONCLUSION

The profile of junior injuries in the Australian national tennis program revealed that there was no sex difference in injury incidence, yet male injuries were more severe. The lumbar spine presented as the most frequent region of injury resulting in the most time-loss. Junior males experienced high shoulder, wrist and knee injury incidence and severity yet knee incidence shifted downwards over time. Junior females also experienced a high incidence of shoulder as well as trunk and abdominal injuries which trended up over time. The incidence of injuries also increased with age. Collectively, these findings describe common injury trends in elite junior tennis via assessment of injury incidence, severity, age and changes over time, whilst

utilising a recommended exposure measure. In practice, this insight can inform injury prevention and training programs, equipment selection as well as tournament scheduling for elite junior tennis players.

5.8. PRACTICAL IMPLICATIONS

- No sex-based differences in injury incidence relative to exposure hours, and greater junior male injury severity compared to females, provides insight for sex-specific injury prevention and treatment programs.
- There is a need for enhanced lumbar spine injury prevention strategies in both sexes and all junior ages.
- The awareness of the increase with injury incidence with age from 13 through to 18-year-old national, junior tennis players may assist with load monitoring, tournament scheduling, equipment selection and training programs to mitigate the injury risk.

6. CHAPTER 6: STUDY 3 - PREDICTIVE MODELLING OF INJURY IN TENNIS: DETERMINING THE BEST INTERNAL WORKLOAD CALCULATION AND TIMEFRAME

This chapter is comprised of the following paper under final (minor) review in the *British Journal of Sports Medicine*.

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Reid M. Predictive modelling of injury in tennis: determining the best internal workload calculation and timeframe Br J Sports Med, **Under Final (minor) Review**.

6.1. LINKING PARAGRAPH

Studies 1 and 2 describe the nature of injuries (occurrence, region, severity) sustained by both elite junior and professional tennis players. However, missing from these studies are the identification of their aetiology. One of the primary risk factors for injury is overload from training and competition. The associations between load and injury have been investigated in sports such as Australian football, soccer, cricket and rugby league, though remains unexplored in tennis (25, 28, 29, 147). However, the workload models commonly adopted to explore the relationship to injury risk in these other sports have been criticised for their low validity and lack of physiological merit – leading to alternative models being recommended (30-34). In addition, few studies in any sports have assessed the ability of training loads to *predict* subsequent injuries rather than simply measure the *association*. The ability to predict injuries is important as it highlights the strength of a model in determining future injury outcomes rather than just the level of risk, as per association models. Therefore, Study 3 aimed to determine the best internal workload model and timeframe for predicting injuries in elite tennis.

6.2. ABSTRACT

Aim: To determine the best internal workload model and timeframe to predict injury in elite tennis. **Methods:** Daily training loads, recorded as session-RPE, and injury incidence data (2012-2016) from nationally ranked tennis players ($n = 101$, 19.1 ± 2.8 y, 91 ± 112 national ranking) were obtained. Injuries included those where any day of training or matchplay was restricted or lost. Multiple workload metrics, including variations of ACWR and EWMA as well as daily loads, monotony and strain were assessed over numerous timeframes (8 time points between 1-60 days) to predict subsequent injury. Predictive performance of the models was assessed via AUC of ROC curves and reported as $AUC \pm 95\%$ confidence limits, sensitivity and specificity. **Results:** The daily rolling average load and EWMA models performed best ($\geq 0.76 \pm 0.04$ AUC), largely owing to predicting non-cases rather than injuries (≥ 0.16 sensitivity, ≥ 0.74 specificity). There were no predictive differences between timeframes. All other models performed relatively poorly ($0.50-0.66 \pm 0.0$). Non-injured players experienced higher loads compared to injured players (mean $\pm$ SD; 714 ± 521 au, 565 ± 426 au). **Conclusions:** The best predictive workload-injury models used daily rolling averages and EWMA regardless of the tested timeframes. This suggests the load model selection is more important than the timeframe selection for predicting injuries in tennis. The performance of these models was primarily determined by the accurate prediction of non-cases, where loads were higher. All other models performed poorly, including ACWR, highlighting the importance of establishing sport-specific predictive models for injuries rather than adopting those from other sports.

6.3. INTRODUCTION

In elite junior and senior level tennis, players contest between 22-35 officially sanctioned tournaments per calendar year(35), frequently including repeated transcontinental travel. Therefore, preparation time is sparse, often only equating to 30% of the time that players are in competition (35). These intensive scheduling demands, coupled with the repetitive and high velocity joint and muscle actions that underpin stroke and movement production in tennis (35, 41) pose injury risk (65). A growing body of evidence has highlighted the epidemiology of injuries among elite tennis players (10, 181), however, the aetiology of such injuries is unknown. Workloads have been utilised as a measure of injury risk in many sports, yet the relationship of workloads and injury in tennis has not been examined.

The relationship between workload and injury has been the source of considerable investigative interest; with evidence from sports including cricket, rugby and Australian football showing varying levels of association between particular external and internal workload profiles and injury (25, 30, 31, 147). For example, a doubling of injury risk was evident in the subsequent week of cricket when there was a spike in balls bowled (as a measure of external load) in the current week (25). The same injury risk was observed when loads were reported as an internal load via sRPE (3). Whilst internal and external loads have also been acutely described in tennis (6), there has been no reported association or prediction of injury. Additionally, measurement of external load in tennis is difficult owing to the limited validity of global positioning system technologies for tennis, the impracticality of manual notation and the absence of validated inertial racquet-mounted technologies (145). Therefore, markers of internal tennis load that are more readily available, such as sRPE (3), represent an important initial step in the analysis of the workload–injury relationship in tennis.

Conceptually, the origins of the recent load and injury relationship research can be traced back to the fitness-fatigue model of Banister et al. (1975). This model describes the dose-response relationship to training, where a performance outcome is based on the difference in a positive fitness response to negative fatigue response (151). Similarly, the ACWR (147) is an adapted representation of the positive fitness (chronic load) and negative fatigue (acute load) response to training. In this case, injury rather than performance is the outcome measure, raising speculation over the relevant application of the Banister fitness-fatigue model to such contexts (151). Selected timeframes of acute (1-week) and chronic (4-weeks) loads presented in the literature have also been criticised as being arbitrarily allocated to fatigue and fitness respectively (30). Given these criticisms, recent variations in the calculation and timeframes of daily load metrics have been suggested as better indicators of injury risk, than the common ACWR calculated over 7 and 28-days (30, 31, 33, 34). These include an incorporation of a decay factor (33) to the quantification of load over time, as well as the utilisation of monotony and strain to account for variability in training loads and training stress (155). The removal of acute load from chronic load calculation has also been recommended (34). Additionally, the ability to predict injuries from workload, rather than just assess the injury risk, is important in determining future injury outcomes (sensitivity) and non-cases (specificity)(31). This level of insight can guide the optimisation of training loads to minimise injury risk. However, findings in Australian football and soccer highlight current limitations with the ACWR to accurately predict true positive and negative injury cases (31, 32). As reference, Fanchini et al. (2018) found the injury predictive ability of ACWR in soccer to be similar to chance. As the load-injury relationship in tennis remains unexplored, determining the most appropriate load calculation method and timeframe to predict tennis injury seems an obvious place to start. Therefore, the objective of this study was to compare the prediction accuracy of different models using internal training load (sRPE; (3)), over multiple timeframes, on the musculoskeletal injuries of elite junior and senior tennis players.

6.4. METHODS

6.4.1. PARTICIPANTS

The study was conducted as part of Tennis Australia's injury surveillance program and included 101 players (58 males, 43 females, mean $\pm$ SD age, 19.1 ± 2.8 y). Players were ranked domestically (91 ± 112), and held international junior ($n = 97$; 499 ± 577) and/or senior ($n = 59$; 583 ± 537) rankings. The following proportion of participants competed in the five individual competitive seasons: all ($n = 27$), four ($n = 11$), three ($n = 23$) and two ($n = 40$). Given the year-round but highly individualised nature of tournament tennis, systematic control of the competition and training schedules was not possible (35). Age-appropriate informed consent, from each participant or guardian, was obtained and ethics were approved by Australian Catholic University Human Ethics Committee.

6.4.2. PATIENT INVOLVEMENT

Patients were not involved in setting the research agenda as the outcomes are targeted towards tennis coaches, strength and conditioning coaches and practitioners working with the participants.

6.4.3. DEFINING INJURY

Injuries were medically diagnosed and defined as sport incapacity, whereby a player was sidelined or restricted due to the inability to perform planned training or matchplay based on loss or abnormality of bodily structure or functioning (164). Recurrent injuries, also coded in the dataset, were defined as an injury to the same region and linked to an initial injury which occurred after a player's full return to participation from the initial injury (163). The current study used OSICS to classify injuries (159). Tennis injury records were maintained by the organisation's physiotherapists and medical doctors. As the relationship between injury

region/type and workload was not the focus of the current study, all injuries were aggregated in the same way.

6.4.4. INTERNAL WORKLOAD AND INJURY DATA COLLATION AND MODELLING

Internal workload was defined as sRPE (3) with RPE obtained from the Borg CR10 scale (47) 30-minutes post-session utilising a mobile phone application accessible to all players. All workload and injury data on each player over the five-year period was compiled. Daily workload values were then utilised to test the injury prediction performance of the seven workload metrics. The metrics were (a) rolling average of daily loads, (b) ACWR, (c) ACWR with the acute load omitted from the chronic load calculation, (d) EWMA, e) EWMA with the acute load omitted from the chronic load calculation, (f) monotony, g) strain. Both (c) and (e) were tested due to the existence of mathematical coupling (34) in metrics (b) and (d) as the acute timeframe is included in both the numerator and denominator. The load calculation and selected timeframes for each model are featured in Table 17.

Table 17: Load metrics and timeframes modelled to determine the injury prediction accuracy

Model	Acute timeframes (days)	Chronic timeframes (days)	Formula
a) Rolling averages of daily load	1, 3, 5, 7, 14, 21, 28, 60	NA	Rolling average of total daily load for each timeframe (W1)
b) Acute to chronic workload ratios using rolling averages	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$W1/0.25 \times (W1 + W2 + W3 + W4)$
c) Acute to chronic workload ratios with the acute load omitted from the chronic load calculation (34)	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$ACWR = W1/0.25 \times (W2 + W3 + W4 - W1)$
d) Exponentially weighted moving averages (154)	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$ $\lambda_a = 2/(N+1)$ $EWMA \text{ ACWR} = EWMA_{acute}/EWMA_{chronic}$
e) Exponentially weighted moving averages with the acute load omitted from the chronic load calculation (34, 154)	1, 3, 4, 7, 14, 21	7, 14, 21, 28, 60	$EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$ $\lambda_a = 2/(N+1)$ $EWMA \text{ ACWR} = EWMA_{acute}/EWMA_{(chronic - acute)}$
f) Monotony	1, 3, 5, 7, 14, 21, 28, 60	NA	W1/Standard Deviation of W1
g) Strain	1, 3, 5, 7, 14, 21, 28, 60	NA	$(W1/\text{Standard Deviation of } W1) \times \text{Load}$

6.4.5. *MISSING DATA*

The retrospective and applied setting for which the data was obtained resulted in missing data (53%). To increase the power and accuracy of the study analysis in the presence of missingness, multiple imputations for training load were conducted, which is appropriate and justified for longitudinal data (165). To strengthen the imputation procedure, the available training loads for each subject were assessed for normality prior to imputation. The variability in each subject's available training loads was replicated within the imputations. Five imputations were undertaken, as recommended by Allison (2000), and were developed in R Statistics using the 'Amelia' package (165). The mean value of the five imputations for each data point was included in the final dataset for analysis. Sex (male or female), state of training (Australian states), ranking (national), tournament or training week, tournament/training location (home state or away) as well as loads experienced pre and post the missing days were factored into the imputation calculations to assign the most appropriate load values.

6.4.6. *STATISTICAL ANALYSES*

All modelling was conducted in R Statistics (R Core Team, 2012) using the dplyr, lme4, zoo, pROC, ROCR and caret packages. For each workload method, a logistic regression model was fit relating the workload method to injury. In order to test the predictive performance, sequential training and testing of the models was performed. This involved fitting the logistic model for every month of the last two years of data, using the most recent three years of training in each case. The assessment of loads in the lead up to a recurrent injury were omitted to assess the performance of each load metric and timeframe to initial injury outcomes. To evaluate the overall performance of each model, AUC of ROC curves were utilised, including all two years of test outcomes obtained from the sequential training and testing approach. The AUC summarises the discriminative ability of each model across a full range of sensitivity and specificity cut-offs (167) which refer to the detection of true positives and true negative

respectively (167). Therefore, the $AUC \pm 95\%$ CI determined the predictive ability of each model, with a perfect predictive model equating to an $AUC = 1$, and a model performing the equivalent of chance corresponding to an $AUC = 0.5$ (167). The sensitivity and specificity values for each of the model and timeframe outcomes were utilised to assess the performance of each model in detecting injuries (true positives) and non-cases (true negatives)(167). To determine the comparative predictive strength of the model outcomes, the AUC CIs were assessed. If there was no overlap between models or timeframes, then a difference was established (168). However, if the CIs between models and timeframes overlapped, the difference between models was not considered to be practically important (168). To determine the direction of each models relationship to injury, the training load dataset was split into deciles. The models and timeframes were then rerun only including the top (highest) and bottom (lowest) deciles individually. The change in the model outcomes, compared to the global model outcome, determined the direction of each model and timeframe to injury. Specifically, the changes in the sensitivity and specificity value alongside the AUC changes.

6.5. RESULTS

6.5.1. INJURY DETAILS

There were 327 male and 258 female injuries over the time period which equated to 2.8 and 2.7 injuries per 1,000 exposure hours respectively.

6.5.2. MODEL PERFORMANCE

The rolling average of daily loads and EWMA were the best performing models with AUCs of $\geq 0.76 \pm 0.04$ (Figure 14 and 15). There was no practical important difference between these models across all timeframes (Figure 14 and 15, Table 18 and 19). The sensitivity (0.16

- 0.22) and specificity (0.74 - 0.79) scores suggest that both models performed better in detecting non-cases (true negatives) rather than injuries (true positives; Table 18 and 19). The predictive ability of all ACWR timeframes, ACWR and EWMA with the acute load omitted from the chronic load calculation as well as strain were poor, with outcomes similar to chance (AUCs: 0.50 - 0.61 $\pm$ 0.05; Figure 14 and 15). The monotony model showed variability in predictive ability by timeframe with monotony calculated over 60-days performing better than all other monotony timeframes (0.66 $\pm$ 0.05; Figure 15). Similarly, performance was improved in detecting non-injuries as opposed to the occurrence of injury (Table 18 and 19).

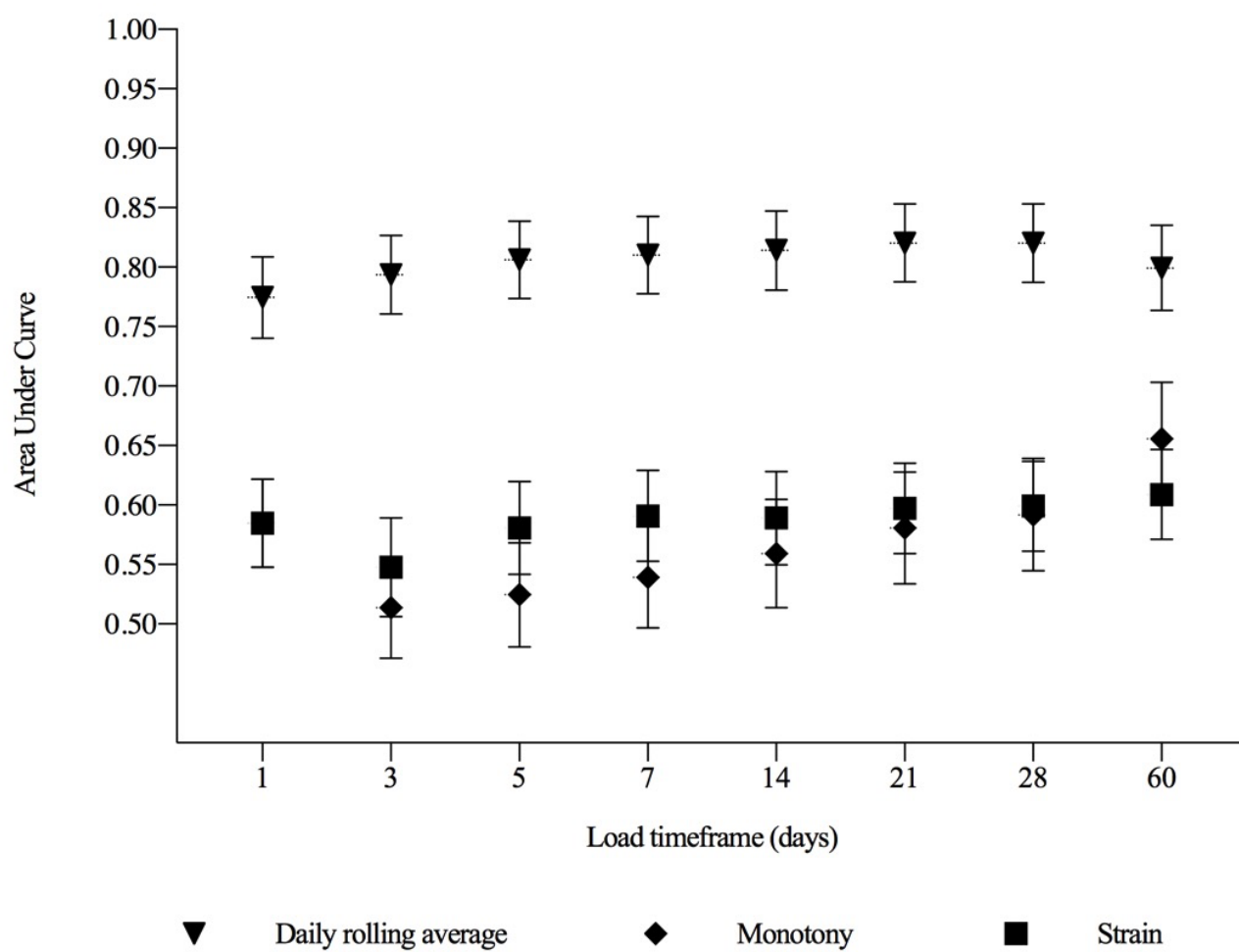


Figure 14: Area under the curve values ($\pm$ 95% confidence interval) for daily rolling average (a), monotony (f) and strain (g) models

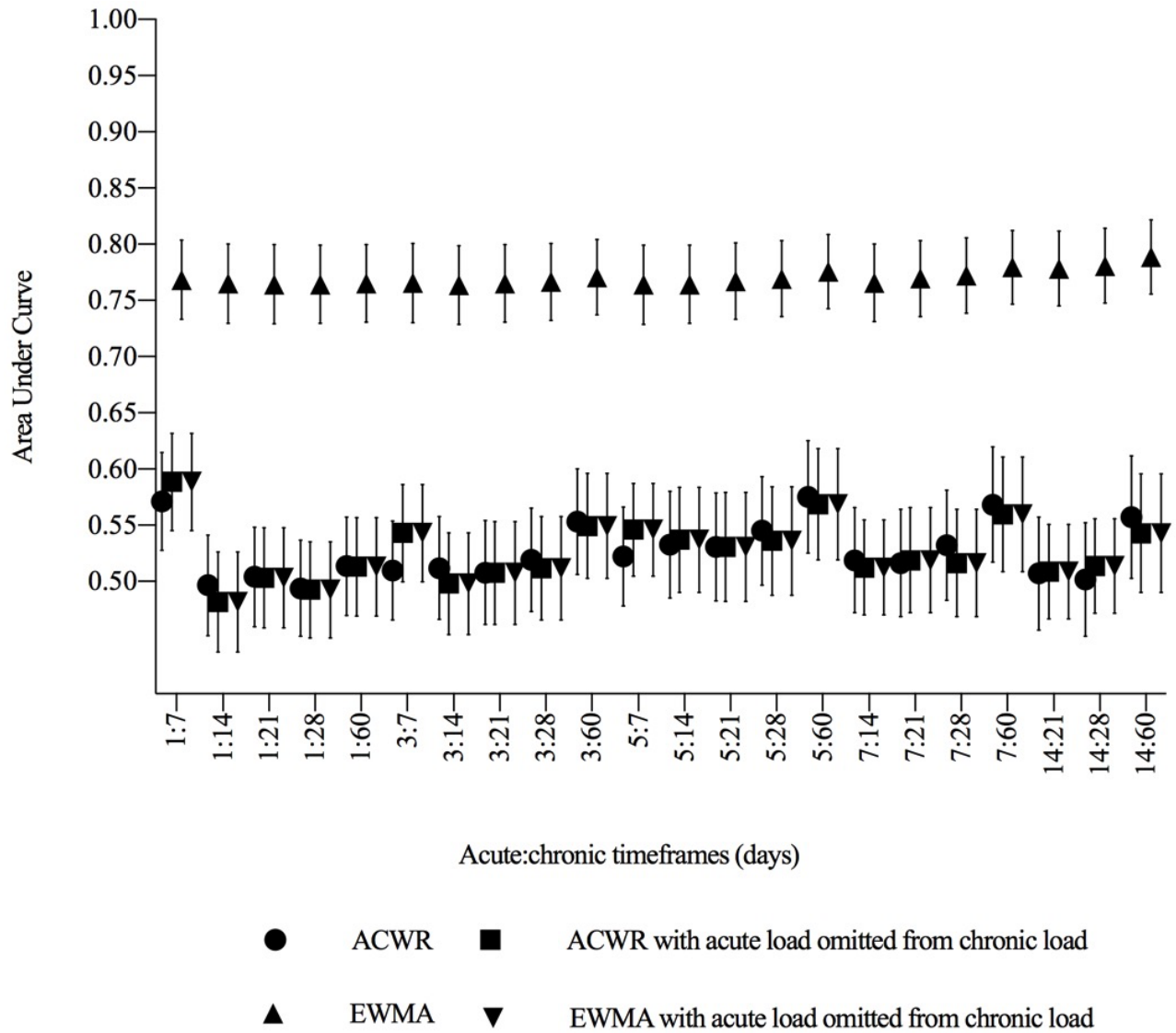


Figure 15: Area under the curve values ($\pm$ 95% confidence interval) for ACWR (b), ACWR with acute load omitted from chronic load (c), EWMA (d) and EWMA with acute load omitted from chronic load (e) models

Table 18: Sensitivity and specificity values for daily rolling average, monotony and strain models over all timeframes

Timeframe (days)	Daily Rolling Average		Monotony		Strain	
	Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity	Specificity
1	0.16	0.74	0.08	0.58	0.08	0.60
3	0.18	0.76	0.07	0.52	0.07	0.54
5	0.20	0.77	0.07	0.52	0.08	0.60
7	0.20	0.77	0.07	0.54	0.08	0.60
14	0.21	0.77	0.07	0.55	0.08	0.60
21	0.22	0.78	0.07	0.57	0.08	0.61
28	0.22	0.78	0.08	0.57	0.08	0.61
60	0.22	0.76	0.08	0.64	0.08	0.62

Sensitivity: true positive values divided by all positive values, specificity: true negative values divided by all negative values

Table 19: Sensitivity and specificity values for ACWR, ACWR acute omitted from chronic, EWMA and EWMA acute omitted from chronic models over all timeframes

Timeframes (acute:chronic)	ACWR		ACWR acute omitted from chronic		EWMA		EWMA acute omitted from chronic	
	Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity	Specificity
1:7	0.07	0.56	0.07	0.58	0.18	0.77	0.08	0.60
1:14	0.07	0.48	0.07	0.48	0.17	0.77	0.07	0.48
1:21	0.07	0.51	0.07	0.51	0.17	0.76	0.07	0.50
1:28	0.07	0.50	0.07	0.50	0.17	0.76	0.07	0.49
1:60	0.07	0.53	0.07	0.52	0.17	0.77	0.07	0.50
3:7	0.07	0.48	0.07	0.54	0.18	0.77	0.07	0.56
3:14	0.07	0.52	0.07	0.48	0.17	0.76	0.07	0.50
3:21	0.07	0.52	0.07	0.52	0.17	0.77	0.07	0.50
3:28	0.07	0.53	0.07	0.52	0.17	0.77	0.07	0.50
3:60	0.07	0.57	0.07	0.56	0.17	0.77	0.07	0.54
5:7	0.07	0.53	0.07	0.54	0.17	0.76	0.07	0.55
5:14	0.07	0.55	0.07	0.55	0.17	0.76	0.07	0.54
5:21	0.07	0.55	0.07	0.55	0.17	0.77	0.07	0.53
5:28	0.07	0.56	0.07	0.55	0.17	0.77	0.07	0.54
5:60	0.07	0.59	0.07	0.58	0.18	0.78	0.07	0.57
7:14	0.07	0.54	0.07	0.51	0.17	0.77	0.07	0.51
7:21	0.07	0.54	0.07	0.59	0.17	0.77	0.07	0.52
7:28	0.07	0.54	0.07	0.54	0.18	0.77	0.07	0.52
7:60	0.07	0.58	0.07	0.57	0.18	0.78	0.07	0.56
14:21	0.07	0.49	0.07	0.51	0.18	0.78	0.07	0.51
14:28	0.07	0.49	0.07	0.51	0.18	0.78	0.07	0.51
14:60	0.07	0.54	0.07	0.53	0.19	0.79	0.07	0.55

Sensitivity: true positive values divided by all positive values, specificity: true negative values divided by all negative value

6.5.3. *DIRECTION OF LOAD AND INJURY RELATIONSHIPS*

Non-injured players experienced higher loads than injured players with mean $\pm$ standard deviation loads of 714 ± 521 au as compared to 565 ± 426 au respectively. AUCs, sensitivity and specificity of the top (highest) decile, as compared to the initial model outcomes showed a 0.01 - 0.03 increase in AUC with a 0.04 - 0.07 increase in specificity values without a change in sensitivity values across all models and timeframes. Conversely, the AUCs of the bottom (lowest) decile displayed a 0.01 - 0.04 reduction with a 0.02 - 0.08 reduction in specificity values compared to the initial models with, again, no change in sensitivity.

6.6. DISCUSSION

The aim of this study was to assess the injury prediction accuracy of various internal load metrics, across different timeframes, among a cohort of elite tennis players. The rolling average of daily loads and EWMA models were the best performing models with the ability to detect at least 76% of injury outcomes, primarily non-cases. The loads experienced by the players were higher when an injury did not occur. This suggests that uninjured players are more tolerant to higher training loads which deserves further exploration. There was no difference in the predictive ability between any tested timeframes of the daily rolling average and EWMA models indicating that model selection may be more important than timeframe selection. All other tested models performed relatively poorly in predicting injury outcomes, including the ACWR model over all examined timeframes (<58% of injury outcomes). Consequently, the use of rolling average or EWMA may be the most appropriate approach when using daily internal load (sRPE; (3)) to assess workload related injury risk in tennis. Further, given the use of the ACWR model in many sports, the poor predictive results might prompt reconsideration of the status quo.

6.6.1. INJURY PREDICTION ABILITY OF WORKLOAD METRICS IN TENNIS VERSUS THOSE ADOPTED IN OTHER SPORTS

The most commonly adopted load metric for assessing injury risk in both team and individual sports is ACWR (25, 147, 189) with 7-day (1-week) acute loads and 28-day (4-weeks) chronic loads the most common timeframes. These timeframes are justified by classic micro and mesocycle training and competition durations of the relevant sports but are arbitrary in their capture of fatigue and fitness (189). However, when assessing the injury *prediction* performance of ACWR over a variety of timeframes, these findings show the model has limited predictive ability in tennis (AUC: $<0.58 \pm 0.05$). Such low predictive strength may relate to recent criticisms that the ACWR misrepresents the Banister Fitness-Fatigue model. Specifically, the use of injury rather than performance as the outcome represents a different paradigm, resulting in poor injury prediction ability. Additionally, it may highlight the lack of physiological evidence to support selected timeframes of fatigue and fitness resulting in the inability to detect injury. However, further exploration is needed to justify these suppositions. Consequently, although an association to injury risk has been established in some sports (25, 147, 189), the ability to predict injuries with ACWRs in tennis is not supported by this study.

Other models tested appear to have greater predictive performance. That is, rolling average of daily loads and EWMA provide alternative approaches with stronger predictive outcomes in tennis. These approaches predicted 76-82% of observations and non-observations, independent of the tested timeframes. An explanation of why the daily rolling average and EWMA performed better than ACWR may appear in the way acute loads are accounted for in the calculations. Daily rolling averages only capture an individual (acute) load without the inclusion of an underlying chronic load. Additionally, although the EWMA model includes a chronic load, it assigns a higher weighting to more recent loads. This is different to the ACWR which considers each acute and chronic day to have the same influence on injury risk.

Furthermore, both rolling averages and EWMA have been reported as good predictors of injury in other sports (33, 152). Specifically, weekly rolling averages performed well in determining injuries in rugby league players, and EWMA was found to be relatively sensitive at detecting injuries in Australian football (33, 152).

Of interest, this study found a clear difference in the predictive ability of the EWMA model with and without the acute load included in the chronic load calculation. Specifically, the inclusion of acute load in the chronic calculation improved the model's performance. The reason for the difference may also be an artefact of the importance and weighting of the acute load, or perhaps that both models are being assessed for predictive ability rather than association. As a prediction model aims to predict future outcomes rather than testing the explanatory ability, as per an association model, the existence of mathematical coupling does not interfere with the predictive testing (34). This highlights the importance of injury aetiology studies to be explicit in their methodological approach and subsequent interpretation of their findings. Regardless, the outcomes of this study suggest that daily rolling average and EWMA load metrics are more effective in injury prediction than ACWR, in tennis.

However, it must be noted that the performance of daily rolling average and EWMA models is mostly attributed to detecting when injuries did not occur as opposed to when they did. Nevertheless, when interpreted alongside the finding that loads were higher in non-cases, practitioners can yield meaningful insight for injury prevention. As the loads experienced were higher when players were uninjured/healthy, this might suggest that these players have a better load tolerance, potentially due to greater physical capacity. However, further investigation is needed to support this suggestion.

6.6.2. THE INJURY PREDICTION ABILITY OF MONOTONY AND STRAIN IN TENNIS

Monotony and strain, measures of training load variability and stress (155), performed poorly in predicting injury outcomes in this cohort. Most timeframes delivered outcomes marginally better than chance, with one exception being monotony assessed over 60-days reporting a fair injury prediction accuracy (AUC: 0.66 ± 0.05). Again, this performance is largely owing to the prediction of non-cases. Interestingly, Carey et al. (2018) also reported poor predictive power for monotony in Australian football, suggesting that certain athletes can tolerate repetitive training without impacting on injury risk. Furthermore, it is important to note that both the Carey study as well as the current study considered monotony and strain calculated per day and not per session (31). The sessional calculation of monotony and strain may better reflect within day variability and stress (155) and improve the predictive performance of these models. The incorporation of a decay factor as per EWMA, may also change the monotony and strain model outcomes and should be explored in the context of load variability and stress as it relates to injury in tennis.

6.6.3. POSSIBILITIES FOR IMPROVING THE MODELS PREDICTIVE PERFORMANCE

There is great complexity in the injury epidemiology and potential aetiology in tennis. As described by Reid et al. (2018), there are clear differences in the mechanical loads experienced and tolerated by the upper and lower limbs in tennis. As such, quantifying loads in tennis to determine an injury outcome may need to include different metrics. For example, the number of strokes hit may be a relevant external load measure for the assessment of upper limb injuries, while distance covered or the type and magnitude of change of direction may have the same utility for lower limb injuries (187). Therefore, using internal training loads to predict injury as is done in this study, may be strengthened by limb-specific external load measures. Additionally, an exploration of the training loads experienced during training versus competition, as well as load during rehabilitation from injury, may produce different

predictive outcomes for subsequent injury (88). Therefore, developing a predictive model that encapsulates all types of training periods may enhance its performance.

6.6.4. LIMITATIONS

The main limitation of this study is missing workload data. This is a result of the retrospective and ‘real world’ nature of the data collection. As abovementioned, multiple imputations were utilised to overcome the level of missingness with as much rigour as possible (166, 167). A second limitation may be the inclusion of all players in the dataset without clustering by age, sex, physical capacity, injury region and or/type or competition phase. This may limit the findings for a targeted cohort and should be considered for future research. Another limitation is the class imbalance of the dataset whereby the majority of outcomes were non-cases rather than cases. Therefore, the performance of the models is skewed as is evident by the high specificity values compared to sensitivity values. Lastly, a potential limitation may be born out of a reduction in loads after an initial injury. Particularly, during the rehabilitation phase of injury the ability of players to tolerate high loads may diminish and this may not be adequately captured in the data upon their return to full training. Theoretically, this could result in lower load prescription whilst physical capacity is redeveloped or, alternatively, players reporting higher RPEs (and sRPEs) for the same external load. Therefore, this may have impacted on the loads included in the model calculations for subsequent injuries.

6.7. CONCLUSION

Workload models calculated as daily rolling averages and EWMA were the best predictors of subsequent injury and non-injury in elite tennis players. There was no difference in timeframe dependent model performance, suggesting that model selection is more important. Although

the adoption of ACWR is common practice in many sports, this study highlights that alternative models are more suitable for injury prediction in tennis. Critically, the rolling average and EWMA models performed better in predicting when injuries did not occur as compared to when they did occur. This, combined with the finding that loads were higher when players were uninjured suggests these players may be able to tolerate higher loads and this should form the basis of future research.

6.8. WHAT ARE THE NEW FINDINGS?

- The rolling average of daily loads and EWMA models were the best performing workload models in this study with no difference between models or timeframes suggesting load metric selection is more important than timeframe selection.
- The ACWR across all tested timeframes had poor injury predictive ability in tennis.
- Non-injured players experienced higher loads as compared to injured players suggesting a load tolerance.

7. CHAPTER 7: STUDY 4 - MULTIVARIATE MODELLING OF INTRINSIC AND EXTRINSIC RISK FACTORS TO INJURY IN ELITE JUNIOR TENNIS PLAYERS

This chapter is comprised of the following paper under review in the *British Journal of Sports Medicine*.

Gescheit DT, Cormack SJ, Duffield R, Kovalchik S, Kemp J, Reid M. Multivariate modelling of intrinsic and extrinsic risk factors to injury in elite junior tennis players. *Br J Sports Med*, **Under Review**.

7.1. LINKING CHAPTER

Study 3 highlighted that internal loads, calculated as daily rolling averages and exponentially weighted moving averages, are able to predict non-cases (true negatives) in elite junior players. Whilst these findings represent a first exploration of the relationship between workload and injury, the lack of utility of this model may be an artefact of the univariate analysis of internal loads and injury. That is, as injuries are complex and multifactorial (7, 8), univariate approaches may oversimplify the injury paradigm in tennis. Consequently, Study 4 aimed to understand what combination of risk factors were most associated with injury in elite junior tennis players. In particular, sex, age, playing standard, competition phase, internal and external workloads, wellbeing, physical capacity and musculoskeletal function were assessed for their interrelationship and association with injury. The results of which can help to guide the selection of factors that should be monitored when assessing injury risk among elite junior players in a national tennis program.

7.2. ABSTRACT

Aim: To determine the association of intrinsic and extrinsic risk factors with injuries in elite junior tennis players. **Methods:** Daily training loads, training types, perceptual wellbeing and soreness, as well as baseline musculoskeletal function and physical capacity measures were collected between 2017-2018 from junior players in a national program (26 males, 23 females, mean $\pm$ SD age 15.6 ± 2.0 y, peak national ranking 143 ± 128). Training loads included serve counts and sRPE calculated as daily load and 21-day rolling average in the lead up to injury. Injuries ($n = 78$) included those where training or matchplay days were restricted or lost. Univariate Cox Proportional Hazard models determined the first factor in the forward step selection for the multivariate Cox Proportional Hazard model. The multivariate model determined the aggregated factors that had the best strength of association to injury with results reported as hazard ratios $\pm$ 95% CI. **Results:** The multivariate analysis revealed that a lower serve count (-0.02 ± 0.00) and more body-regions with soreness on day of injury (0.84 ± 0.48), combined with lower multistage fitness test score (-0.46 ± 0.23) and slower modified 505 COD speed test (3.47 ± 2.88) were best at detecting injury hazard. **Conclusions:** The interplay of serve loads, regions of body soreness, aerobic capacity and COD speed provided the highest association with injury. Therefore, injury risk is greatest in players with limited pre-existing physical capacities, coupled with lower serve loads and more soreness on day of injury. These risk factors have currency as injury prevention and training monitoring tools in high-performance tennis.

7.3. INTRODUCTION

Elite junior tennis player development incorporates large volumes of on- and off-court training within congested yearly tournament schedules (35). These volumes, and the high variability in week-to-week training and competition demands (based on the knock-out format of most tennis tournaments), may manifest in injury risk that limits the performance and progression of players (35). Historically, individual risk factors have been associated with injury in junior tennis players; including age, sex, physical growth and a variety of specific musculoskeletal function and physical capacity tests (12, 16, 20, 79, 97). However, injuries are multifactorial (17) and awareness of the inter-relationship of risk factors on tennis player susceptibility to injury is critical but remains unexplored.

Precursors to injury can include non-modifiable and modifiable intrinsic risk factors; such as age, sex, musculoskeletal function, physical capacity, perceptual wellbeing and playing standard (17). Conversely, extrinsic injury risk factors can include the volume, type and intensity of training and matchplay (17). Understanding the effects of these risk factors on injury informs the use of screening tools and the monitoring of appropriate measures over time (20, 97). For example, reduced hip range of motion in female tennis players was associated with abdominal strain injuries (20). Although this is informative for the monitoring of a univariate risk factor, other factors such as age, sex and training loads may have also had an impact on the abdominal injuries, yet were unexplored (20).

While multifactorial approaches to assessing injuries in other sports are common (23, 24, 190), such research in tennis remains sparse. For example, across 16 other sports, a rise in training volume and intensity coupled with a decrease in sleep duration resulted in a higher injury risk in elite youth athletes (24). Additionally, slower and less agile female rugby

players with hip flexor tightness were at higher risk of injury (190). Moreover, Australian footballers with lower chronic loads coupled with high running distances were at greater injury risk (23). Such findings show the interaction between intrinsic and extrinsic risk factors, particularly those that profile the physical capacity, perceptual wellbeing and training loads of athletes (23, 24, 190). Therefore, the modelling of multiple injury risk factors in tennis is critical to understand injury risk and provide guidance for the monitoring of appropriate risk factors in training and competition.

Consequently, the aim of this study was to model the relationship of intrinsic and extrinsic risk factors with injury in elite junior tennis players. Specifically, player demographics, workloads, training type, characteristics of the musculoskeletal system, physical capacity, national tennis ranking and perceived wellbeing was modelled with the aim of determining which aggregation of these risk factors has the best strength of association to subsequent injury.

7.4. METHODS

7.4.1. PARTICIPANTS

Twenty-six male (15.5 ± 1.6 y) and 23 female (15.6 ± 2.3 y) nationally-supported junior tennis players with mean peak national rankings of 173 ± 140 and 112 ± 115 respectively, participated in the study. The study period included a 500-day period from the start of 2017 through to mid-2018 when all players were actively part of the national program. The systematic control of player competition and training schedules was not possible due to the applied setting of the study. Informed consent was obtained from all participant guardians as all players were under the age of 18. The Australian Catholic University's human ethics committee approved the study (2015-192E).

7.4.2. PATIENT INVOLVEMENT

Patients were not involved in setting the research agenda. However, results will be disseminated to all participants via an infographic as well as the continual targeted monitoring of the associated risk factors.

7.4.3. RISK FACTORS

Both extrinsic and intrinsic risk factors were collected during the study period for all participants. Extrinsic risk factors included external and internal training loads quantified via serve counts and sRPE (3) respectively. These were collected via athlete self-reporting in a custom built mobile phone application after the final training session/match of each day (Table 20). Athlete self-reported serve load was selected owing to resource burden of manual notation and the scarcity of validated tennis-specific inertial technologies (145) limiting the capture of other external load measures. Yet, athlete self-reporting of daily external loads are routinely performed in other sports and show appropriate validity as a count of actions in tennis (169). Internal sRPE loads were classified as on-court or off-court (i.e. gym, conditioning) loads; with on-court loads categorised as training or competitive matchplay load. Both internal and external loads were quantified as raw total daily values on the day of injury as well as the rolling average of the previous 21-days in the lead up to injury. The rolling average of the previous 21-days was selected based on unpublished observations suggesting this load metric and timeframe has some injury prediction ability in a similar cohort of tennis players (Study 3).

Non-modifiable intrinsic risk included sex, and age calculated at the start of the data collection period. Modifiable intrinsic risk factors comprised daily wellbeing ratings, baseline physical capacity and musculoskeletal function measures and playing standard assessed via

peak national ranking during the study period. Daily wellbeing included each player's self-reported assessment of sleep quality, mood, worry, fatigue and appetite (114), as well as perceived body region soreness and corresponding magnitude. These measures were entered in the same mobile phone application as the reported training loads 30min post-waking on a 0-10 Likert scale, where 10 was the best score and 0 the worst (170). Sleep duration was obtained in the same way and reported to the nearest 30min. Physical capacity measures included a 5m and 20m sprint test, modified 505 COD speed test (94), vertical jump and maximal multistage 20m shuttle run test (95) (Table 20). Only single time point physical capacity measures existed and are treated as baseline measures recorded at the start of the data collection period. Similarly, baseline musculoskeletal screening measures including assessments of joint pain, strength and flexibility, were obtained for each player by a qualified physiotherapist (Table 20). The same physiotherapist undertook all musculoskeletal screenings to ensure intra-rater reliability ($ICC > 0.83$, $CV\% < 8.6$).

Table 20: Musculoskeletal screening, fitness testing and training load measures and frequency of capture

Risk factor	Description	Unit of measure	Frequency of data capture
Musculoskeletal screening battery			
Dominant single leg squat	Unilateral lower limb mobility and strength	1: good, 2: fair, 3: poor	At baseline
Thoracic overhead extension	Thoracic flexibility	1: within normal limits, 2: stiff, 3: hypermobile	At baseline
Scapula dyskinesis	Scapula function in flexion	1: normal, 2: abnormal	At baseline
Glenohumeral internal rotation deficit	Difference in shoulder range of motions	degrees difference	At baseline
Dominant supine hip internal rotation	Hip internal rotation	1: within normal limits, 2: stiff, 3: hypermobile	At baseline
Dominant supine hip external rotation	Hip external rotation	1: within normal limits, 2: stiff, 3: hypermobile	At baseline
Squeeze test	Hip adduction	1: good, 2: fair, 3: poor	At baseline
Dominant Thomas test	Hip extension	1: above horizontal, 2: horizontal, 3: below horizontal	At baseline
Fitness testing battery			
5m sprint	Acceleration	seconds	At baseline
20m sprint	Speed	seconds	At baseline
Dominant side modified 505 change of direction speed test (94)	Change of direction speed test from stationary start	seconds	At baseline
Double leg vertical jump height	Leg power	cm	At baseline
Maximal multistage 20m shuttle run test score (95)	Aerobic capacity	decimal score	At baseline
Load measures			
Total Load	Internal load	sRPE	Daily
On-court load	Tennis internal load	sRPE	Daily
Off-court load	Gym internal load	sRPE	Daily
21 day rolling average total load	Internal load	sRPE	Daily
21 day rolling average on-court load	Tennis internal load	sRPE	Daily
21 day rolling average off-court load	Gym internal load	sRPE	Daily
Serve count	Number of serves hit	count	Daily
21 day rolling average serve count	Number of serves hit	sRPE	Daily

7.4.4. INJURY DEFINITION

Injuries were defined as sport incapacity, whereby a player was sidelined or restricted due to the inability to perform planned training or matchplay based on loss or abnormality of bodily structure or functioning (164). Recurrent injuries were recorded as injuries of the same type and to the same region as a preceding initial injury. However, recurrent injuries were not included in the analysis due to potential training load and tournament scheduling adaptations as a result of an initial injury which may have impacted the assessment of these variables in the modelling (64). Additionally, only musculoskeletal injuries were included in the dataset (lacerations/abrasions, bruising/haematomas and illnesses were omitted) to ensure that the injuries were more directly attributable to risk factors. All injuries were treated equally in the analysis. The time to injury was counted as the number of days to injury from the start of the assessment period.

7.4.5. DATA PRE-PROCESSING

Multiple steps were needed to prepare the data for analysis. As is common in applied elite sport research, the training load and wellbeing data were incomplete. To enhance the accuracy and power of the modelling, multiple ($n = 5$)(166) imputations were utilized to combat the missingness which is appropriate for longitudinal data (165). The imputations were developed using the ‘Amelia’ package (165) in R Statistics (R Core Team, 2012). The normality of distribution of the observed data for each imputed training load and wellbeing variable was initially examined, with all variables being normally distributed. Sex, peak national ranking, competition phase (tournament or training day) as well as each preceding variable with imputed data were utilized in the subsequent imputation to best determine each assigned imputed value. The mean of the five imputations for each missing data point was adopted in the complete dataset for analysis.

7.4.6. COLLINEARITY

Highly correlated risk factors can violate the multivariate model outcomes (171). Therefore, the collinearity of each variable to each other was assessed via Pearson's correlations and Chi-Square analysis in R statistics (R Core Team, 2012). Interestingly, all fitness testing and musculoskeletal screening measure outcomes which were tested on both the dominant and non-dominant side of the athlete had very strong collinear relationships ($r > 0.80$)(172). Additionally, 5m and 10m sprint outcomes were strongly correlated ($r = 0.91$). Subsequently, one variable in each collinear pair was omitted from the dataset. The dominant side measure was retained for all collinear pairs tested on each side of the body, as well as the 5m sprint time due to this distance being more specific to the sprint distance demands in tennis matchplay as compared to 10m (173).

7.4.7. STATISTICAL ANALYSES

All statistical analyses were conducted in R statistics (R Core Team, 2012) using the dplyr and survival packages. Cox Proportional Hazards models was used to investigate the association between the injury outcome and one or more of the predictor variables, namely the risk factors, via a forward step selection process (171). A univariate Cox analysis of each risk factor was conducted initially to determine the first factor in forward step selection process for the multivariate analysis, with the most statistically significant variable selected ($p < 0.05$ in Wald test)(171). The corresponding effect was added to the multivariate model and the process repeated until none of the remaining variables met the significance level in association to both injury and the other significant effects (171). Results are reported at HR $\pm$ 95% CI.

7.5. RESULTS

7.5.1. INJURY PROFILE

There were 78 injuries during the study period, with 18 males and 19 females incurring an injury. Twenty-three athletes incurred more than one injury during the time period and twelve athletes did not suffer an injury at all. The mean time to injury within the collection period was 235 ± 145 days, with the mean age of the injured cohort being 15.2 ± 2.1 years.

7.5.2. UNIVARIATE COX ANALYSIS FOR FIRST FACTOR OF THE FORWARD STEP SELECTION PROCESS FOR THE MULTIVARIATE ANALYSIS

The initial univariate Cox analysis to determine the first step in the forward step selection resulted in significant associations of the maximal multistage 20m shuttle run test score (-0.17 ± 0.14), serve count (-0.01 ± 0.01), count of body areas reported sore (0.42 ± 0.33) and the mean soreness score (0.17 ± 0.13) with injury (Table 21). Serve count had the strongest association with musculoskeletal injury ($p = 0.01$) and was therefore selected as the first step for the multivariate Cox analysis.

Table 21: Univariate Cox Proportional Hazard model outcomes including Hazard Ratios (HR) $\pm$ 95% Confidence Intervals and p values

Parameter	Univariate models		
	HR	$\pm$ 95% CI	P value
Age	-0.10	0.11	0.09
Sex	0.38	0.46	0.10
Schedule mode	0.03	0.74	0.93
Ranking group	0.08	0.12	0.19
Dominant single leg squat	0.24	0.36	0.19
Thoracic overhead extension	-0.16	0.50	0.53
Scapula dyskinesis	-0.15	0.48	0.54
Glenohumeral internal rotation deficit	-0.02	0.02	0.06
Dominant supine hip internal rotation	0.16	0.33	0.34
Dominant supine hip external rotation	0.11	0.54	0.69
Squeeze test	0.30	0.33	0.08
Dominant Thomas test	-0.15	0.32	0.35
5m sprint	-0.49	2.36	0.69
20m sprint	-0.67	0.92	0.16
Dominant side modified 505 change of direction speed test	0.49	1.45	0.51
Double leg vertical jump height	-0.01	0.03	0.56
Beep test score	-0.17	0.14	0.02
Hours of sleep	-0.01	0.33	0.96
Rating of appetite	0.12	0.25	0.17
Rating of worry	-0.05	0.25	0.70
Rating of mood	<0.01	0.25	0.99
Rating of sleep quality	-0.04	0.22	0.75
Rating of fatigue	0.02	0.20	0.87
Total Load	<0.01	<0.01	0.75
On-court load	<-0.01	<0.01	0.73
Off-court load	<0.01	<0.01	0.56
21 day rolling average total load	<0.01	<0.01	0.68
21 day rolling average on-court load	<0.01	<0.01	0.75
21 day rolling average off-court load	<0.01	<0.01	0.77
Serve count	-0.01	0.01	0.01
21 day rolling average serve count	-0.00	0.01	0.16
Areas of soreness	0.42	0.33	0.01
Average rating of soreness	0.17	0.13	0.01

7.5.3. MULTIVARIATE COX ANALYSIS

The multivariate Cox model analysis showed lower serve count (-0.02 ± 0.00), more body regions reported as sore (0.84 ± 0.48), a lower multistage 20m shuttle run test score (-0.46 ± 0.23) and a slower modified 505 COD speed test time (3.47 ± 2.88) were significantly and collectively associated to injury (Table 22).

Table 22: Steps in Multivariate Cox Proportional Hazard model including Hazard Ratios (HR) $\pm$ 95% Confidence Intervals and p values

Parameter	Multivariate models			
	HR	±95% CI	P value	
Step 1				
Serve Count	-0.01	0.01	0.01	
Step 2				
Serve Count	-0.01	0.01	<0.01	
Count of areas of soreness	0.67	0.38	<0.01	
Step 3				
Serve Count	-0.02	<0.01	<0.01	
Count of areas of soreness	0.82	0.44	<0.01	
Beep test	-0.36	0.21	<0.01	
Step 4				
Serve Count	-0.02	<0.01	<0.01	
Count of areas of soreness	0.84	0.48	<0.01	
Beep test	-0.46	0.23	<0.01	
Dominant side modified 505 change of direction speed test	3.47	2.88	0.02	

7.6. DISCUSSION

The aim of the study was to determine which combination of intrinsic and extrinsic risk factors best explain injury risk in a national junior tennis program. Specifically, the association of age, sex, training load, musculoskeletal function, physical capacity, peak national ranking and daily wellbeing ratings to subsequent injury were explored. The multivariate model that best explained the injury hazard in elite junior tennis players included lower serve counts, a greater number of perceived sore body regions, lower aerobic capacity

and slower COD speed. Correspondingly, this study also suggests that other risk factors such as internal load, musculoskeletal function, age, sex, ranking and competition phase may not add to the understanding of the injury risk in elite junior tennis.

7.6.1. LOW SERVE LOADS AND INJURY

The serve has commonly been reported to elevate injury risk in tennis players, primarily due to the repetitive large ranges of motion, multi-joint loading and rotational speeds demanded of the stroke (191). Therefore, lower serve loads being associated with subsequent injury seems counterintuitive. Previous studies show that acute mechanical overhead loads may heighten injury risk in the subsequent days (146, 192). Correspondingly, baseball pitchers were also more susceptible to injury in the 72h following a bout of high-volume pitching (146). These findings, coupled with the repetitive nature and mechanics of serve, suggests a heightened risk of injury following high serve loads which may continue to manifest even when overhead loads are reduced. The timeframes of serve load quantification in this study fail to explicitly explore loads in the days prior to injury beyond the 21-day rolling average. As such, the low serve load on day of injury may have been precautionary due to the perceived risk of injury from a previous high load bout not captured in the dataset. However, further exploration of the serve and training loads in the days prior to an injury is needed to explicitly understand the relationship between low serve loads and injury.

7.6.2. BODY SORENESS AND INJURY

Alongside low recent serve load, a higher number of sore body areas was found to be associated with injury risk. Isolated body regions with reported muscle soreness have been commonly associated with injury in sport (124, 193). For example, it has been shown that shoulder soreness in elite female water polo players is associated with ensuing injury (193), while higher lower-limb ratings of soreness have been found to increase injury risk in elite

footballers (124). In tennis, multi-match day and consecutive day matches have also shown spikes in perceived soreness coupled with elevated muscle damage markers (6, 52). Perceived soreness can form in response to the physical movement patterns (i.e. high eccentric loads) or represent resultant muscle damage (119, 123). The specific mechanism of how perceived soreness is associated to injury has been attributed to either a psychological stress response or a by-product of a physiological stress response (119, 194). Regardless of explicit cause or load, increased perceived ratings of body soreness were evident on the day of injury and, thus, should be monitored as in elite junior tennis players.

7.6.3. AEROBIC CAPACITY, CHANGE OF DIRECTION SPEED AND INJURY

Both aerobic capacity and COD speed have been associated with elite tennis performance (93, 195), though their relationship with injury remains unknown. However, limited aerobic capacity and COD speed have been consistently shown to increase injury risk in other sports including Australian football, rugby league, rugby sevens and ballet (97, 98, 148, 190). Explanations for the associations found in this study may relate to the high physical and movement demands of elite competitive tennis and the undefined duration of matches (6, 173). Specifically, players undertake an average of four COD per point and compete in matches lasting from 1 to 5+ hours (6, 173). This may limit the ability of players with lower aerobic capacity and slower COD speed to achieve optimal court placement for repetitive ball strikes over an extended period of time (173). Such reoccurring demands may compromise movement mechanics resulting in overload of the musculoskeletal system (126). Of note, COD speed was not associated with injury in the univariate analysis in this study; suggesting that it is only when slower COD speed is coupled with other variables, including lower aerobic capacity, as well as low serve loads and more widespread body soreness, that it becomes an important risk factor for injury.

7.6.4. THE COMBINED RELATIONSHIP OF THESE RISK FACTORS TO INJURY

While we have explored the rationale linking each individual risk factor to injury, the unique aspect of this study is their collective association to injury in elite tennis players. As abovementioned, players with lower aerobic capacity and slower COD speed may be less able to tolerate the demands of elite tennis which requires both high fitness levels and explosive changes of direction (35). This may heighten the risk of injury by way of inefficient movement patterns and/or musculoskeletal overload (126) which can result in an increased levels of physiological and/or perceptual soreness (6). As a result of the soreness itself, or the perception of greater injury risk due to soreness, physiotherapist, coaches or the athletes themselves may reduce serve loads on the day of injury. Alternatively, players may be unable to perform more serves on day of injury due to the accumulation of physical and perceived stress from the other risk factors. However, the time-course and sequence of events in the lead up to injury needs to be further explored to comprehensively understand these complex interactions.

7.6.5. RISK FACTORS NOT IN THE MODEL

An understanding of why certain risk factors did not have an association to injury in this study is also informative for decision-making regarding the resourcing and monitoring of such factors. For example, no measure of internal load featured in the multivariate model. Perhaps the inclusion of an external load measure in the model limited the influence of internal load in explaining injury hazard. Correspondingly, the explanatory power of external loads over internal loads, as found in this study, is consistent with findings in soccer (196). Interestingly however, the opposite was found in cricket (25). In addition to internal loads, no musculoskeletal function or wellbeing measures (excluding soreness areas) were shown to be associated with injury hazard. This may be attributable to the wellbeing data only being assessed on the day of injury and musculoskeletal screenings only conducted at the start of the study period. This may not be frequent enough, or miss the important time-capture window to

influence injury risk. Though in support, the lack of association between wellbeing and musculoskeletal screening measures and injury is evident in a multivariate analyses of injury risk factors in Australian football (23).

Additionally, sex, ranking, competition phase (training versus tournament) and age did not contribute to the injury risk in this cohort. The association between sex and injury risk in tennis literature is inconclusive (16, 181). Therefore, this may suggest that both sexes are equally susceptible to injury risk rendering it a factor unable to assist in further explain why such injuries occur. Additionally, the narrow range in players' peak national rankings may have limited the ability for the model to differentiate playing standards which could have hindered its association to injury. Furthermore, it has been found that there is a greater prominence of injuries during competition as compared to training (14). Injuries in competition are generally acute in nature, whereas injuries during training are typically chronic (14). However, the nature of the injuries (acute or chronic) in this study were not categorized. Similarly, a relationship between age and injury has been shown previously, with older junior athletes likely to sustain more injuries (12). This is commonly attributed to a rise in injury risk during peak height velocity (79). Therefore, it may have been expected that age would feature in this study's multivariate model. However, the period of data capture may have been too short to determine within-player physical adaptations with age.

7.6.6. LIMITATIONS

There are a number of limitations that may have impacted the results in this study. Firstly, the measure of serve load is not a complete profile of external load, which may include total groundstrokes hit, on-court activity profile metrics (i.e. speed and distance) or off-court training (i.e. tonnage from strength training). Unfortunately, these variables were unavailable due to data collection and technological limitations. With the advent of Hawkeye technology

(142) and wearable inertial sensors (145), the ability to quantify global external load measures will become more accessible. Missing data was also apparent due to challenges with player compliance of data entry. Specifically, across the internal training load, serve load and wellbeing measures, the level of available data was 71%. However, as abovementioned, an appropriate statistical technique was utilised to combat this (165, 166). Additionally, the small dataset limited the statistical power to undertake a corresponding prediction model (197). This would have provided further insight into the specificity and sensitivity of the model and should be explored on a larger dataset. Also, as the start of the study period was aligned to the start of a calendar year, the time to injury must be considered a limitation due to a computational approach to timeframe selection. The limitation of timeframe selection may also be apparent in the load measure calculations. As only the load on day of injury as well as the rolling average of the previous 21-days were captured, the model fails to consider the relationship of alternative load timeframes in the lead up to injury which may have affected the multivariate model outcome.

7.7. CONCLUSION

The combination of low serve loads, more perceived widespread body soreness, low aerobic capacity and slow COD speed are the combined factors most associated with injury in elite junior tennis players. The findings also suggest that internal load, age, sex, musculoskeletal function, national ranking and competition phase do not improve injury hazard detection in junior elite tennis players if the other variables are monitored. Therefore, this provides tennis and physical performance coaches, as well as medical staff, direction for the targeted monitoring of risk factors and the subsequent develop injury prevention and training strategies to mitigate injury risk.

7.8. WHAT ARE THE NEW FINDINGS?

- The aggregation of low serve counts, more body sites with perceived soreness, lower aerobic capacity and slower change of direction speed are the factors most associated with injury in a national elite junior tennis program.
- Internal training loads (sRPE) do not provide any further insights on injury hazard in elite junior tennis players when external load, measure via daily serve count, is monitored in conjunction with soreness areas, aerobic capacity and change of direction speed.
- Musculoskeletal screenings, sex, age, ranking and competition phase do not assist in understanding injury risk in elite junior tennis players when serve load, soreness areas and physical capacity are monitored collectively.

8. CHAPTER 8: DISCUSSION AND CONCLUSIONS

8.1. THESIS AIMS

This thesis investigated a more detailed epidemiological profile of elite junior and adult tennis, as well as the aetiology of injuries via univariate and multivariate analyses of risk factors. Specifically, Studies 1 and 2 provided a comprehensive account of the in-event injury epidemiology at the Australian Open Grand Slam, the pinnacle of the tennis pathway, as well as within a junior national program, which feeds that pathway. Studies 1 and 2 were needed given previous attempts to profile elite junior and adult injuries are limited in their methodological design as well as consistency and comparability of findings (9-11, 15, 36). Specifically, key factors such as injury severity and changes over time in injury incidence were missing, and exposure measure selection limited the interpretation and comparison of the findings (9-11, 15, 36). Accordingly, Studies 1 and 2 assessed these factors in both elite junior and adult cohorts to subsequently provide a more descriptive addition to the existing tennis injury epidemiology research. These findings also highlight the commonalities and differences between injuries across the entire elite tennis pathway which has implications for short and long-term injury prevention strategies.

While more detailed descriptions of elite tennis injuries are important, an understanding of why these injuries occur is more informative for the development of targeted and holistic injury prevention strategies. However, the current literature on injury aetiology in elite tennis is sparse (12); a gap that Studies 3 and 4 aimed to address. Specifically, Study 3 assessed the load-injury relationship in elite tennis which has not been examined in tennis previously but is well researched in many elite sports (25, 29, 148). The methodological approaches undertaken in other sports, as well as recent criticisms in the calculation and interpretation of the load-

injury relationship (30-34) were utilised to develop the aim and approach of Study 3. Subsequently, a series of univariate analyses were undertaken to determine the best internal load metric and timeframe to predict injuries in elite tennis. The findings provide alternative workload monitoring approaches to what has previously been established in other sports. Although these outcomes are insightful and practical, the assessment of internal loads in isolation may oversimplify the dynamic and complex nature of injuries (7, 8). Consequently, Study 4 aimed to build on Study 3 through a multivariate assessment of risk factors to injury in elite tennis. The risk factors explored are commonly utilised in elite sport, but are resource-laden in their administration and ongoing monitoring. Therefore, the findings from Study 4 provide holistic and pragmatic outcomes for tennis stakeholders in the selection of risk factors to quantify and monitor, as well as strategies to mitigate such risk.

8.2. KEY FINDINGS

8.2.1. *INJURY EPIDEMIOLOGY OF THE ELITE TENNIS PLAYER PATHWAY*

The findings of Studies 1 and 2 highlight consistencies in the body-region injury incidence throughout the elite tennis pathway. Specifically, the lumbar spine and shoulder were commonly and most severely injured independent of player sex, competition phase, playing standard and age. Injuries to both the lumbar spine and shoulder have frequently been linked to the physical demands of the tennis serve, which require large movement and rotational forces of both body-regions (198, 199). The finding that these injuries are present throughout the elite tennis player career suggests that previous attempts to mitigate shoulder and lumbar spine injuries in elite tennis have not been successful or that these injuries are seemingly part of player development within the sport (198, 199). Regardless of the effectiveness or lack of historical injury prevention strategies, both the lumbar spine and shoulder should be integrated into all injury prevention strategies throughout the elite tennis pathway.

Additionally, these findings suggest that the technical development of the serve, as well as the management of serve loads, should be closely monitored as they may be the impetus for lumbar spine and shoulder injuries and their long-term presence in both elite junior and adult tennis (42, 182, 199).

Alternatively, the comparative findings of Studies 1 and 2 highlight that there are sex differences in injury incidence by age, playing standard and competition phase. Specifically, no injury incidence sex differences were found in the junior cohort (total of 2.7 male injuries v 2.8 female injuries per 1,000 exposure hours), but female professionals competing at the Australian Open presented with more injuries than their male counterparts (total of 201.7 female injuries v 148.6 male injuries per 10,000 game exposures). These sex-based injury incidences discrepancies across the pathway are consistent with conjecture in previous tennis injury epidemiology findings (9-11). Similarly, the severity of injuries found in Studies 1 and 2 varied. Junior male player injuries were more severe than those sustained by their female counterparts (3.6 v 1.1 days lost respectively), but there was no sex-difference in the treatment cost of injuries at the Australian Open (3.6 male v 1.1 female treatments per injury). These inconsistencies highlight that, beyond body-regions, the injury profile of elite tennis players changes throughout the course of the pathway. This is aligned to the sex-based discrepancies found in the existing body of literature (9-11, 19). Therefore, this suggests that injury incidence and severity by sex are unique to the cohort and/or may be impacted by other factors such as age. Specifically, the increase in injury incidence with age, as found in Study 2, may have confounded the sex injury incidence findings. In support, age has commonly been reported to be associated with injury in tennis and other sports (12, 14). It has been surmised that this association may be attributable to the physical growth of adolescents (68) or a rise in the volume and intensity of training and matchplay as players age (75). Regardless, the sex-based differences in elite junior and adult tennis injury incidence highlights risk groups of

players to direct the focus of injury prevention strategies. Additionally, these discrepancies suggest that tennis and physical preparation coaches, as well as medical staff working with select cohorts of elite tennis players need to explore and understand the unique sex-based injury patterns rather than rely on research which is not specific to their playing group.

The discrepancy in exposure measures selected may have also impacted on the sex differences between Studies 1 and 2. Specifically, 10,000 game exposures were utilised in Study 1 with 1,000 exposure hours adopted in Study 2. Therefore, the direct comparison of injury rates across studies is limited and fraught with potential error. The reason for the variation in exposure measures was largely owing to data availability, as well as an attempt to provide precision in the description of the training/match demands within the relevant populations. Inconsistency in exposure measure selection is common in tennis injury epidemiology literature (9, 10, 15). This is regardless of the fact that the consensus statement on epidemiological studies of medical conditions in tennis recommends the utilisation of 1,000 exposure hours to report injury rates (64). However, exposure hours overlooks the fact that external loads can vary between hours of training/matchplay (41, 44). Therefore, there is scope to improve the precision of exposure measure selection when reporting injury rates. To address this, Appendix 1 includes a supplementary discussion paper aligned to this thesis. The findings highlight that external workload measures, including distance covered and number of balls hit, are more precise in their description of match demands as compared to match duration. This outcome suggests that perhaps the recommended reporting of injuries per 1,000 exposure hour needs to be reconsidered. Whilst not an explicit aim of this thesis, the reporting of more granular and appropriate exposure measures for reporting injury incidence data is an important avenue for future research that underlies much of what is reported in the current thesis.

8.2.2. *ELITE TENNIS INJURY AETIOLOGY*

Studies 1 and 2, as well as the supplementary study in Appendix 1, provide new descriptive insights into the injury profile of elite tennis. Yet until now, the cause of these injuries, remained unexplored in tennis. As overload is commonly reported to be a common risk of injury in elite athletes, training loads have been heavily researched for their relationship to injury (25, 29, 147). However, this insight has been missing in tennis. With this gap in mind, Study 3 explored the internal workload-injury relationship in elite tennis. Internal training loads, calculated via daily rolling averages or EWMA, irrespective of timeframe, were able to predict a high proportion of non-injuries (true negatives) in an elite national tennis program. This suggests that model selection is more important than the timeframe selection when assessing tennis injuries using internal load. However, no model and timeframe performed well in predicting injuries (true positives) including ACWR, which is frequently used in many elite sports to assess the association to injury. This is consistent with recent findings in Australian football and soccer (31, 32) suggesting that sports should formulate their own load metric selection for injury prediction rather than simply adopting metrics from other sports.

Study 3 also discovered that non-injured players had higher loads across all models as compared to injured players. This may be an artefact of non-injured players having a higher load tolerance or having greater physical capacity – both of which are speculated to reduce the risk of injury in other sports (25, 97). Thus, the Study 4 findings suggesting lower aerobic capacity and slower COD speed heighten injury risk supports this concept. However, further investigation is needed given the cohorts, risk factor selection and data-capture timeframes assessed in Studies 3 and 4 are different which prevents categorical statements of their relationship with injury. Overall, the lack of injury prediction ability in Study 3, coupled with the higher loads experienced by non-injured players suggests that internal loads assessed in isolation may oversimplify the multifactorial nature of injuries (7, 8).

Therefore, analysis of a broader set of commonly measured risk factors, inclusive of internal *and* external loads, was undertaken in Study 4. The findings show that aerobic capacity, COD speed, external load in the form of serve counts, as well as perceived soreness have the strongest collective association to injury. The explicit mechanism for how these risk factors interrelate is unknown but it may be that players in poor physical condition are less able to tolerate the high fitness and explosive COD demands of elite tennis (41, 173). This may cause inefficient movement patterns and/or overload which can heighten injury risk and also result in greater perceived body soreness (6, 173). The soreness itself, or the perception of greater injury risk due to soreness, may result in physiotherapists, coaches or athletes themselves selecting to reduce serve loads on the day of injury. Alternatively, players may be unable to perform more serves on day of injury due to the accumulation of physical and perceived stress from the other risk factors. Regardless of the time-sequence of events, these risk factors should be monitored and managed to mitigate the risk of injury. Study 4 also highlighted that other measured risk factors such as age, sex, competition phase, playing standard, internal loads, musculoskeletal screening measures and perceived wellbeing measures did not improve the strength of the associations. The disparate sex findings between Studies 1 and 2 may explain why sex contributed little to the multivariate model. Additionally, age may not have assisted in detecting injury risk because the timeframe of Study 4 was not long enough to capture the impact of age on injury (as discussed in Study 2).

It is also of interest that internal loads, calculated in the same way as Study 3, did not feature in the multivariate model in the Study 4 outcome. This may be an artefact of the addition of an external load measure, in this case serve loads, or the combination of multiple risk factors in Study 4 which nullified the impact of internal loads on injury risk. The explanatory power of external loads over internal loads has also been found in professional soccer players (196). Therefore, further research on the dose-response relationship in elite tennis may assist in

providing greater insight. Regardless, the overall findings from Study 4 guide the selection of risk monitoring tools, question the efficacy and value of other techniques, and provide direction for injury prevention strategies.

8.3. LIMITATIONS

- There was a high level of missing data in both Studies 3 and 4. The ‘real world’ setting of these studies meant that the datasets were reliant on elite tennis players to input their daily training loads. These players undertake frequent international travel and also have competing interests, such as schoolwork and media commitments, which subsequently limited their data entry compliance. However, the statistical techniques to combat the missing data were robust and recommended for longitudinal study designs (166).
- The metric and time point selections in Study 4 may have impacted on the multivariate model results. Firstly, no measure of player strength was captured in the fitness testing battery which is an important physical capacity in tennis (35). Despite its potential importance, an assessment of strength in this playing group is not routinely conducted. Secondly, measures of fitness capacities and musculoskeletal screenings were only captured at baseline owing to the difficulty associated with capturing these measures more regularly. However, if measured more frequently, the outcomes of the multivariate model may have been different. Therefore, the relationship between the frequency and type of these measures and injury detection should be further explored.
- The assessment of changes over time in injury incidence in Study 2 is limited by the small dataset. This resulted in large confidence intervals and subsequent uncertainty in the interpretation of the results.
- Recurrent injuries were not included in Studies 3 and 4. As previous injury history is a risk factor for subsequent injuries (87), monitoring this may have adjusted the findings.

However, the loads experienced in the rehabilitation phase of an initial injury would have skewed the load measures resulting in an alternative limitation. Therefore, recurrent injuries and their respective loads were omitted for this reason.

- Peak height velocity was not included in Study 4 as it was not part of the anthropometry testings in the national program. As peak height velocity is a well reported injury risk (68), it may have impacted on the model outcomes.
- Only serve count was utilised as an external load measure in Study 4. Given serve count does not encapsulate a complete external load profile, a more complete representation of external load (e.g. speed and distance, total shot count) may have impacted the findings.
- The timeframes selected for the analysis of internal and external load data in Study 4 were dictated by the findings of Study 3. However, given the difference in variable selection and statistical modelling between studies, perhaps alternative timeframes should have been modelled in Study 4 to better understand the risk.
- The predictive strength of the multivariate model in Study 4 was unable to be assessed due to the small sample size limiting its statistical power.

8.4. PRACTICAL APPLICATIONS

The key outcomes of this body of research provide some practical insights for tennis players, coaches and medical/physiotherapy staff. Specifically:

- Guidance for in-event medical resourcing including staffing, equipment and referrals -
Based on the findings in Studies 1 and 2, decisions can be made about the number and type (i.e. specialists) of staff that need to be present on each day of a professional tennis event or in a national program. Additionally, the body-region and severity findings can highlight which injuries are likely to require more treatment and subsequently medical resourcing.

- Targeted injury prevention strategies by sex, age and body region - The findings from Studies 1 and 2 suggest injury prevention programs should place greater emphasis on professional female tennis players and older junior athletes. Additionally, the lumbar spine and shoulder should be the primarily focus of region-specific injury prevention programs, coupled with the development and management of serve loads.
- Workload selection, calculation and timeframe selection for the prediction of injuries and non-injuries - The findings from Study 3 suggest that daily rolling averages or EWMA, regardless of timeframe, could be utilised to predict non-injuries in elite tennis players. Additionally, the findings suggest that the ACWR should not be utilised in elite tennis.
- The selection of injury risk factors to monitor - Study 4 highlights that serve loads, perceived muscle soreness, aerobic capacity and change of direction speed should be monitored in elite tennis to determine injury risk. The findings provide guidance for the focus of on and off-court training including the monitoring of serve loads that mimic match serve loads, and the development of aerobic and COD capacities.
- Determination of risk factor efficacy and/or frequency of capture - The findings from Study 4 also provides insight into which risk factors may not need to be measured in elite tennis or warrant further exploration. Specifically, given musculoskeletal screening and fitness testing are laborious, time-consuming and resource-laden, perhaps the findings from Study 4 can guide decision-making around their breadth and frequency of capture.

8.5. RECOMMENDATIONS FOR FURTHER RESEARCH

The findings from this thesis provide numerous directions for future research which can enhance the broader understanding of what and why injuries occur in elite tennis.

Specifically:

- Examination of exposure measure selection for reporting injury rates is needed to provide more precision in the description of training/match demands.
- Given the wide confidence intervals describing injury incidence changes over time in Study 2, this should be explored further with a larger dataset.
- An adaptation of the monotony and strain calculations in Study 3 should be explored to better understand their predictive relationship to injury. Specifically, calculating session-to-session monotony, instead of daily monotony, may provide a more precise indication of training variability to improve injury prediction performance.
- The relationship between higher internal workloads and injury needs to be further analysed, particularly on account of the finding in Study 3 that non-injured players presented with higher load.
- The relationship between internal and external loads in tennis can be further scrutinised given internal loads displayed some predictive performance in Study 3 but did not feature in the multivariate model Study 4, yet serve load (an external load measure) did.
- The predictive ability of multifactorial models of elite tennis injury risk factors should be explored.
- The frequency and type (i.e. test of maximum strength, power, repeated effort ability) of fitness testing and musculoskeletal screening data capture should be investigated as it relates to injury risk in elite tennis.

8.6. CONCLUSIONS

This thesis provides a detailed description of the injury epidemiology of the elite tennis pathway particularly as it relates to sex, age and region injury incidence, as well as their severity and changes over time. Specifically, sex discrepancies in injury incidence and severity were found between elite junior and adult tennis players. Yet, there was consistency in the body-regions of injury with lumbar spine and shoulder injuries common and severe throughout the pathway. Additionally, injuries were found to increase with age in a junior national tennis program. The exploration of the aetiology of elite tennis injuries undertaken in this thesis suggests that, in isolation, internal loads calculated as daily rolling averages and EWMA have some predictive ability in determining injury non-cases in elite tennis. However, no model performed well in predicting injuries including the commonly adopted ACWR. Additionally, non-injured players had higher loads compared to those who were injured. These findings suggest that the univariate investigation of the internal load-injury relationship may oversimplify the multifactorial nature of injuries. Consequently, when the aetiology of elite tennis injuries was explored via multiple risk factors, the findings suggest that serve loads, perceived soreness, aerobic capacity and COD speed should be measured in elite tennis populations to mitigate the risk of injury. Overall, this thesis adds breadth to the injury epidemiological profile of elite tennis injuries and provides novel and practical understanding and outcomes of the aetiology of these injuries.

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APPENDIX I: SUPPLEMENTARY DISCUSSION PAPER - IMPROVING THE REPORTING OF TENNIS INJURIES: THE USE OF TIME OR WORKLOAD DATA AS THE DENOMINATOR?

Publication statement:

This appendix is comprised of the following Discussion paper published in the *British Journal of Sports Medicine* which is a supplementary paper to this thesis.

Reid M, Cormack SJ, Duffield R, Kovalchik S, Crespo M, Pluim B, **Gescheit DT**. Improving the reporting of tennis injuries: the use of workload data as the denominator? Br J Sports Med, doi: <http://dx.doi.org/10.1136/bjsports-2017-098625>.

Advances in technology have changed the way that we understand and consume sports performance. From an injury epidemiology perspective, the data generated from these technologies - particularly those related to player exposure or load - can also provide cause to reconsider accepted norms of how to report injury data. Using tennis as a case study, we highlight the opportunity for these new data to provide richer and more meaningful injury insights.

Historically, epidemiology researchers have identified bespoke units of measurement to express each sport's injury narrative. In 2009, respected industry professionals suggested that tennis injuries be reported per 1,000 player hours rather than athletic exposures (such as 1,000 matches) due to large variations in the time component of such exposures (64). This goes some way to addressing the lack of uniformity in tennis injury data, which McCurdie et al. (2016) have identified as the most significant challenge to understanding injury in elite tennis. However, given the streams of data now available, it seems timely to revisit whether this recommended choice of exposure remains as pertinent as it once was?

Gescheit et al. (2017) recently highlighted how the choice of exposure can influence study conclusions. For example, when comparing female muscle injury rates using game exposures (strongly correlated to match duration) versus set exposures at the Australian Open between 2011-16, they found 14% variation in the number of reported injuries over time. This finding, as with the initial recommendation from Pluim et al. (2009), support the selection of an exposure measure that represents the smallest common unit of matchplay, which may vary depending on the population of interest (professional vs junior) and technology accessible (Hawkeye vs match clock). Furthermore, given that the injuries sustained in tennis are a direct result of the mechanical loads imposed on the musculoskeletal system (200, 201), it seems

intuitive to consider different denominators in determining the rate of injury for different parts of the body. For example, some measure of ball striking should logically feature in an upper-limb/body exposure and distance run might be a more appropriate exposure measure for the lower-limb.

We analysed a subset of the data and aligned it with real-time multi-camera ball and player tracking (HawkEye data) from the corresponding professional tennis matches. The subset included absolute injury counts, while the HawkEye data included hitting volumes (the number of serves, groundstrokes and volleys played by both players), movement distances (the combined distance traversed by both players when the ball was in play) and durations (match time). A linear model was fit to each 2-way combination of exposure measures (duration-hitting volume, duration-distance, distance-hitting volume) and we examined the choice of exposure related to the strength of association (explained by variation from the r^2 statistic in a linear regression) (Figure 17 and Table 23).

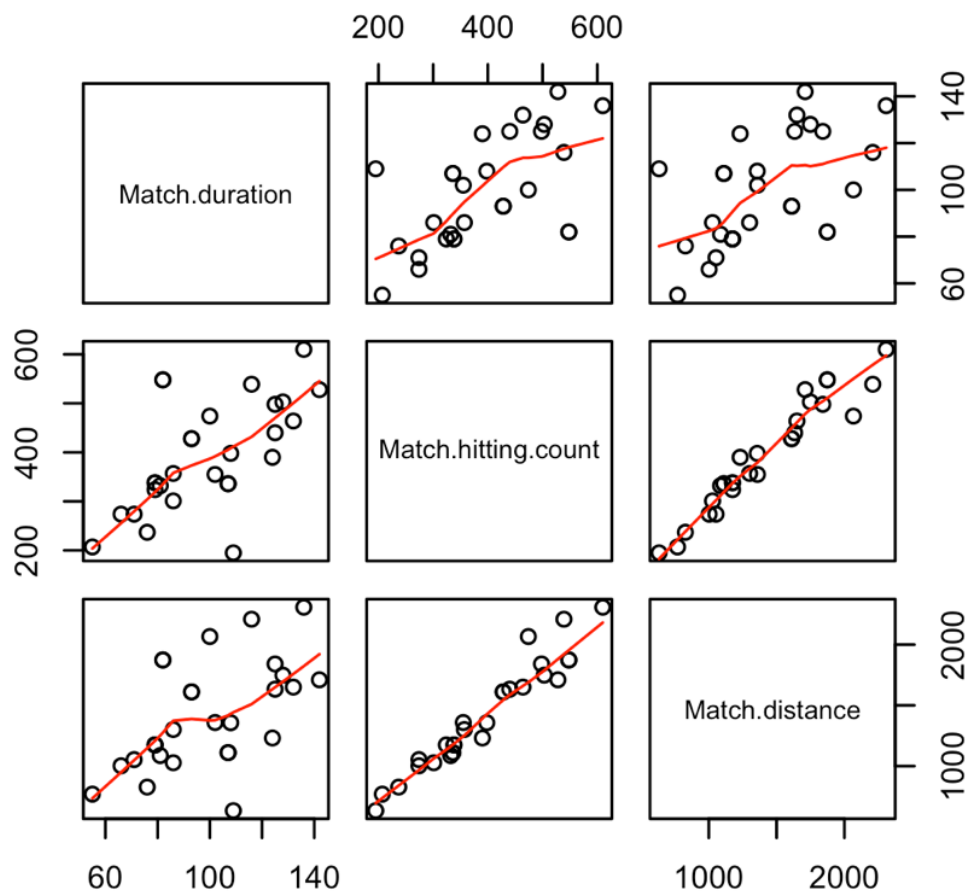


Figure 17: Scatterplot representation of the association between match duration, hitting count and distance in elite tennis matches

Table 23: Description of the strength of the associations between elite tennis match duration, hitting count and duration

Match variable 1	Match variable 2	r^2	σ^2
Match distance	Total shots	0.93	60.21
Match duration	Total shots	0.37	37.51
Match duration	Match distance	0.30	39.61

Match duration was only moderately related to hitting volume ($r^2 = 0.37$) and match distance ($r^2 = 0.30$), with only 37% and 30% of the respective variance explained. This questions the use of match duration as the gold standard measure of injury exposure at the professional level. Indeed, while match duration may hold some value in comparing gross injury trends between populations or represent the most pragmatic injury exposure measure for many junior or recreational tennis populations (where technology is constrained), it has limited utility in describing injury relative to the physical demands of professional tennis.

There was a much stronger association between match distance and hitting volume, our proxies for lower and upper-limb load. We believe that this can be interpreted in two ways. First, it might be that the lower and upper limb load in tennis are strongly correlated. Second, it may be that neither exposure measure adequately captures the intensity of the movement or stroke, which logically relates to joint loading and deserves further enquiry. Either way, these points reinforce the importance of selecting an exposure measure (denominator) based on the numerator of interest, which in our view, is often overlooked or oversimplified in tennis research. Although not something that we have entertained here, taken further, the type (joint v muscular) or mechanism (acute v chronic) of injury may even influence the denominator chosen.

So, how should tennis researchers report injury in the future? Fundamentally, the choice of exposure method needs to be tailored to the research question of interest, the population and technology available. To that end, our work here shows that the current norm of reporting injury rates relative to match time provides limited insight and should be reconsidered at the professional level. New workload data are promising in this regard as they may serve as denominators to more precisely inform the tennis injury debate.

APPENDIX II: RESEARCH PORTFOLIO

Publications

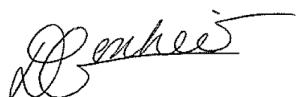
1. **Gescheit DT**, Cormack SJ, Duffield R, Kovalchik S, Wood TO, Omizzolo M, Reid M. Injury epidemiology of tennis players at the 2011–2016 Australian Open Grand Slam. Br J Sports Med 2017;51(17):1289-1294.

Please view the published version online at: <http://dx.doi.org/10.1136/bjsports-2016-097283>

Contribution statement: DG was primarily responsible for the design, data collection and analysis, and overall management of this project. All authors were involved in the concept and design of the study and preparation of the manuscript.

Approximate percentage contributions – D. Gescheit 75%, S. Cormack 5%, R. Duffield 5%, S. Kovalchik 5%, T. Wood 2.5%, M. Omizzolo 2.5%, M. Reid 5%.

I acknowledge that my contribution to the above publication is 75%:



Danielle Gescheit

Date 28/08/2018

As principal supervisor, I certify that the above contributions are true and correct:



Stuart Cormack

Date 28/08/2018

Co-author signatures:



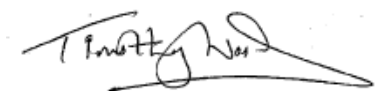
Rob Duffield

Date 28/08/2018



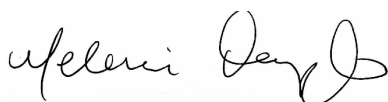
Stephanie Kovalchik

Date 28/08/2018



Tim Wood

Date 28/08/2018



Melanie Omizzolo

Date 28/08/2018



Machar Reid

Date 28/08/2018

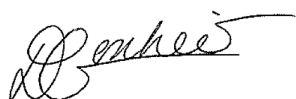
2. **Gescheit DT**, Cormack SJ, Duffield R, Kovalchik S, Wood TO, Omizzolo M, Reid M. A multi-year injury epidemiology analysis of an elite national junior tennis program. J Sci Med Sport 2018; In Press.

Please view the published version online at: <https://doi.org/10.1016/j.jsams.2018.06.006>

Contribution statement: DG was primarily responsible for the design, data collection and analysis, and overall management of this project. All authors were involved in the concept and design of the study and preparation of the manuscript.

Approximate percentage contributions – D. Gescheit 75%, S. Cormack 5%, R. Duffield 5%, S. Kovalchik 5%, T. Wood 2.5%, M. Omizzolo 2.5%, M. Reid 5%.

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Machar Reid

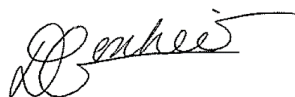
Date 28/08/2018

3. **Gescheit DT**, Cormack SJ, Duffield R, Kovalchik S, Reid M. Predictive modelling of injury in tennis: determining the best internal workload calculation and timeframe. Br J Sports Med, **Under Final (minor) Review**.

Contribution statement: DG was primarily responsible for the design, data collection and analysis, and overall management of this project. All authors were involved in the concept and design of the study and preparation of the manuscript.

Approximate percentage contributions – D. Gescheit 80%, S. Cormack 5%, R. Duffield 5%, S. Kovalchik 5%, M. Reid 5%.

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Date 28/08/2018

Co-author signatures:

A handwritten signature in black ink, appearing to be 'RD' or 'Rob Duffield'.

Rob Duffield

Date 28/08/2018

A handwritten signature in black ink, clearly legible as 'Stephanie Kovalchik'.

Stephanie Kovalchik

Date 28/08/2018

A handwritten signature in black ink, appearing to be 'Machar Reid'.

Machar Reid

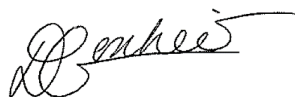
Date 28/08/2018

4. **Gescheit DT**, Cormack SJ, Duffield R, Kovalchik S, Kemp J, Reid M. Multivariate modelling of intrinsic and extrinsic risk factors to injury in elite junior tennis players. Br J Sports Med, **Under Review**.

Contribution statement: DG was primarily responsible for the design, data collection and analysis, and overall management of this project. All authors were involved in the concept and design of the study and preparation of the manuscript.

Approximate percentage contributions – D. Gescheit 75%, S. Cormack 5%, R. Duffield 5%, S. Kovalchik 5%, J. Kemp 5%, M. Reid 5%.

I acknowledge that my contribution to the above publication is 75%:



Danielle Gescheit

Date 28/08/2018

As principal supervisor, I certify that the above contributions are true and correct:



Stuart Cormack

Date 28/08/2018

Co-author signatures:

A handwritten signature in dark ink, appearing to be 'Rob Duffield', enclosed in a rectangular box.

Rob Duffield

Date 28/08/2018

A handwritten signature in dark ink, appearing to be 'Stephanie Kovalchik', enclosed in a rectangular box.

Stephanie Kovalchik

Date 28/08/2018

A handwritten signature in dark ink, appearing to be 'Justin Kemp', enclosed in a rectangular box.

Justin Kemp

Date 28/08/2018

A handwritten signature in dark ink, appearing to be 'Machar Reid', enclosed in a rectangular box.

Machar Reid

Date 28/08/2018

5. Reid M, Cormack SJ, Duffield R, Kovalchik S, Crespo M, Pluim B, **Gescheit DT**.

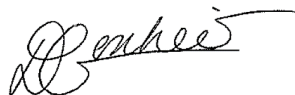
Improving the reporting of tennis injuries: the use of workload data as the denominator? Br J Sports Med, bjsports-2017.

Please view the published version online at: <http://dx.doi.org/10.1136/bjsports-2017-098625>

Contribution statement: MR, DG and SK were primarily responsible for the design, data collection and analysis, and overall management of this project. All authors were involved in the concept and design of the study and preparation of the manuscript.

Approximate percentage contributions – M. Reid 40%, S. Cormack 2.5%, R. Duffield 2.5%, S. Kovalchik 10%, M. Crespo 2.5%, B. Pluim 2.5%, D. Gescheit 40%

I acknowledge that my contribution to the above publication is 40%:



Danielle Gescheit

Date 28/08/2018

As principal supervisor, I certify that the above contributions are true and correct:



Stuart Cormack

Date 28/08/2018

Co-author signatures:

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Machar Reid

Date 28/08/2018

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Rob Duffield

Date 28/08/2018

A cursive signature that reads 'Stephanie Kovalchik'.

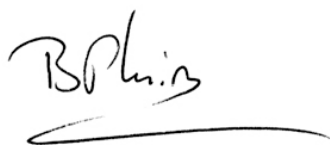
Stephanie Kovalchik

Date 28/08/2018

A cursive signature that reads 'Miguel Crespo'.

Miguel Crespo

Date 28/08/2018

A cursive signature that reads 'B. Pluim'.

Babette Pluim

Date 28/08/2018

APPENDIX III: ETHICS APPROVAL NUMBERS

Study 1 - ACU Human Ethics Committee Approval Number: 2015-200N

Study 2 - ACU Human Ethics Committee Approval Number: 2015-196N

Study 3 - ACU Human Ethics Committee Approval Number: 2015-198N

Study 4 - ACU Human Ethics Committee Approval Number: 2015-192E

APPENDIX IV: PARTICIPANT CONTRACT AND CONSENT FORM

Your Agreement to the Conditions of this Letter of Support

By signing below you confirm that you understand and agree with all obligations and terms contained in this Letter of Support and the Tennis Australia 2018 Standard Athlete Terms and Conditions including:

1. General Obligations
2. Anti- Doping Obligations
3. Tennis Integrity Obligations
4. Consent to treat you and store your Medical Records
5. Consent to use your Image Rights
6. Release and Indemnity
7. Confidentiality Obligations
8. Personal Information

A true and correct PDF signed copy of this Letter of Support may be used in place of the original for any purpose.

Signed by the Athlete:

(Athlete's signature)

(Name of Athlete)

Date

For Athletes under 18 only

As **Parent/Guardian of the Athlete** you acknowledge and agree to the terms of the Agreement on behalf of the Athlete (including the provision of consents and releases). You also agree to comply with and be bound by all Tennis Australia policies and understand that if you breach any of those policies and/or do anything which has the potential to bring the sport of tennis in Australia into disrepute TA may vary or remove the support provided to the Athlete under this Agreement.

(Parent/Guardian's signature)

(Name of Parent/Guardian)

Date

Annexure A
Tennis Australia 2017 Standard Athlete Terms and Conditions

Tennis Australia Limited ABN 61 006 281 125 (TA) is delighted to offer you (the **Athlete**) the benefits set out in your Letter of Support from 1 December 2017 - 31 December 2018 (**Term**) on the terms and conditions set out in your Letter of Support and in these Tennis Australia 2017 Standard Athlete Terms and Conditions (together the **'Agreement'**).

1. General obligations

1.1 You must:

- (a) comply with the terms of this Agreement and all TA and ITF policies, procedures, By-Laws, guidelines, rules and regulations, including the Anti-Doping Policy, Medication and Needles Policy, Supplements and Sports Food Policy, Member Protection Policy, Disciplinary Policy, Code of Behaviour, Tournaments & Competitions, Social Media Policy and other policies of which you are advised by TA;
- (b) not at any time be convicted of, or charged with, any serious offence involving violence, alcohol or drugs, or any sex offence, or any offence which is punishable by imprisonment;
- (c) advise TA of any injury you may have prior to entering into this Agreement or injury you sustain during the Term;
- (d) use TA preferred providers for health services unless otherwise agreed with TA;
- (e) subject to (f) below, advise TA after seeking treatment from any third party health service provider, including relevant details of any such treatment and/or medications;
- (f) provide TA with prior notice before seeking treatment from any third party health service provider in the case of musculoskeletal issues, and thereafter provide TA with the relevant details of any such treatment and/or medication;
- (g) be available for medical/physiotherapy screenings, physical testing, technical analysis and other research activities as requested by TA;
- (h) seek TA's consent prior to bringing any third parties (including, but not limited to, external coaching staff and third party allied health service providers) onto TAs premises to use National Academy facilities;
- (i) upon request by TA, complete surveys and/or participate in research administered or approved by TA, provided that you can withdraw that consent at any time in relation to any particular survey or research activity;
- (j) take out and maintain, at your cost, top level private hospital and ancillary health insurance and ambulance cover at all times and provide a copy to TA of such insurance; and
- (k) advise TA of any existing management, sponsorship or other endorsement contracts to which you are a party at the time of executing this Agreement, or which you enter into during the Term.

2. Anti-Doping Obligations

2.1 You agree:

- (a) that you are bound by and will comply with TA's Anti-Doping Policy (available at www.tennis.com.au/doc/tennis-australia-anti-doping-policy), the ITF Anti-Doping Policy, and the World Anti-Doping Code;
- (b) to truthfully make any statutory declarations regarding anti-doping matters as required by TA from time to time;
- (c) to achieve results of any medical assessment and testing requested by TA to the complete satisfaction of TA; and
- (d) to be available for sample collection and provide accurate and up to date whereabouts information on a regular basis to TA or directly to the ITF pursuant to the World Anti-Doping Code.

2.2 For the purposes of determining whether or not you have committed a violation of TA's Anti-Doping Policy you authorise TA and ASADA and their authorised officers to, during the Term of this Agreement:

- (a) search such bags and other items that you have in your possession whilst on TA property and at all TA training and competition venues;
- (b) search your clothing and person; and
- (c) take and retain any substance or evidence of a potential violation of TA's Anti-Doping Policy that they may discover as a result of such search and which they believe or suspect to be a substance or method prohibited under the World Anti-Doping Code.

2.3 You agree to fully co-operate and assist TA and ASADA, including by attending an interview and truthfully answer questions; provide information; and produce documents for any investigation being conducted by TA and ASADA, even if to do so may tend to incriminate you or expose you to a penalty, sanction or other disciplinary measure. Your obligations under this

- clause continue notwithstanding the conclusion or termination of this Agreement, to the extent that an investigation involves matters existing during the Term of this Agreement.
- 2.4 Nothing in this Agreement negates or detracts from your obligations, responsibilities and liability under TA's Anti-Doping Policy.

3. Tennis Integrity Obligations

- 3.1 You agree to comply with all the provisions of the Tennis Anti-Corruption Program (a copy of which is included in the 2017 Official Grand Slam® Rule Book) including but not limited to adhering to the prohibitions on gambling and betting and reporting any knowledge or suspicion of such behaviour to the Tennis Integrity Unit as soon as possible.
- 3.2 For the purposes of determining whether or not you have committed a violation of the Tennis Anti-Corruption Program you authorise TA, the Tennis Integrity Unit and their authorised officers to, during the Term of this Agreement:
- (a) search such bags and other items that you have in your possession whilst on TA property and at all TA training and competition venues;
 - (b) search your clothing and person; and
 - (c) take and retain any evidence of a potential violation of the Uniform Tennis Anti-Corruption Program that they may discover as a result of such search (including, without limitation, itemized telephone billing statements, text of SMS messages sent and received, banking statements, Internet service records, computers, hard drives and other electronic information storage devices).
- 3.3 You agree to fully co-operate and assist TA and the Tennis Integrity Unit, including by attending an interview and truthfully answer questions; provide information; and produce documents for any investigation being conducted by TA and/or the Tennis Integrity Unit, even if to do so may tend to incriminate you or expose you to a penalty, sanction or other disciplinary measure. Your obligations under this clause continue notwithstanding the conclusion or termination of this Agreement, to the extent that an investigation involves matters existing during the Term of this Agreement.

4. Consent to treat you and collect and store your Medical Records and Performance Data

- 4.1 You consent to TA's health service providers screening and treating you and collecting and storing records of consultation or treatment information and other personal information about you including your past, present and future health or medical records in any form. This may include information related to any injuries or illness for which you have received treatment, related treatment notes, related diagnostic test results and clinically significant findings associated with your medical care, whether created by TA or a third party and held on file by TA ("Medical Records") including by storing those Medical Records in TA's Athlete Management System ("AMS") subject to TA complying with relevant privacy and health records legislation.
- 4.2 You consent to TA disclosing your Medical Records to emergency medical providers, your coach and other relevant health professionals who require the information for purposes of treating you and to use your Medical Records for the purpose of assessing and improving TA's programs, and in surveys and research conducted or approved by TA.
- 4.3 You consent to TA providing your Medical Records to the ITF and ATP/WTA as well as TA obtaining your Medical Records from the ITF and ATP/WTA.
- 4.4 You also consent to TA collecting and storing your performance data and information in the AMS subject to TA complying with relevant privacy and health records legislation. You acknowledge that any information collected may be disclosed by TA to your coaches and other professionals who are involved in your coaching or training, for the purpose of administering TA's high performance programs generally, as well as for the purposes of assessing and improving TA's programs and research purposes (which may be on an anonymised basis).
- 4.5 You understand that you have no proprietary rights to or in the AMS or the Medical Records and other data entered into the AMS and that upon the termination or expiry of this Agreement, TA will retain a copy of all Medical Records for the purpose of assessing and improving TA's programs, and in surveys and research conducted or approved by TA and will otherwise deal with your Medical Records in accordance with applicable legislation.
- 4.6 If you have access to the AMS you must keep confidential all medical and health information contained in the AMS, except to the extent necessary to enable you to receive medical treatment.
- 4.7 You agree that the consents set out in this clause will survive termination or expiry of this Agreement and will be binding on you.

5. Consent to use your Image

- 5.1 Subject to law and to the extent permitted by law, and subject to clause 5.2, you consent to TA, its State Member Associations (MA) and TA's and each MA's respective coaches, trainers officers, employees, contractors, representatives, agents and assignees: taking, using, distributing, copying, modifying, sub-licensing and otherwise dealing with any images and footage of you (including without limitation photographs, electronic images, sound recordings,

visual footage audio-visual footage and any other reproductions), obtained in connection with this Agreement, including without limitation obtained at TA or MA premises, National Academy environments, public or government premises, during your participation in TA and MA events or any other tennis matches, during tennis training, activities, camps, tours and national teams/competitions in any platform or format whatsoever (including without limitation TA's restricted systems and platforms, or publicly accessible platforms such as the internet and social media channels) in perpetuity world-wide for any purpose in TA's discretion (including without limitation for coaching, teaching, technical analysis, promotional, advertising or marketing purposes) without payment to you (**the Image Rights**). You agree to assign all copyright and all other intellectual property rights in the Image Rights to TA.

- 5.2 You agree that TA may allow the use of your Image Rights by TA partners in promotional, advertising or marketing materials for the purposes of advertising their association with TA. TA acknowledges that if you have a conflicting commercial arrangement you may by notification to TA withdraw your consent to such particular use of your Image Rights by TA partners.

6. Release and Indemnity

- 6.1 You acknowledge the risks associated with your participation in TA activities (both on TA and any third party's property) and accept those risks knowingly and voluntarily.
- 6.2 You agree not to sue and hereby release, indemnify and keep indemnified TA, its officers, directors, employees, representatives and agents of and from any and all claims, demands, suits, however arising that you may have for or as a result of loss of your life, injury, damage or loss of any description whatsoever and however caused that you may sustain or suffer or sustain to the fullest extent permitted by law including against any claims, proceedings, actions, damages, losses, costs and expenses arising or incurred by TA as a result of or in connection with your breach of your Agreement your misconduct and/or your wilful, unlawful or negligent act or omission.
- 6.3 You agree that the release and indemnity and the assumption of risk contained in this clause will operate in favour of TA whether personally or by virtue of its vicarious liability for the acts or neglect of any person and binds your heirs, executors assigns and personal representatives.

7. Confidentiality Obligations

- 7.1 You acknowledge that the terms of this Agreement are confidential.
- 7.2 Both parties must take reasonable steps to ensure that they, their employees, advisers and agents do not use or disclose any part of this Agreement, any information in respect of this Agreement or any confidential information of the other party except to the extent that it is required by law; it is required for the performance of the party's obligations under this Agreement; the other party has consented in writing to such disclosure or use; or the party discloses any part of this Agreement or information in respect of this Agreement to that party's professional adviser.

8. Personal Information

You consent to TA collecting, holding, using and sharing personal information about you in connection with this Agreement and the support provided to you by TA on the terms and conditions set out in TA's privacy policy available at <http://www.tennis.com.au/privacy>.

Annexure B

PLAYER VALUES - What we stand for

COMPETE

- *Fight for every point from start to finish*
- *Take responsibility for all of your actions ~ no excuses*
- *Focus on effort and finding solutions*

COMMIT

- *Work hard and dedicate yourself to every aspect of your journey*
- *Be willing to learn, accept feedback and implement with conviction*
- *Strive to be better every day and be courageous*

RESPECT

- *Show respect for yourself, opponents and people supporting you including family, coaches, peers, your team, officials and property*
- *Respect the game overall*
- *Respect your opportunity*

Annexure C
Waiver and Release Form

USE OF TENNIS AUSTRALIA GYMNASIUMS

THIS IS AN IMPORTANT DOCUMENT AFFECTING YOUR RIGHTS. YOU SHOULD READ THIS DOCUMENT VERY CAREFULLY AND SIGN IT ONLY AFTER YOU ARE SATISFIED THAT YOU UNDERSTAND AND ACCEPT ALL TERMS AND CONDITIONS

I the Athlete **acknowledge and agree** that this is a legal document affecting my rights and:

1. **In this agreement**
 "Tennis Australia Gymnasiums" means the gymnasiums, equipment and facilities run by TA including
 - NSW: Sydney Olympic Park, New South Wales Institute of Sport
 - WA: State Tennis Centre, Burswood
 - VIC: Eastern Plaza Gymnasium and the Tennis World Gymnasium
 - TAS: Domain Tennis Centre
 - SA: Memorial Drive
 - QLD: Queensland Tennis Centre, Griffith University, The Queensland Academy of Sport
 - ACT: The National Sports Centre in Lyneham, the Australian Institute of Sport in Bruce.**"Claim"** means and includes any action, suit, proceeding, claim, demand, losses, damage, liability, cost or expense however arising including but not limited to negligence.
 "Gym Activities" means the use or enjoyment of the Tennis Australia Gymnasiums
 "Melbourne Park" is the precinct of that name located at the corner of Batman Avenue and Swan Street Melbourne.
 "MOPT" means Melbourne and Olympic Park Trust and where the context provides, includes its directors, employees, contractors and agents.
 "TA" means Tennis Australia Limited trading as Tennis Australia and where the context provides, includes its directors, employees, contractors and agents.
 "Tennis Activities" means Gym Activities and Tennis World Activities.
 Tennis Workout means a group fitness activity of that name and conducted by, on behalf of, under the auspices of and/or under the guidance of a tennis professional nominated by Tennis World and/or TA, and which may including tennis drills, warm-up, cardio workout, and cool-down.
 "Tennis World Activities" means any use, participation in or enjoyment of the tennis courts and other related facilities at Melbourne Park and Albert Reserve, including:
 - (a) Tennis Workouts, Cardio Tennis tournaments and social competitions, tennis coaching or tuition of any description and school holiday camps and programs conducted by, on behalf of, or under the auspices of Tennis World and/or TA; and
 - (b) any other tennis related activity conducted by, on behalf of, or under the auspices of Tennis World and/or TA.**"Tennis World Gymnasium"** means the gymnasium equipment and facilities located at Melbourne Park, and operated by or under the auspices of Tennis World.
2. **Warning:** I acknowledge that I am exposed to certain risks during any participation in Tennis Activities including but not limited to:
 - (a) I may be physically or mentally injured, maimed or killed;
 - (b) Other participants may act dangerously or with lack of skill;
 - (c) My property may be damaged, lost or destroyed.I acknowledge that accidents can and often do happen which may result in me being injured or killed, or my property being damaged. I acknowledge that the Tennis Activities are not patrolled by supervisors (at all times) and participation in Tennis Activities is entirely at my own risk.
I will not participate in the Tennis Activities while intoxicated or affected by drugs. I may assume a role involving responsibility for the safety of others participating in the Tennis Activities. This means I will accept responsibility for the safety of another person and if an injury occurs as a result of my careless act, omission or negligence then I fully assume responsibility for any harm done and I do not hold TA or MOPT responsible. I have voluntarily read and understood this warning and accept and assume the inherent risks in participating in the Tennis Activities.
3. **Not Used**
4. **Release and Indemnity:** In consideration of my participating in Tennis Activities, I agree that, to the extent permitted by law:
 - (a) I release TA and MOPT from all Claims that I may have or may have had but for this release arising from or in connection with my participation in any Tennis Activities; and

(b) I agree to indemnify, defend and hold harmless TA and MOPT in respect of any Claim by any person arising as a result of or in connection with my participation in any Tennis Activities.

4. **Fitness to Participate:** I declare that I am medically and physically fit and able to participate in any Tennis Activities. I will immediately notify TA of any change to my medical condition, fitness or ability to participate. I understand that if TA were not provided with all relevant and necessary information about my health and capacity they would not be able to fully appreciate the risk of harm or injury to me in providing instruction and in allowing me to participate in Tennis Activities. I understand that TA will continue to rely upon this declaration as evidence of my fitness and ability to participate.
6. **Severance:** If any provision of this document is invalid or unenforceable, the phrase or clause is to be read down, if possible, so as to be valid and enforceable. If the phrase or clause cannot be so read down it will be severed to the extent of the invalidity or unenforceability. Such severance does not affect the remaining provisions of this Waiver and Release

Executed as a DEED POLL in favour of TA and MOPT.

I have read, understood (and if under 18 have had it explained to me by my parent / legal guardian), **acknowledge and agree** to the above terms including the warning, release and indemnity and attached notice.

Signed: Print

Name.....

Dated:

If under 18 years of age parent / legal guardian must sign the following

Acceptance of Terms of Agreement and Indemnity

I [insert name] have read this Waiver and Release, understand it and have explained the contents to [insert name]. I acknowledge the terms and agree to [insert name] being bound by its terms.

In consideration of [insert name] participating in the Tennis Activities I agree to indemnify TA and MOPT from and against any third party Claim arising or incurred by TA and / or MOPT as a result of or in connection with [insert name] misconduct or negligence.

Signed: Print Name

.....

Dated:

APPENDIX V: SUPPLEMENTARY TABLES PUBLISHED WITH STUDY 1

Supplementary Table 1: Injury Incidence $\pm$ 95% confidence interval and rate ratio (RR), per 1,000 set exposures, for male and female injury occurrence and in-event treatment frequency by region over the 2011 to 2016 Australian Open (2013-2016 for in-event treatment frequency)

Region	Male				Female			
	Injury Occurrence		In-event treatment frequency		Injury Occurrence		In-event treatment frequency	
	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR
Head	0.00 $\pm$ 0.18	1.0	0.00 $\pm$ 0.28	1.0	-0.11 $\pm$ 0.26	0.4	0.04 $\pm$ 0.33	1.6
Neck	-0.11 $\pm$ 0.30	0.4	0.65 $\pm$ 0.77	90.7	-0.11 $\pm$ 0.33	0.4	1.03 $\pm$ 0.81	39.4
Shoulder	-0.10 $\pm$ 0.47	0.8	0.05 $\pm$ 0.55	1.2	0.55 $\pm$ 0.63	2.0	0.51 $\pm$ 1.18	1.8
Upper Arm	0.09 $\pm$ 0.23	3.2	0.30 $\pm$ 0.45	5.8	0.00 $\pm$ 0.29	1.0	0.38 $\pm$ 0.58	5.2
Elbow	0.27 $\pm$ 0.39	2.6	0.04 $\pm$ 0.58	1.1	-0.27 $\pm$ 0.47	0.4	0.16 $\pm$ 0.90	1.3
Forearm	-0.07 $\pm$ 0.27	0.5	-0.38 $\pm$ 0.55	0.1	-0.02 $\pm$ 0.20	0.8	0.00 $\pm$ 0.37	1.0
Wrist	0.14 $\pm$ 0.40	1.7	-0.09 $\pm$ 0.58	0.7	0.35 $\pm$ 0.60	2.3	0.73 $\pm$ 0.95	3.5
Chest	0.00 $\pm$ 0.15	0.9	0.00 $\pm$ 0.00	0.0	-0.01 $\pm$ 0.22	0.9	-0.34 $\pm$ 0.56	0.3
Thoracic Spine	-0.04 $\pm$ 0.17	0.6	-0.48 $\pm$ 0.52	0.1	0.09 $\pm$ 0.26	1.8	0.22 $\pm$ 0.80	2.2
Trunk and Abdominal	-0.37 $\pm$ 0.40	0.2	0.00 $\pm$ 0.52	1.0	-0.30 $\pm$ 0.51	0.4	-0.50 $\pm$ 1.01	0.3
Lumbar Spine	-0.10 $\pm$ 0.38	0.7	-0.67 $\pm$ 0.99	0.6	0.05 $\pm$ 0.44	1.3	0.99 $\pm$ 1.23	-18.1
Hip and Groin	-0.47 $\pm$ 0.37	0.2	0.89 $\pm$ 0.76	4.1	-0.30 $\pm$ 0.42	0.3	-0.27 $\pm$ 0.94	0.4
Pelvis/Buttock	-0.20 $\pm$ 0.28	0.1	0.04 $\pm$ 0.32	1.7	-0.11 $\pm$ 0.33	0.5	-0.01 $\pm$ 0.74	1.0
Thigh	0.16 $\pm$ 0.50	1.8	-0.40 $\pm$ 0.77	0.3	-0.07 $\pm$ 0.52	0.8	-0.11 $\pm$ 0.86	0.7
Knee	-0.44 $\pm$ 0.65	0.5	-0.11 $\pm$ 0.64	0.7	0.22 $\pm$ 0.60	1.5	-0.26 $\pm$ 0.97	0.6
Lower Leg	-0.19 $\pm$ 0.24	0.2	-0.02 $\pm$ 0.29	0.8	0.12 $\pm$ 0.39	2.6	0.65 $\pm$ 0.69	37.5
Ankle	0.25 $\pm$ 0.49	2.0	-0.10 $\pm$ 0.58	0.8	0.22 $\pm$ 0.51	1.6	1.03 $\pm$ 1.35	2.4
Foot	-0.12 $\pm$ 0.23	0.4	-0.53 $\pm$ 0.52	0.2	-0.13 $\pm$ 0.52	0.8	-0.67 $\pm$ 1.05	0.3

Supplementary Table 2: Injury Incidence $\pm$ 95% confidence interval and rate ratio, per 1,000 set exposures, for male and female injury occurrence and in-event treatment frequency by type over the 2011 to 2016 Australian Open (2013-2016 for in-event treatment frequency)

Type	Male				Female			
	Injury Occurrence		In-event treatment frequency		Injury Occurrence		In-event treatment frequency	
	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR
Muscle Injury	-1.30 $\pm$ 0.89	0.4	0.20 $\pm$ 0.90	1.3	-0.55 $\pm$ 1.07	0.7	0.02 $\pm$ 1.13	1.0
Joint Sprains	0.28 $\pm$ 0.69	1.3	-0.14 $\pm$ 1.12	0.9	-0.18 $\pm$ 0.93	0.9	0.73 $\pm$ 1.14	2.2
Tendon Injury	-0.48 $\pm$ 0.78	0.6	-0.42 $\pm$ 0.92	0.6	-0.14 $\pm$ 0.81	0.9	1.11 $\pm$ 0.98	3.2
Synovitis, Impingement, Bursitis	-0.06 $\pm$ 0.60	0.9	-0.23 $\pm$ 0.96	0.8	0.42 $\pm$ 0.72	1.7	0.14 $\pm$ 1.32	1.1
Cartilage Injury	-0.07 $\pm$ 0.28	1.5	-0.92 $\pm$ 1.12	0.2	0.06 $\pm$ 0.26	1.6	-1.48 $\pm$ 1.50	-0.2
Stress Fracture	0.06 $\pm$ 0.22	2.2	0.15 $\pm$ 0.40	3.4	0.22 $\pm$ 0.45	2.4	0.64 $\pm$ 0.77	3.9
Organ Injury	-0.00 $\pm$ 0.18	0.9	0.00 $\pm$ 0.00	0.0	-0.11 $\pm$ 0.26	0.4	-0.01 $\pm$ 0.37	0.9
Chronic Instability	-0.02 $\pm$ 0.17	0.6	0.00 $\pm$ 0.00	0.0	-0.07 $\pm$ 0.29	0.5	0.24 $\pm$ 0.55	3.6
Nerve Injury	0.01 $\pm$ 0.16	1.2	0.00 $\pm$ 0.00	0.0	-0.02 $\pm$ 0.29	0.8	-0.08 $\pm$ 0.65	0.6
Arthritis	-0.02 $\pm$ 0.21	0.7	0.00 $\pm$ 0.00	0.0	-0.02 $\pm$ 0.21	0.8	-0.11 $\pm$ 0.44	0.4
Other Stress/Over use Injury	0.01 $\pm$ 0.17	1.2	0.00 $\pm$ 0.29	1.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0
Fracture	0.00 $\pm$ 1.15	1.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0
Joint Dislocation	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	0.02 $\pm$ 0.20	1.3	0.00 $\pm$ 0.00	0.0
Whiplash	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	-0.02 $\pm$ 0.20	0.8	0.00 $\pm$ 0.00	0.0

Supplementary Table 3: Injury Incidence $\pm$ 95% confidence interval and rate ratio, per 1,000 match exposures, for male and female injury occurrence and in-event treatment frequency by region over the 2011 to 2016 Australian Open (2013-2016 for in-event treatment frequency)

Region	Male				Female			
	Injury Occurrence		In-event treatment frequency		Injury Occurrence		In-event treatment frequency	
	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR
Head	0.00 $\pm$ 0.50	1.0	0.00 $\pm$ 0.79	1.0	-0.24 $\pm$ 0.59	0.4	0.09 $\pm$ 0.76	1.5
Neck	-0.30 $\pm$ 0.82	0.4	1.82 $\pm$ 2.15	137.3	-0.25 $\pm$ 0.77	0.4	2.39 $\pm$ 1.88	37.2
Shoulder	-0.26 $\pm$ 1.30	0.8	0.15 $\pm$ 1.52	1.2	1.27 $\pm$ 1.46	2.0	1.18 $\pm$ 2.75	1.8
Upper Arm	0.25 $\pm$ 0.64	3.2	0.83 $\pm$ 1.25	5.9	0.01 $\pm$ 0.67	1.0	0.88 $\pm$ 1.35	5.2
Elbow	0.75 $\pm$ 1.06	2.7	0.10 $\pm$ 1.62	1.1	-0.62 $\pm$ 1.07	0.4	0.34 $\pm$ 2.08	1.3
Forearm	-0.18 $\pm$ 0.75	0.5	-1.05 $\pm$ 1.53	0.1	-0.03 $\pm$ 0.47	0.8	0.00 $\pm$ 0.85	1.0
Wrist	0.41 $\pm$ 1.10	1.7	-0.24 $\pm$ 1.60	0.7	0.80 $\pm$ 1.39	2.2	1.67 $\pm$ 2.21	3.4
Chest	-0.01 $\pm$ 0.42	1.0	0.00 $\pm$ 0.00	0.0	-0.03 $\pm$ 0.50	0.9	-0.79 $\pm$ 1.29	0.3
Thoracic Spine	-0.09 $\pm$ 0.46	0.7	-1.35 $\pm$ 1.44	0.1	0.19 $\pm$ 0.60	1.8	0.88 $\pm$ 1.35	5.2
Trunk and Abdominal	-1.01 $\pm$ 1.10	0.2	-0.02 $\pm$ 1.43	1.0	-0.70 $\pm$ 1.17	0.4	-1.16 $\pm$ 2.36	0.2
Lumbar Spine	-0.26 $\pm$ 1.03	0.7	-1.84 $\pm$ 2.76	0.6	0.12 $\pm$ 1.02	1.3	2.30 $\pm$ 2.83	-16.6
Hip and Groin	-1.26 $\pm$ 1.01	0.2	2.49 $\pm$ 2.12	4.1	-0.72 $\pm$ 0.96	0.4	-0.58 $\pm$ 2.19	0.4
Pelvis/Buttock	-0.55 $\pm$ 0.78	0.1	0.12 $\pm$ 0.89	1.7	-0.23 $\pm$ 0.75	0.5	0.00 $\pm$ 1.73	1.0
Thigh	0.43 $\pm$ 1.38	1.8	-1.09 $\pm$ 2.12	0.3	-0.15 $\pm$ 1.20	0.8	-0.23 $\pm$ 2.02	0.7
Knee	-1.19 $\pm$ 1.78	0.5	-0.27 $\pm$ 1.79	0.7	0.53 $\pm$ 1.38	1.6	-0.61 $\pm$ 2.26	0.6
Lower Leg	-0.52 $\pm$ 0.65	0.2	-0.07 $\pm$ 0.81	0.8	0.29 $\pm$ 0.90	2.6	1.54 $\pm$ 1.63	44.0
Ankle	0.70 $\pm$ 1.36	2.0	-0.25 $\pm$ 1.61	0.8	0.54 $\pm$ 1.17	1.7	2.30 $\pm$ 3.12	2.3
Foot	-0.31 $\pm$ 0.63	0.4	-1.45 $\pm$ 1.43	0.2	-0.30 $\pm$ 1.20	0.8	-1.57 $\pm$ 2.44	0.3

Supplementary Table 4: Injury Incidence $\pm$ 95% confidence interval and rate ratio, per 1,000 match exposures, for male and female injury occurrence and in-event treatment frequency by type over the 2011 to 2016 Australian Open (2013-2016 for in-event treatment frequency)

Type	Male				Female			
	Injury Occurrence		In-event treatment frequency		Injury Occurrence		In-event treatment frequency	
	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR	Incidence Rate $\pm$ 95% confidence interval	RR
Muscle Injury	-3.49 $\pm$ 2.45	0.4	0.57 $\pm$ 2.51	1.3	-1.24 $\pm$ 2.46	0.7	0.06 $\pm$ 3.38	1.0
Joint Sprains	0.85 $\pm$ 1.90	1.4	-0.35 $\pm$ 3.12	0.9	-0.40 $\pm$ 2.13	0.9	2.24 $\pm$ 3.44	2.3
Tendon Injury	-1.27 $\pm$ 2.15	0.6	-1.16 $\pm$ 2.56	0.6	-0.29 $\pm$ 1.87	0.9	3.32 $\pm$ 2.95	3.2
Synovitis, Impingement, Bursitis	-0.15 $\pm$ 1.64	0.9	-0.63 $\pm$ 2.68	0.8	1.01 $\pm$ 1.66	1.8	0.29 $\pm$ 3.06	1.1
Cartilage Injury	-0.21 $\pm$ 0.78	1.5	-2.51 $\pm$ 3.10	0.3	0.15 $\pm$ 0.61	1.7	-3.33 $\pm$ 3.47	-0.2
Stress Fracture	0.16 $\pm$ 0.61	2.2	0.41 $\pm$ 1.16	3.4	0.50 $\pm$ 1.03	2.4	1.48 $\pm$ 1.79	3.8
Organ Injury	-0.01 $\pm$ 0.49	1.0	0.00 $\pm$ 0.00	0.0	-0.24 $\pm$ 0.59	0.4	-0.04 $\pm$ 0.86	0.9
Chronic Instability	-0.06 $\pm$ 0.47	0.7	0.00 $\pm$ 0.00	0.0	-0.15 $\pm$ 0.67	0.5	0.60 $\pm$ 1.30	3.8
Nerve Injury	0.03 $\pm$ 0.44	1.3	0.00 $\pm$ 0.00	0.0	-0.03 $\pm$ 0.67	0.9	-0.17 $\pm$ 1.50	0.6
Arthritis	-0.05 $\pm$ 0.57	0.7	0.00 $\pm$ 0.00	0.0	-0.04 $\pm$ 0.47	0.8	-0.27 $\pm$ 1.03	0.4
Other Stress/Over use Injury	0.04 $\pm$ 0.46	1.3	0.01 $\pm$ 0.82	1.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0
Fracture	0.01 $\pm$ 0.42	1.1	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0
Joint Dislocation	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	0.03 $\pm$ 0.47	1.3	0.00 $\pm$ 0.00	0.0
Whiplash	0.00 $\pm$ 0.00	0.0	0.00 $\pm$ 0.00	0.0	-0.03 $\pm$ 0.47	0.8	0.00 $\pm$ 0.00	0.0