The Use of Therapeutic Exercise to Target the Temporal Characteristics of Muscle Activation Following Hamstring Muscle Injury in Professional Australian Football Players

Submitted by

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Preface

When Collingwood Football Club won the Australian Football League (AFL) premiership in 2010, the season included one other personal milestone. I commenced my professional doctorate while working as a rehabilitation coach at the club. I have found it interesting, as I prepare to submit this thesis, to reflect on what things were like at the time. I remember watching athletes being taken through dynamic warm-ups and completing activation exercise to ‘fire-up’ their glutes before each session. We had recently purchased a real-time ultrasound unit and hours were spent fine-tuning the activation of obscure deep muscles within the hip and trunk. The prevailing view was that muscle activation and muscle patterning during movement were important components of injury prevention and rehabilitation.

The intensity of muscle activation and strength always seemed quite similar concepts to me, and hard to differentiate, so I took a greater interest in motor patterning and muscle activation timing. Hamstring injuries were the most prevalent injury in the AFL in 2010 and remain so today. This also seemed like a good area in which to focus our research. Winning the premiership that year helped justify our high performance program. I was becoming a believer in our approach and wanted to learn more. Like a lot of things we do in clinical practice it was hard to tell what actually worked.

A career move in 2011 landed me at the Essendon Football Club in a similar role, but in a completely different world. The 2012 AFL season saw unprecedented numbers of hamstring muscle injuries at the Essendon Football Club in what was a highly dysfunctional program. The only upside, at least from a research point of view, was that we were able to access and investigate a large group of players who had recently sustained a hamstring muscle injury. La Trobe University had also recently acquired an electromyography (EMG) telemetry unit, which allowed us to take a practical and sport-specific approach to our major investigation.

The progression of this doctorate has been over a substantially longer time than intended. Most significantly, a doping scandal broke at the Essendon Football Club that led to me taking over the high-performance program. I worked hard over a number of years to steady the ship, rebuild the confidence of our players in sports science and sports medicine, and get things back on track. I also came to realise that processing EMG data takes a lot of time. There were 1800 strides of EMG data to be analysed, and from start to finish it was taking me approximately two hours to process each one. Thankfully, technology improved over time so things got a little quicker, and I brought in some help towards the end. Eventually, despite all of the professional disruption, and thanks to some incredible patience from my wife, the data were processed and we could analyse our results.

In some ways the world has not changed all that much over the last ten years. While the real-time ultrasound units have gradually been shuffled into storage cupboards, practitioners in elite sport are still including activation exercises in their warm-ups, and I still get told with confidence how important motor patterning and muscle activation are for our athletes. I hope that this journey, which is outlined in the thesis below, helps make things a little clearer for those in elite sporting settings, and in some way assists our decision making as we consider how to best invest our valuable and limited time with our athletes.

Abstract

Hamstring muscle injuries have the highest incidence and prevalence of any injury in the Australian Football League (AFL). It has been proposed that the onset and offset timing of muscle activation during high-speed running may influence hamstring muscle injury and re-injury risk. There are conflicting reports as to whether muscle activation timing is altered following hamstring muscle injury. One modality that has been reported to improve the timing of muscle activation following injury is therapeutic exercise.

This thesis aimed to investigate whether the temporal characteristics of muscle activation are altered following hamstring muscle injury and explore the use of therapeutic exercise to improve the timing of muscle activation during high-speed running in professional AFL players. A systematic review, targeted projects and an applied research study were undertaken to gather information on the use of exercise to improve muscle activation in elite sport and to guide the design of a major research study.

The major research study recruited professional AFL players with a recent history of hamstring muscle injury and used electromyographic telemetry to assess the muscle activation timing of their hamstring and gluteus maximus muscles during high-speed overground running. No changes to the temporal characteristics of muscle activation were found compared to players from the same club who had never had a hamstring muscle injury. The second component of the study investigated the acute effect of a low-load activation exercise protocol targeting the gluteus maximus and hamstring muscles. No effect on muscle activation timing during high speed running was observed.

This thesis concludes that the temporal characteristics of muscle activation are unaffected by a recent hamstring muscle injury, and that low load muscle activation exercises do not have an acute effect on the temporal characteristics of gluteus maximus and hamstring muscle activation, during high-speed running in professional AFL players.

Statement of Authorship

This thesis includes work by the author that has been published or accepted for publication as described in the text. Except where reference is made in the text of the thesis, this thesis contains no other material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma. No other person's work has been used without due acknowledgment in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

With regard to the extent of collaboration with another person or persons, although the publications involve joint authorship, I have made a significant and leading contribution to the work, equivalent to that expected for a traditional thesis. This thesis includes work by the author that has been published as described in the text. I am the primary author on the five manuscripts presented in this thesis. Where articles have been co-authored, the contributions have been clearly acknowledged.

This research was supported by an Australian Government Research Training Program Scholarship .

The major research project was approved by the Faculty Human Ethics Committee (FHEC11/170). The letter of ethics approval is contained in Appendix A.

Signed:

Justin Crow
Date: 21/08/2020

Acknowledgements

It is quite surreal to be in a position to submit this thesis after all this time. It has been a long road and I have been very fortunate to have benefited from good support for the entirety of the journey.

I am incredibly thankful for the remarkable patience of my supervisors, Dr. Tania Pizzari and Dr. Adam Semciw. Aside from the fact it is quite incredible that they were actually able to remain in a supervisory role for a decade, they were always available, helpful and caring mentors who I would have been completely lost without. I hope they take great pleasure in finally wiping my name from their whiteboards.

For research of this nature to take place you need the support and trust of players, coaches and administrators and I would like to acknowledge all of those people along the way who have given some of their time and energy to contribute to the completion of this project. I am also indebted to fellow physiotherapist, Jamon Couch, for his assistance with our data processing.

It is around the time that I started this doctoral program that I met my wife and best friend, Laura Szekfy. Together we have thrived throughout a whirlwind of crazy events taking place around us, and last year we welcomed our first child into the world. Indeed, the biggest motivation for finishing this thesis has been the promise of having more time to spend with our daughter. I am excited for spending the rest of our lives together and am incredibly thankful for everything that has been sacrificed to allow me to progress through this degree.

Publications Forming Part of This Thesis

Crow, J., Pizzari, T., & Buttifant, D. (2011). Muscle onset can be improved by therapeutic exercise: A systematic review. *Physical Therapy in Sport, 12(4), 199-209.*

Crow, J. (2011). The role of the strength and conditioning coach in optimising muscle patterning following injury. *Journal of Australian Strength and Conditioning,* 19(3), 100-104.

Crow, J., Buttifant, D., Kearney, S., & Hrysomallis, C. (2012). Low load exercises targeting the gluteal muscle group acutely enhance explosive power output in elite athletes. *Journal of Strength and Conditioning Research,* 26(2), 438-442.

Crow, J., Semciw, A., Couch, J., & Pizzari, T. (2020). Does a recent hamstring muscle injury affect the timing of muscle activation during high speed overground running in professional Australian Football players? *Physical Therapy in Sport,* 43, 188-194.

Crow, J., Semciw, A., Couch, J., & Pizzari, T. (Submitted). Can activation exercise alter muscle activation timing during high-speed running in professional Australian Football players? *Science and Medicine in Football,* Submitted.

Publications Not Forming Part of This Thesis but Published During the Candidature

Carey, D., Ong, K., Crow, J., Morris, M., & Crossley, K. (2016). Predicting ratings of perceived exertion in Australian football players: methods for live estimation. *International Journal of Computer Science in Sport*, 15(2), 64-77.

Carey, D., Blanch, P., Crossley, K., Ong, K., Crow, J., & Morris, M. (2017). Training loads and injury risk in Australian football – differing acute:chronic workload ratios influence match injury risk. *British Journal of Sports Medicine*, 51, 1215-1220.

Carey, D., Ong K., Whiteley, R., Crossley, K., Crow, J., & Morris, M. (2018). Predictive modelling of training loads and injury in Australian football. *International Journal of Computer Science in Sport*, 17(1), 49-66.

Carey, D., Crow, J., Ong, K., & Blanch, P. (2018). Optimising pre-season training loads in Australian football. *International Journal of Sports Physiology and Performance*, 13, 194-199.

Carey, D., Crossley, K., Whiteley, R., Mosler, A., Ong, K., & Crow, J. (2018). Modelling training loads and injuries: The dangers of discretization. *Medicine and Science in Sport and Exercise*, 50(11), 2267-2276.

List of Abbreviations

1RM	1 Repetition maximum
3RM	3 Repetition maximum
ACL	Anterior cruciate ligament
ACT	Activation group
AFL	Australian football league
ACL	Anterior cruciate ligament
ANOVA	Analysis of variance
CI	Confidence interval
CMJ	Countermovement jump
CON	Control group
DCF	Deep cervical flexors
EMG	Electromyography
ER	External rotation
EXP	Experimental group
FAI	Femoroacetabular impingement
FAI	Functional ankle instability
FHEC	Faculty human ethics committee
GMax	Gluteus maximus
GM-P	Gluteal muscle protocol
GPS	Global positioning system
H	Hours
HS	Hamstring
Hz	Hertz
IO	Internal oblique
IR	Internal rotation
IQR	Interquartile range
LL	Lower limb

MG	Medial Gastrocnemius
MR	Magnetic resonance
MRI	Magnetic resonance imaging
PFPS	Patellofemoral pain syndrome
PhD	Doctor of philosophy
RCT	Randomised controlled trial
ROM	Range of movement
RTU	Real time ultrasound
SD	Standard deviation
SMD	Standardised mean difference
TA	Tibialis anterior
TrA	Transversus abdominus
TFL	Tensor fascia latae
VL	Vastus lateralis
VMO	Vastus medialis oblique
WBV	Weight bearing vibration
WBV-P	Weight bearing vibration protocol

Thesis Aim

To investigate the temporal characteristics of muscle activation following hamstring muscle injury and explore the potential use of exercise to acutely improve the timing of muscle activation in professional Australian Football players.

Objectives of the Thesis

The objectives were to:

1. Conduct a systematic review into the effectiveness of therapeutic exercise in altering the temporal characteristics of muscle activation following injury.
2. Investigate and report on current clinical practices relating to muscle activation following injury in the context of Australian football.
3. Determine the practicality of completing research into muscle activation within a professional Australian Football training environment.
4. Investigate the temporal characteristics of muscle activation during high speed overground running in professional Australian Football players following recent hamstring muscle injury.
5. Investigate the acute effect of therapeutic exercise on the temporal characteristics of muscle activation during high speed overground running in professional Australian Football players.

Thesis Outline

This thesis begins with an introduction to the problem of hamstring muscle injury in professional Australian football players and discusses the potential use of exercise to address the temporal characteristics of muscle activation following hamstring muscle injury.

A systematic review was completed to ascertain what is known about the role of exercise in improving the temporal characteristics of muscle activation following injury. The manuscript "Muscle onset can be improved by therapeutic exercise: A systematic review" is presented in Chapter Two in its peer reviewed and published format.

Chapter Three details an exploration into the state of clinical practice at the time using a series of targeted projects. These projects examined expertise from the fields of physiotherapy and strength and conditioning. The first part of this process involved the identification and recruitment of leaders in the field of physiotherapy to a facilitated workshop. Preparation for the workshop included developing a booklet for attendees and providing a report on the workshop outcomes to the host organisation. The booklet titled "Muscle Activation around the hips and pelvis in the context of Australian Football" is contained in Appendix B and the workshop report is contained in Appendix C. The second part of this process involved the observation of experts in the field of strength and conditioning and culminated in accreditation of the author as a strength and conditioning coach. The process included the publication of a manuscript titled "The role of the strength and conditioning coach in optimising muscle patterning following injury" which is presented in Chapter Three in its peer reviewed and published format.

A research study was completed to test the practicality and effectiveness of using different therapeutic exercises to target acute changes in muscle activation in a professional Australian football training environment. The manuscript "Low load exercises targeting the gluteal muscle group acutely enhance explosive power output in elite athletes" is presented in Chapter Four in its peer reviewed and published format. This chapter is also used to outline the learnings and practical insights gained from the investigation.

Chapter Five outlines the first part of the major research project. A research study was completed to establish whether the temporal characteristics of muscle activation are altered during high speed overground running following hamstring muscle injury in professional Australian Football players. The manuscript "Does a recent hamstring muscle injury affect the timing of muscle activation during high speed overground running in professional Australian Football players?" is presented in its peer-reviewed and published format.

Chapter Six is used to outline the second part of the major research project, an investigation into the acute effect of a targeted therapeutic exercise protocol on the temporal characteristics of muscle activation during overground running in professional Australian Football players. The manuscript "Can activation exercise alter muscle activation timing during high-speed running in professional Australian Football players?" is presented in the format required for submission to Science and Medicine in Football where it is currently under consideration.

The main findings, potential practical implications, and strengths and limitations of this thesis are discussed in Chapter Seven. Directions for future research and overall conclusions are also contained within this chapter. The overall progression of the thesis is represented below in **Figure 1**.

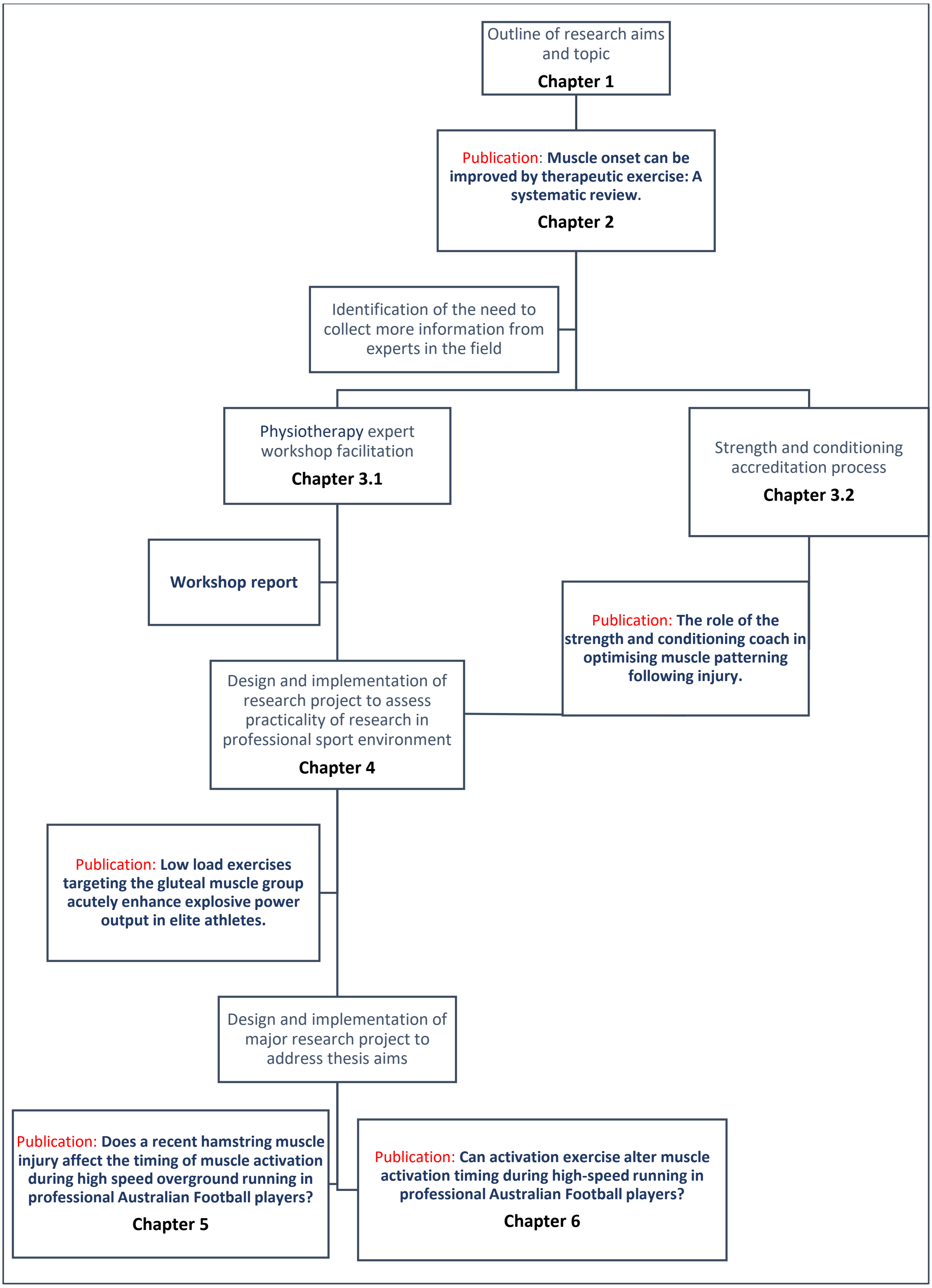

Figure 1: Progression of thesis

Chapter One: Introduction

1.1 Hamstring muscle injuries in the Australian Football League (AFL)

Hamstring muscle injury has the highest incidence and prevalence in the AFL, with each club sustaining an average of 7 new hamstring muscle injuries during the AFL season, and losing an average of 25.2 matches to player unavailability (Australian Football League, 2019). Hamstring muscle injuries can negatively impact team performance (Hägglund et al., 2013) and the financial burden of these injuries is also substantial. It has been estimated that in 2012 the average cost to an AFL club of a single hamstring muscle injury was $40,021 Australian dollars (Hickey, Shield, Williams & Opar, 2014).

Despite a considerable investment in prevention and rehabilitation programs from AFL clubs a high rate of injury recurrence also exists. In the 2018 AFL season, the hamstring muscle injury recurrence rate was reported as 20% which is consistent with the 10-year average of 20.5% (Australian Football League, 2019).

Australian football has movement demands that are somewhat similar to other football codes including a combination of kicking, tackling and jumping. However, it has greater high-speed running requirements than other codes (Saw et al., 2018). This is an important difference given that the majority of hamstring muscle injuries sustained in professional football occur during high-speed running (Ekstrand, Waldén & Hägglund, 2016).

1.2 Hamstring muscle function during running

During high-speed running, the gluteus maximus and hamstring muscles work as hip extensors in the late swing and stance phases of the gait cycle, to control knee and hip extension (Dorn, Schache & Pandy, 2012; van den Tillaar, Solheim & Bencke, 2017). Two distinct loading peaks have been reported in the hamstring muscles during the high-speed running gait cycle. The first during late swing, and the second during early stance phase

(Chumanov, Heiderscheit & Thelen, 2011). Peak hamstring muscle activation occurs during terminal swing phase (Schache, Dorn, Blanch, Brown & Pandy, 2012), and the magnitude of peak hamstring muscle activation is observed to increase as running speed is increased (Higashihara, Ono, Kubota, Okuwaki & Fukubayashi, 2010).

1.3 Effect of prior injury on hamstring muscle function during running

Following hamstring muscle injury, residual deficits to hamstring muscle strength and flexibility persist, and these changes are observed even after an athlete has returned to competition (Maniar, Shield, Williams, Timmins & Opar, 2016). Although these identified changes could be expected to impact on the running performance of an athlete and the function of the hamstring muscles during running, evidence for this is limited and conflicting.

1.3.1 Changes to kinematics and kinetics following hamstring muscle injury

There is a lack of consensus on the existence of altered running kinematics following hamstring muscle injury. In a study of 30 soccer players with a recent history of hamstring strain and a group of 30 matched controls, no differences in running kinematics were identified during overground sprinting (Schuermans, van Tiggelen, Palmans, Danneels, & Witvrouw, 2017b). Another study observed greater peak hip flexion, anterior pelvic tilt and tibial internal rotation asymmetries between the injured and uninjured limbs within a group of nine athletes with a history of hamstring muscle injury compared to a group of eight uninjured controls during steady-state treadmill running (Daly, McCarthy Persson, Twycross-Lewis, Woledge, & Morrissey, 2016). Disparities between the tasks investigated, sample size, and the differences in outcome variables (asymmetry between limbs versus direct comparison of limbs between groups) may explain the different results reported by these two studies.

Other studies have compared injured and uninjured limbs within the same subject. Silder, Thelen, and Heiderscheit (2010) reported no differences between limbs in 18 athletes during high-speed treadmill running. Lee, Reid, Elliott & Lloyd (2009) also found no kinematic differences between limbs, except for decreased hip flexion angle during late swing phase in the injured side in 12 athletes (Lee, Reid, Elliott, & Lloyd, 2009). A decreased hip flexion angle during late swing phase refers to a reduced total hip flexion range of movement during swing phase on the injured side resulting in asymmetric movement. In contrast, another study reported increased hip flexion angle during late swing phase, decreased hip flexion angle in mid-swing, increased knee flexion angle in late swing, and reduced anterior pelvic tilt angle in late stance phase in the injured side of 10 athletes during overground running (Higashihara et al., 2019).

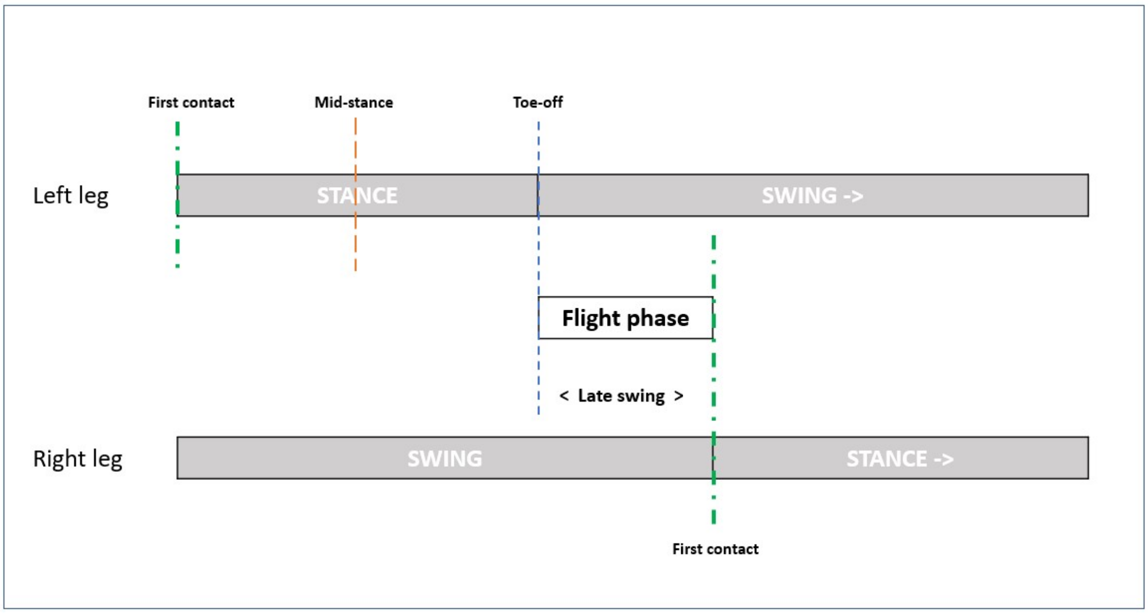

Figure 2.3.1: The stance phase and swing phase of running

1.3.2 Changes to muscle activity during running

Neuromuscular inhibition is another sequelae of hamstring muscle injury that has been proposed to contribute to an increased risk of hamstring muscle injury recurrence (Opar, Williams, & Shield, 2012). It remains unclear whether the magnitude of muscle activation is altered during running following hamstring muscle injury. One study has reported no changes in muscle activation intensity between injured and uninjured limbs (Silder et al., 2010), while another has reported lower biceps femoris muscle activation during late swing phase in previously injured limbs (Higashihara et al., 2019). Lower activation ratios of the biceps femoris relative to other muscle groups including the ipsilateral gluteus maximus and erector spinae muscles (Daly et al., 2016) were recorded in previously injured athletes during running.

The relationship between electromyographic (EMG) signal intensity and muscular force production is influenced by various factors including muscle shortening velocity and can be difficult to determine. This might be a factor in the conflicting outcomes of these studies.

1.3.3 Changes to the temporal characteristics of muscle activity during running

It has been suggested that the best use of the EMG signal is to describe the onset and offset timing of muscle activation (Maniar et al., 2020). Changes to the timing of muscle activity can develop following injury in the presence of pain (Hodges & Moseley, 2003) and joint pathology (Stokes & Young, 1984). This can result in changes to the control and function of the affected area (Hodges & Tucker, 2011). Importantly, changes may persist after the individual becomes asymptomatic and symptoms have resolved (MacDonald, Moseley, & Hodges, 2009). Only one previous study has looked specifically at the temporal properties of the hamstring muscles during running. Silder et al. (2010) reported no differences between injured and uninjured limbs in the onset and offset timing of the hamstring muscles during high speed treadmill running in a group of 18 athletes with a history of hamstring muscle injury.

Altered hamstring muscle activation timing following hamstring muscle injury has been investigated in a task other than running. Earlier onset timing of the biceps femoris and medial hamstrings following hamstring muscle injury has been observed during transition from double leg to single leg stance (Sole, Milosavljevic, Nicholson, & Sullivan, 2012).

Prior to this thesis, no research had investigated muscle onset and offset timing of the hamstring muscles between groups of recently injured and uninjured subjects during over-ground running.

1.4 Relevance of hamstring muscle temporal characteristics to injury risk

The neuromuscular activation pattern of the gluteus maximus and hamstring muscles is proposed to be an important factor in both hamstring muscle rehabilitation and injury prevention (Heiderscheit, Sherry, Silder, Chumanov, & Thelen, 2010; Schuermans, Danneels, van Tiggelen, Palmans, & Witvrouw, 2017c). Evidence for value of this factor for identifying an athlete with an increased risk of hamstring is again controversial and limited.

Soccer players with delayed onset of their hamstring muscles in a prone hip extension exercise (Schuermans, van Tiggelen, & Witvrouw, 2017a), and who had lower amplitudes of gluteal muscle activity during overground maximal acceleration (Schuermans et al., 2017c), were more likely to suffer a hamstring strain in the following 1.5 seasons. In contrast, the onset timing of the biceps femoris and medial hamstrings during isokinetic strength testing was unrelated to the prospective risk of hamstring muscle injury in the following season (van Dyk et al., 2018). In this study, and throughout the thesis, 'medial hamstrings' refers to the semimembranosus and semitendinosus muscles as the activity of these two muscles is unable to be effectively differentiated using surface EMG. It is possible that the different results in these two studies may be explained by the low task-specificity of the isokinetic test relative to overground maximal acceleration.

1.5 The use of targeted therapeutic exercise to improve the temporal characteristics of muscle activation

There is evidence to support the use of therapeutic exercise to improve the temporal characteristics of muscle activity following a variety of injuries (Arendt-Neilsen & Falla, 2009). For example, acute improvements in the timing of muscle activation during functional activity have been demonstrated following a bout of repeated voluntary isometric contractions in asymptomatic subjects with a recurrent or chronic low back pain in three separate studies (Suehiro, Ishida, Hobara, Osaka, Kurokomi, & Watanabe, 2021; Tsao, Druitt, Schollum, & Hodges, 2020; Tsao, Galea & Hodges, 2010). Cohen, Gerloff, Ikoma, and Hallett (1995) reported that targeted therapeutic exercise can acutely shift the motor cortical representation of the targeted muscle, and any acute changes in muscle timing are likely due to this mechanism of motor cortical reorganisation.

A nine-week exercise intervention targeting the hip extensor muscles reported earlier muscle onset timing of the gluteus maximus during a prone hip extension test but not during more sport-specific movement (Rainsford, 2015). To the best knowledge of the author no research into the acute effects of targeted therapeutic exercise on the temporal characteristics of hamstring or gluteus maximus muscle activation had been published prior to this thesis.

The aims of this thesis were to further investigate the temporal characteristics of muscle activation following hamstring muscle injury and explore the potential use of exercise to acutely improve the timing of muscle activation in professional Australian Football players.

Chapter Two: Systematic Review Into the Use of Therapeutic Exercise to Improve the Temporal Characteristics of Muscle Activation Following Injury

The existence of altered muscle onset timing following injury has been documented in a number of injuries that are commonly seen in sports settings such as anterior cruciate ligament injury (Bryant, Newton, & Steele, 2009), longstanding groin pain (Cowan et al., 2004), low back pain (Hodges, 2001), shoulder impingement (Moraes et al., 2008) and patellofemoral pain syndrome (Chester et al., 2008).

Therapeutic exercise is a treatment option that may be used to specifically target the onset timing of muscles following injury. A systematic review was undertaken with the primary objective of determining the effectiveness of therapeutic exercise for improving the timing of muscle onset following injury. The systematic review also sought to better understanding what exercise prescription parameters are most effective at achieving these outcomes.

As the submission of this thesis has taken place 10 years after the publication of this systematic review, an updated literature search was undertaken with an identical search strategy applied. Additional research papers that fit the inclusion and exclusion criteria, and were published after the initial search strategy took place in March 2010, are summarised below in Table 1.

Table 1. Summary of additional studies published after March 2010 found using systematic review search strategy.

Study	Design	Participants	Intervention	Outcome
De Mey, Danneels, Cagnie, & Cools (2012)	Case series Pre-post test	n = 40 Exp ALL = Athletes with shoulder impingement symptoms	Exp = 6 wks x daily HEP with 4 x general strength ex: 3 x 10 each	No pre-post training effect for upper trapezius, middle trapezius, lower trapezius, or serratus anterior measured with surface EMG
Dinesha & Prasad (2011)	Pre-post test	n = 15 Exp A (2 week program) n = 15 Exp B (4 week program) ALL = recurrent ankle sprains in recreational athletes	Exp A = 2 weeks daily HEP instability training Exp B = 4 weeks daily HEP instability training	Earlier muscle onset time relative to trap door perturbation for both tibialis anterior ($p<0.001$) and peroneus longus ($p = 0.016$) in the 4/wk program compared to the 2/wk program measured with surface EMG.
Ortega-Cebrian, Girabent-Farres, Whiteley, & Bagur-Calafat (2021)	Pre-post test	n = 37 Exp ALL = Shoulder impingement syndrome	Exp = 12 wks x 3/week general strength training	Earlier muscle onset time relative to deltoid onset during arm movement seen in the anterior deltoid ($p = 0.00$) and upper trapezius ($p = 0.00$) muscles but not in mid-deltoid, posterior deltoid, lower trapezius, serratus anterior, pectoralis major, subscapularis, supraspinatus and infraspinatus muscles when measured with surface EMG for all muscles except subscapularis, supraspinatus and infraspinatus muscles that were measured with indwelling EMG.
Sharma, Hussain, & Sharma (2021)	Pre-post test	n = 40 Exp ALL = Shoulder impingement syndrome	Exp = 8 wks x daily HEP with 6 x general strength exercises (1 x 10 each)	No change in muscle onset relative to deltoid onset during arm movement in serratus anterior, upper trapezius, mid trapezius or lower trapezius measured with surface EMG
Sierra-Guzman, Jimenez, Ramirez, Esteban, & Abian-Vicen (2018)	RCT	n = 17 Exp A (with WBV) n = 17 Exp B (w/o WBV) n = 16 Con ALL = recreational athletes with self-reported CAI	Exp A = 6 weeks x 3/wk Bosu instability training with concurrent WBV Exp B = 6 weeks x 3/wk Bosu instability training without concurrent WBV Con = no exercise given	Earlier muscle onset time relative to sudden inversion seen in peroneus longus ($p = 0.007$), peroneus brevis ($p = 0.003$), and tibialis anterior ($p = 0.007$) from pre to post testing in Exp A (instability training with WBV) but not in the Exp B or Con groups (all $p>0.05$) when measured with surface EMG.
Suehiro, Ishida, Kobara, Osaka, Kurozumi. & Watanabe (2021)	Pre-post test	n = 15 Exp ALL = recurrent low back pain	Exp = 3 x 10 abdominal hollowing single-session.	Earlier muscle onset time relative to deltoid onset during arm movement for IO/TrA and multifidus measured with surface EMG
Tsao, Druitt, Schollum, & Hodges (2010).	Pre-post test	n = 20 Exp ALL = nonspecific lbp	Exp = Single-session: 3 x 10 isolated isometric contractions of lumbar multifidus at 5% RMS max and 3 x 10 lumbar extensions at 5% RMS max	Earlier muscle onset time relative to deltoid onset during arm movement for multifidus ($p<0.036$) and OI/TrA ($p=0.026$) measured with surface EMG

Exp = Experimental group; wks = weeks; HEP = home exercise program; EMG = Electromyography; lbp = low back pain; CAI = chronic ankle instability, WBV = Weightbearing vibration, IO/TrA = Internal Oblique/Transversus Abdominus, RMS = Root Mean Square, Con = Control group.

The additional 7 studies published after March 2010 that fit the inclusion and exclusion criteria studied a mix of the general population and recreational athletes. They investigate muscle onset time following a 6-12 week course of general strength exercise in subjects with shoulder impingement (De Mey, Danneels, Cagnie, & Cools, 2012; Ortega-Cebrian, Girabent-Farres, Whiteley, & Bagur-Calafat, 2021; Sharma, Hussain, & Sharma, 2021), following a 2-6 week course of instability training in subjects with chronic ankle instability (Dinesha & Prasad, 2011; Sierra-Guzman, Jimenez, Ramirez, Esteban, & Abian-Vicen, 2018), and following a single session of isolated muscle training in subjects with nonspecific (Tsao, Druitt, Schollum, & Hodges, 2010) and recurrent (Suehiro, Ishida, Kobara, Osaka, Kurozumi, & Watanabe, 2021) low back pain.

Overall, the findings were not favourable in the shoulder with two studies finding no treatment effect (de Mey et al., 2012; Sharma et al., 2021), and one finding earlier muscle onset following treatment in two muscles (anterior deltoid and upper trapezius) but not in eight others (middle deltoid, posterior deltoid, serratus anterior, middle trapezius, lower trapezius, supraspinatus, subscapularis and infraspinatus) (Ortega-Cebrian et al., 2021).

In the ankle, instability training led to earlier muscle onset after 4-weeks of training than 2-weeks of training in the peroneus longus and tibialis anterior muscles (Dinesha & Prasad, 2011). In one other study in the ankle, six weeks of instability training was only effective at altering muscle onset timing of the Peroneus Brevis, Peroneus Longus and Tibialis Anterior when combined with WBV. Otherwise, instability exercise performed no better than a control group (Sierra-Guzman et al., 2018)

There were two studies that looked at the acute effects of isolated muscle exercise immediately after one single session of isolated muscle training. Both studies were in people with low back pain and both demonstrated earlier onset times following exercise in both the lumbar multifidus and internal oblique/transversus abdominus muscles (Suehiro et al., 2021; Tsao et al., 2010)

Overall, none of these finding from the articles published after March 2010 would have changed the outcome of this thesis, and the heterogeneric sample would have still meant that no meta-analysis was appropriate in the systematic review. The finding of two additional studies that isolated muscle exercise has an acute effect on muscle onset timing reinforces the decision to investigate low load isolated muscle exercises in the major research component of the thesis.

The systematic review is presented below in its peer reviewed and published format:

Crow, J., Pizzari, T., & Buttifant, D. (2011). Muscle onset can be improved by therapeutic exercise: A systematic review. *Physical Therapy in Sport, 12(4), 199-209.*

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Literature Review

Muscle onset can be improved by therapeutic exercise: A systematic review

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Exercise therapy
Electromyography
Skeletal muscle
Systematic review

A B S T R A C T

Objectives: To determine whether therapeutic exercise can improve the timing of muscle onset following musculoskeletal pathology, and examine what exercise prescription parameters are being used to achieve these effects.
Participants: People with a musculoskeletal pathology.
Main Outcome Measure: Muscle onset timing as measured by electromyography.
Results: Sixteen investigations were identified containing 19 therapeutic exercise groups. Three exercise modes were identified including: isolated muscle training, instability training, and general strength training. Isolated muscle training is consistently shown to have a positive effect on the muscle onset timing of transversus abdominus in people with low back pain. There is some evidence from cohort studies that instability training may change muscle onset timing in people with functional ankle instability, however controlled trials suggest that no effect is present. General strength training shows no effect on muscle onset timing in people with low back or neck pain, although one cohort study suggests that a positive effect on gluteus maximus may be present in people with low back pain.
Conclusion: Therapeutic exercise training is likely to improve muscle onset timing. Additionally, isolated muscle training appears to be the best exercise mode to use to achieve these effects.

1. Introduction

Large variabilities in muscle recruitment patterns have been observed for particular movements both within and between normal individuals (Bartlett, Wheat, & Robins, 2007). Notwithstanding this normal variability it has been suggested that changes in muscle activation patterns, in particular the altered timing of muscle onset, which can develop in the presence of pain (Hodges & Moseley, 2003) or joint pathology (Stokes & Young, 1984) might be undesirable. For example, a delay in the activation of the transversus abdominus (TrA) seen in people with chronic nonspecific low back pain has been hypothesised to lead to a reduced ability of the body to attenuate forces within the spine created by limb movement (Hodges & Richardson, 1996). Likewise, a delayed reaction of the peroneal muscles in response to an ankle perturbation may contribute to impaired postural awareness and stability of the ankle in people with functional ankle instability (FAI) (Clark & Burden, 2005).

Altered muscle onset timing has been reported in a wide variety of musculoskeletal conditions including chronic neck pain (Falla, Jull, & Hodges, 2004), shoulder impingement (Moraes, Faria, Teixera-Salmela, & Horizonte, 2008), shoulder pain (Hess et al., 2005), low back pain (Hodges, 2001), sacroiliac joint pain (Hungerford, Gilleard, & Hodges, 2003), longstanding groin pain (Cowan et al., 2004), patellofemoral pain syndrome (PFPS) (Chester et al., 2008), anterior cruciate ligament injury (Bryant, Newton, & Steele, 2009), knee osteoarthritis (Hinman, Bennell, Metcalf, & Crossley, 2002), FAI (Rosenbaum, Becker, Gernrob, & Claes, 2000), and following hip arthroplasty (Vogt, Banzer, Pfeifer, & Galm, 2004). MacDonald, Moseley, and Hodges (2009) have demonstrated that dysfunctional timing of muscle onset can persist even when an individual becomes asymptomatic, and have suggested that the persistence of dysfunctional motor patterns may be an important contributing factor towards injury recurrence. Consequently, it has been postulated that rehabilitation of these conditions should incorporate therapeutic exercise prescription with an aim of improving the onset timing of affected muscles (Arendt-Nielsen & Falla, 2009). When prescribing exercise to improve muscle strength, therapists have clear guidelines about what exercise prescription parameters might best achieve their desired outcomes (Rhea, Alvar, Burkett, & Ball, 2003). No such

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guidelines however currently exist for therapists when prescribing exercise to improve muscle onset timing following injury.

Therefore the primary aim of this review was to establish whether therapeutic exercise can improve muscle onset timing following musculoskeletal pathology. The secondary aim of the review was to establish what exercise prescription parameters are being used to improve muscle onset timing following musculoskeletal pathology.

2. Method

2.1. Identification and selection of studies

A systematic literature search was conducted of MEDLINE, CINAHL, EMBASE, AUSPORT, SPORTDiscus, PEDro and the Cochrane Library from inception to March 2010. Where possible key words were mapped to subject headings, and filters for English language, peer-reviewed studies and human subjects were also applied where available. (See Appendix 1 for the full search strategy). Citation tracking using Google Scholar and reference scanning of the bibliographies of all included studies were undertaken to identify any further relevant trials not captured by the initial search. Key authors in the field were also contacted to enquire about any appropriate research unpublished at the time of the review. References yielded by the search were exported into Endnote X3 (Thomson Reuters, NY).

A set of inclusion and exclusion criteria was established prior to searching. Inclusion criteria are shown in Fig. 1. This review allowed for the inclusion of single-group pre–post design studies as it was considered that limiting this review to level one evidence would not allow for a comprehensive review of the topic. A review of nine physiotherapy journals found that only 12.6% of studies were level one evidence (Paci, Cigna, Baccini, & Rinaldi, 2009), and it was known that single-group pre–post test design studies are prevalent in the literature relevant to this topic (Hall, Tsao, MacDonald, Coppieters, & Hodges, 2009; Tsao & Hodges, 2008). Other non-randomised study designs such as case series were excluded from the review, along with opinion articles and non-systematic reviews.

The review was restricted to electromyographic recording of muscle onset timing because although other methods of measuring muscle activation such as phase contrast magnetic resonance imaging and real-time ultrasound have good precision in measuring muscle activation (Hodges & Moseley, 2003; Rebmann & Sheehan, 2003) they do not currently have the capacity to accurately measure the small changes in timing (in milliseconds) required to compare muscle onset timing. This review was interested in muscle activation in a complete sense that includes the role of both the central nervous system and peripheral mechanisms. Consequently, studies that included people with a neurological injury or that measured only an isolated component of muscle activation such as

Design
- Randomised or quasi-randomised controlled trial
- Single group pre-post test designs

Participants
- Humans
- Musculoskeletal pathology

Intervention
- Therapeutic exercise

Outcome measures
- Electromyographic recording of muscle onset timing

Comparisons
- Not specified

Fig. 1. Inclusion criteria.

reflex arc times were excluded from the review. Where multiple studies used the same participants from one single sample, the study that analysed the largest proportion of the sample was included, and the others excluded, to avoid the analysis of duplicate data or 'double counting' (Senn, 2009). Papers that were not available in the English language, not published in a referred journal or where the full-text was not available were also excluded.

Following the deletion of duplicate studies from the search yield, the abstract and title of the remaining studies were assessed independently by two examiners (JC, TP) and the level of agreement recorded. Studies that remained after the application of inclusion and exclusion criteria were obtained in full-text before being assessed for their appropriateness for inclusion in the review by both examiners in consultation.

2.2. Assessment of characteristics of studies

The methodological quality of the included studies was evaluated independently by two examiners (JC, TP) using a checklist validated for the assessment of the methodological rigor of both controlled and non-controlled studies (Downs & Black, 1998). The Downs and Black checklist has been used previously in systematic reviews that have yielded studies of various designs (Hartling, Crumley, Klassen & Pickett, 2004; Oliver, Connelly, Victor, Shaw, & Whitehead, 2007) and has been shown to have good intra-rater ($r = 0.88$) and inter-rater ($r = 0.75$) reliability (Downs & Black, 1998). The last item of the checklist examining the power of results was adjusted (Deshpande, Khoja, & McKibbon, 2008) so that the maximal quality index that a study could score was 28 points. Discrepancies in ratings of methodological quality between examiners were resolved by discussion until a consensus was reached. Studies were not excluded on the basis of quality. The pathology being investigated, exercise prescription parameters and electromyographic recording protocols were also extracted from each of the included studies.

2.3. Data analysis

The review articles were read and data were extracted by one reviewer (JC) and checked by a second (TP). Pre–post data were extracted from all arms of the included studies, so that in situations where a control group received an exercise intervention it was also subject to data extraction and analysis. This data included the pre and post-intervention means, standard deviations and sample sizes. Where insufficient data were available in the paper to calculate a standardised mean difference (SMD) the relevant authors were contacted by e-mail requesting the desired information. In cases where pre–post data were still not forthcoming and the relevant data were reported clearly in a graph format, the data were estimated from the graph (Herbert, 2000). Where the data provided in a study were insufficient for quantitative analysis, a narrative analysis of results was undertaken.

Analysis of the effects of therapeutic exercise interventions were conducted in appropriate randomised controlled trials (RCT's) using Comprehensive Meta-analysis Version 2 (Borenstein, Hedges, Higgins, & Rothstein, 2005) using post-intervention scores. Due to variability in electromyographic measurement protocols, and as not all outcomes were measured on the same scale, a SMD with 95% CI was calculated to allow comparison between studies. A controlled trial was considered inappropriate for between group analysis if it compared two groups with different pathologies, used healthy people as controls or used contralateral limbs as controls (See Fig. 2). A training cross-over effect has been reported between limbs in the ankle (Uh, Beynonn, Helie & Renstrom, 2000) and there was concern that a contralateral limb may not be an effective control. In controlled trials that were considered inappropriate for between group analysis, the exercise group was analysed as if it was a single-group design.

Analysis of studies with a single-group design involved the calculation of a SMD with 95% CI, this time to represent any change within the exercise group. This analysis utilised a protocol designed to deal with unavailability of full sets of raw data in reviews inclusive of non-randomised studies and also to ensure that the calculation of single-group effect sizes focused on change within an individual (Dodd, Taylor, & Damiano, 2002). This calculation involved the estimation of the pre–post test reliability of studies where the full data set was unavailable using the most conservative pre–post reliability score from available data sets.

It is generally recommended that meta-analysis not be performed in reviews that include a mix of randomised and non-randomised studies (Egger, Schneider, & Davey-Smith, 1998). Accordingly, no meta-analysis was performed in this review.

3. Results

3.1. Flow of studies through the review

From 6924 studies that were identified through electronic searching and one that was identified after contacting key authors as being in press at the time of the review, 49 studies were obtained in full-text (inter-examiner agreement = 94%), of which 16 were included in the review (See Fig. 2).

3.2. Characteristics of included studies

Quality assessment scores were generally adequate and ranged from 14 to 21 (mean score = 16.5 ± 1.91) out of a possible 28 points. Scores for individual studies are reported in Appendix 2. Blinding of subjects was only undertaken by one of the studies (Cowan, Bennell, Crossley, Hodges, & McConnell, 2002), and as would be expected no blinding of the therapist was reported in any of the studies. Studies also scored poorly on items 21 and 22 of the checklist which refer to selection bias, and all single-group studies did not score on items 14, 15, 23 and 24 as these four items target the management of control groups, which are not present in single-group studies. Consequently the highest achievable score was 28 points for a controlled study and 24 for a single-group study. A lack of blinding and the presence of selection biases can potentially lead to an overestimation of effect size (Borenstein, Hedges, Higgins, & Rothstein, 2009) and should be taken into consideration when interpreting the results of this review.

Controlled trials made up 11 out of the 16 included trials, although five of these were considered to be inappropriate for between group analyses. The remaining five studies were of a single-group pre-post test design. Only five included studies reported adequate data for quantitative analysis in the text of their

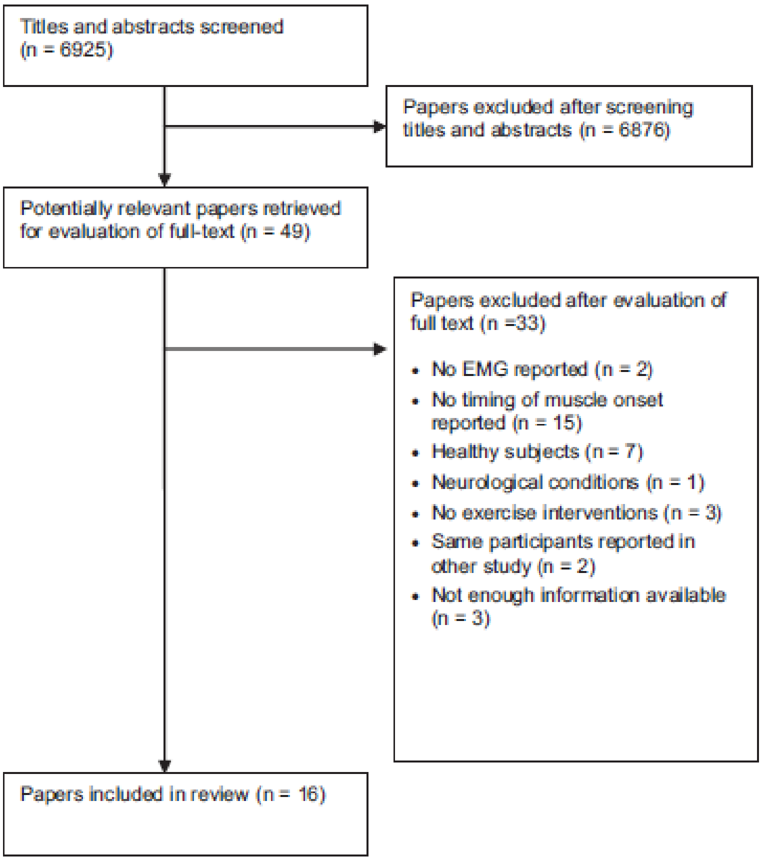

Fig. 2. Flow of studies through the review.

publication, although fortunately most authors were willing to provide required data upon request. Data were unable to be obtained in one study because insufficient data were reported in the text and no response was received from the authors (Chmielewski, Rudolph, & Snyder-Mackler, 2002), and in one other study the required data were unavailable due to damage to vital hardware (Marshall & Murphy, 2008). A summary of included studies is reported in Table 1.

Included studies used at least one of three different exercise modes: isolated muscle training, instability training and general strength training. Combinations of these modes were also present so that the 19 arms of included studies that involved therapeutic exercise were each grouped into one of the following categories: instability training ($n = 5$), isolated muscle training ($n = 4$), general strength training ($n = 5$), general strength/instability training ($n = 4$), general strength/isolated muscle training ($n = 1$).

All included studies described their electromyography recording protocol in detail. The majority of studies used surface electrodes ($n = 11$) with the others using intramuscular electrodes ($n = 5$). Data sampling rates ranged from 500 Hz to 5 kHz. It is commonly recommended that electromyographic sampling be performed at a frequency of at least 800 Hz, as recording below this rate may affect accuracy and resolution of the signal (ISEK, 1997). One study included in the review (Javed, Walsh, & Lees, 1999) used a sampling rate below this level (500Hz), and consequently care must be expressed when interpreting the results of this particular study. A wide variety of approaches were used to determine the exact timing of muscle onset. Visual inspection of the electromyogram signal was used in seven studies, with various computer algorithms used in the others.

Studies that investigated onset timing of muscles around the ankle measured timing in response to an ankle inversion perturbation controlled by a trapdoor. Muscle onset times of TrA or the deep cervical flexor muscles (DCF) were measured in people with chronic nonspecific low back or neck pain in response to a perturbation created by the subject performing a repeated arm flexion/extension movement. Two separate studies measured the onset of the vastus medialis oblique (VMO) relative to the VL during stair ascent and descent in people with PFPS (Boling, Bolgla, Mattacola, Uhl, & Hosey, 2006; Cowan et al., 2002).

3.3. Effect of interventions

For all intervention groups, the muscle onset timing SMD scores are shown in Table 2 for RCT's, and in Table 3 for single-group pre–post test design analyses.

3.3.1. Isolated muscle training

The effects of isolated muscle training were measured by three RCT's and one single-group study. In one study of people with low back pain (Tsao, Galea, & Hodges, 2010) isolated muscle training was found to be superior to walking at improving the onset timing of TrA following two weeks of training in response to both arm flexion (SMD = 2.08, 95% CI 0.95 to 3.21) and extension perturbations (SMD = 1.44, 95% CI 0.43 to 2.45), and superior to general strength training immediately following training in response to an arm extension perturbation (SMD = 2.44, 95% CI = 1.29 to 3.6) in one other study (Tsao & Hodges, 2007). Single-group analysis also supported the finding that isolated muscle training can improve muscle onset timing of TrA in subjects with low back pain. Tsao and Hodges (2008) reported that TrA recruitment was significantly improved from baseline in response to both arm flexion and extension perturbations immediately after one session, after two weeks and four weeks of training, and that the effects had persisted at the six-month follow-up. These outcomes are presented in Table 3. One study (Jull, Falla, Vicenzino, & Hodges, 2009) found that isolated muscle training was no better than general strength training at improving the onset time of the DCF muscles in people with chronic nonspecific neck pain after six weeks of exercise in response to arm flexion (SMD = 0.17, 95% CI −0.47 to 0.80) and extension (SMD = 0.47, 95% CI −0.17 to 1.12) perturbations.

3.3.2. Isolated muscle training and general strength training combined

Isolated muscle training was combined with general strength training in one study that also used other common physiotherapeutic modalities such as patellofemoral joint taping in people with PFPS (Cowan et al., 2002). This combined approach was effective at improving the onset timing of the VMO relative to the VL muscle after six weeks of training during both stair ascent (SMD = 3.72, 95% CI 2.66 to 4.87) and stair descent (SMD = 7.83, 95% CI 5.92 to 9.74) when compared to a control group that received placebo taping and sham ultrasound.

3.3.3. Instability training

The effect of instability training on muscle onset timing was compared to a control group that did no exercise in two RCT's. One study (Clark & Burden, 2005) found no difference between groups for both the onset of peroneus longus (SMD = 0.75, 95% CI −0.19 to 1.69) and tibialis anterior (SMD = 0.92, 95% CI −0.03 to 1.88). Similarly, Eils and Rosenbaum (2001) also found no difference between groups for peroneus longus (SMD = 0.1, 95% CI −0.4 to 0.6) and tibialis anterior (SMD = 0.31, 95% CI −0.28 to 0.91). Single-group analysis of the effects of instability training was undertaken in three studies. The outcomes of these studies were mixed and are reported in Table 3.

3.3.4. Instability and general strength training combined

One controlled trial (Marshall & Murphy, 2008) investigated the effect of combined instability training and general strength training on the onset time of TrA/IO compared to a no exercise group in people with low back pain. Although no data was available to undertake quantitative analysis, the study reported no differences between groups in muscle onset timing in the text of the study. The same training intervention was investigated using a single-group design in another study (Marshall & Murphy, 2006), and reported no significant changes in muscle onset timing of TrA/IO in people with low back pain after 4 weeks, 8 weeks, 12 weeks or 6 months of training. One study (Boling et al., 2006) undertook a single-group analysis of the effect of instability training used in combination with general strength training on the onset time of VMO relative to VL in people with PFPS with strong positive results after six weeks. The results of all single-group analyses are reported in Table 3.

Chmielewski et al. (2002) investigated the effects of a combination of instability training and general strength training following acute rupture of the anterior cruciate ligament of the knee. Although there were insufficient data for quantitative analysis to be undertaken by this review no changes in the onset timing of the VL, medial gastrocnemius, soleus or biceps femoris muscles were reported during walking following the intervention which lasted an average of 20 days.

3.3.5. General strength training

General strength training was compared directly to isolated muscle training in two controlled studies, the results of which are reported above and in Table 3 (Jull et al., 2009; Tsao & Hodges, 2007). General strength training was reported to be inferior at changing TrA onset timing in people with chronic nonspecific low back pain in response to an arm extension perturbation, although no differences

Table 1
Summary of included studies.

Study	Design	Participants	Intervention	Outcome measures
Instability training				
Akhbari et al. (2007)	Single-group pre-post test Quality score: 14	$n = 15$ Exp FAI	Exp = Biode × stability system training × 4 wks 12 min × 3/week	Surface EMG: PL, TA (6 weeks) • Inversion trapdoor • Sampling rate: 1 kHz • Onset decision: 3 SD's above baseline
Clark and Burden (2005)	RCT Quality score: 17	$n = 10$ Exp $n = 9$ Con Both = FAI	Exp = wobble-board training × 4 wks 12 min × 3/week Con = no exercise	Surface EMG: PL, TA (6 weeks) • Inversion trapdoor • Sampling rate: 1 kHz • Onset decision: 2 SD's above baseline
Eils and Rosenbaum (2001)	RCT Quality score: 14	$n = 31$ Exp $n = 17$ Con Both = FAI	Exp = instability circuit training × 6 wks 5–10 min warm-up then 45 s × 12 stations of various instability apparatus × 1/week Con = no exercise	Surface EMG: PL, TA (6 weeks) • Inversion trapdoor • Sampling rate: 1 kHz • Onset decision: visual inspection
Javed et al. (1999)	Prospective cohort with two groups that have different conditions: single-group analysis undertaken Quality score: 17	$n = 10$ unrehabilitated ankle sprain (6–8 wks) $n = 10$ FAI	Exp (unrehabilitated sprain) = wobble-board training daily HEP × 6/weeks Con (FAI) = surgery	Surface EMG: PL (6 weeks) • Inversion trapdoor • Sampling rate: 500 Hz • Onset decision: visual inspection
Osborne et al. (2001)	RCT but used contralateral limbs as controls: single-group analysis undertaken Quality score: 18	$n = 8$ unrehabilitated ankle sprain (6–18 months) $n = 8$ contralateral limbs	Exp (unrehabilitated sprain) = ankle disk training 15 min daily HEP × 8/weeks Con = no exercise	Surface EMG: PL, TA (8 weeks) • Inversion trapdoor • Sampling rate: 5 kHz • Onset decision: 3 SD's above baseline
Isolated muscle training				
Jull et al. (2009)	RCT Quality score: 17	$n = 18$ Isolated $n = 20$ General strength Both = Chronic nonspecific neck pain	Isolated = craniocervical flexion with biofeedback unit in-rooms × 1/week, HEP twice daily × 6 wks 3 × 10 × 5–10 s isometric holds General strength = cervical flexion with high load × 6 wks in-rooms × 1/week, HEP twice daily 1 × 12–15 (12RM) for first 2 wks 3 × 10 (50%, 75%, 10RM) for next 4 wks	Intramuscular EMG: DCF (6 weeks) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: visual inspection
Tsao and Hodges (2007)	RCT Quality score: 19	$n = 11$ Isolated $n = 11$ General strength Both = Chronic nonspecific lbp	Isolated = abdominal hollowing taught with RTU 3 × 10 × 10 s isometric holds at 5% RMS max General strength = general strength training slow sit-up training	Intramuscular EMG: TrA (immediate) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: visual inspection
Tsao and Hodges (2008)	Single-group pre–post test Quality score: 15	$n = 9$ Exp Chronic nonspecific lbp	Exp = abdominal hollowing taught with RTU × 4 wks twice-daily HEP 3 × 10 × 10 s isometric holds	Intramuscular EMG: TrA (immediate, 2 wks, 4 wks and 6 months) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: visual inspection
Tsao et al. (2010)	RCT Quality score: 21	$n = 10$ Exp $n = 9$ Con Both = Chronic nonspecific lbp	Exp = abdominal hollowing taught with RTU × 4 wks twice-daily HEP 3 × 10 × 10 s isometric holds Con = walking × 10 min twice-daily HEP	Intramuscular EMG: TrA (2 weeks) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: visual inspection
General strength training				
Hall et al. (2009)	Single-group pre-post test Quality score: 16	$n = 10$ Chronic nonspecific lbp	Exp = non-isolated core muscle co-contraction training abdominal curl up, side bridge and birddog 5 × 7 s isometric holds	Intramuscular EMG: TrA (immediate) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: visual inspection

(continued on next page)

Table 1 (*continued*)

Study	Design	Participants	Intervention	Outcome measures
Leinonen et al. (2000)	RCT but compared to healthy controls: single-group analysis undertaken Quality score: 16	$n = 19$ Exp (chronic lbp) $n = 19$ Con (Healthy)	Exp = general strength training LL progressive resistance exercise × 1 h in-rooms × 3/week, HEP × 5/week × 10 weeks Con = no exercise	Surface EMG: Gluteus maximus (10 wks) • Measured % of trunk flex/ext cycle • Sampling rate: 2 kHz • Onset decision: +10 μV from baseline
General strength and instability training				
Boling et al. (2006)	RCT but compared to healthy controls: single-group analysis undertaken Quality score: 18	$n = 14$ Exp (PFPS) $n = 14$ Con (Healthy)	Exp = general strength progressions using balance pads 3 × 10 LL progressive resistance exercises × 6 wks in-rooms × 1/week, HEP × 2/week Con = no exercise	Surface EMG: VMO vs. VL (6 wks) • Stair ascent/descent perturbation • Sampling rate: 1 kHz • Onset decision: 3 SD's above baseline
Chmielewski et al. (2002)	Single-group pre-post test Quality score: 17	$n = 9$ Exp Acute ACL rupture	Exp = perturbation training on unstable platforms × 1 h LL progressive resistance exercise × 2–6/wk × 3 wks	Surface EMG: VL,BFem,MG,soleus (3 wks) • Measured % of gait cycle • Sampling rate: 960 Hz • Onset decision: 2.5 times resting signal
Marshall and Murphy (2006)	Single-group pre–post test Quality score: 15	$n = 18$ Exp Chronic lbp	Exp = swiss ball and progressive resistance exercise 2–3 × 8–10 for first 4 weeks with isometric focus 2–3 × 6–8 for next 8 weeks with isotonic focus In-rooms × 1/week, HEP × 2/week	Surface EMG: TrA/IO (1,2,3, and 6 months) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: Integrated profiling
Marshall and Murphy (2008)	RCT Quality score: 16	$n = 24$ Exp (instability and general strength) $n = 26$ Con (general strength) Chronic lbp	Exp = see above Con = commonly prescribed low back strength exercises	Surface EMG: TrA/IO (1,2,3, and 6 months) • Arm flex/ext perturbation • Sampling rate: 2 kHz • Onset decision: Integrated profiling
General strength and isolated muscle training				
Cowan et al. (2002)	RCT Quality score: 19	$n = 22$ Exp $n = 18$ Con PFPS	Exp = isolated VMO exercise using EMG biofeedback and other physiotherapeutic i nterventions including general strength training, taping and stretching in-rooms × 1/week, twice daily HEP × 6 weeks Con = placebo taping and sham ultrasound	Surface EMG: VMO vs. VL (6 wks) • Stair ascent/descent perturbation • Sampling rate: 1 kHz • Onset decision: 3 SD's above baseline

Exp = experimental group, Con = control group, RCT = randomised controlled trial, FAI = Functional ankle instability, TrA = transversus abdominus, DCF = deep cervical flexors, PL = peroneus longus, TA = tibialis anterior, SD = standard deviation, wks = weeks, RTU = real-time ultrasound, lbp = low back pain, LL = lower limb, PFPS = patellofemoral pain syndrome, VMO = Vastus medialis oblique, VL = vastus lateralis, BFem = biceps femoris, MG = medial gastrocnemius, IO = internal oblique.

Table 2
Standardised mean difference (95% CI) of changes in muscle onset timing: between group analysis.

Study	Groups: mean (SD)		Difference between groups
	Instability training	Control	Standardised mean difference (95% CI)
Clark and Burden (2005)			
PL – inversion	61.9 (16.5)	73.2 (11.5)	0.75 (−0.19 to 1.69)
TA - inversion	63.3 (12.7)	75.3 (12.1)	0.92 (−0.03 to 1.88)
Eils and Rosenbaum (2001)			
PL – inversion	64.8 (6.2)	65.4 (5.4)	0.1 (−0.4 to 0.6)
TA - inversion	72.6 (6.7)	74.6 (5.5)	0.31 (−0.28 to 0.91)
	Isolated muscle training	General strength training	
Jull et al. (2009)			
DCF – arm flexion	157.3 (45.1)	165.8 (59.1)	0.17 (−0.47 to 0.80)
DCF – arm extension	81.6 (29.3)	98.9 (40.6)	0.47 (−0.17 to 1.12)
Tsao and Hodges (2007)			
TrA – arm flexion	0.003 (0.014)	−0.006 (0.026)	−0.38 (−1.23 to 0.46)
TrA – arm extension	0.054 (0.015)	0.116 (0.031)	2.44 (1.29 to 3.6)
	Isolated muscle training	Control	
Tsao et al. (2010)			
TrA – arm flexion	−0.012 (0.016)	0.035 (0.026)	2.08 (0.95 to 3.21)
TrA – arm extension	0.008 (0.023)	0.043 (0.024)	1.44 (0.43 to 2.45)
	Isolated and general strength training	Control	
Cowan et al. (2002)			
VMO vs. VL – stair ascent	4.5 (2.6)	−7.4 (3.7)	3.72 (2.66 to 4.78)
VMO vs. VL – stair descent	14.6 (3.3)	−15.8 (4.4)	7.83 (5.92 to 9.74)

TrA = transversus abdominus, DCF = deep cervical flexors, PL = peroneus longus, TA = tibialis anterior, VMO = vastus medialis oblique, VL = vastus lateralis.

between groups were evident during arm flexion. No difference was shown between groups between these two training types in improving the onset timing of the DCF muscles. Single-group analyses of two other studies investigating the effect of general strength training in people with chronic nonspecific low back pain were also undertaken. One study (Leinonen, Kankaanpaa, Airaksinen, & Hanninen, 2000) investigating the effect of six weeks of general strength training on the onset timing of gluteus maximus during trunk flexion and extension reported positive results, while the other (Hall et al., 2009) investigated the immediate effects of general strength training on TrA onset but did not find statistically significant effects for any variables. These single-group analyses are reported in Table 3.

3.4. *Exercise prescription parameters*

3.4.1. *Isolated muscle training*

Isolated muscle training was used to target the onset timing of TrA in people with low back pain, the DCF muscles in people with chronic neck pain, and the VMO in people with PFPS. It has been proposed that this approach might possibly work by facilitating neuroplastic changes within the motor cortex (Tsao et al., 2010). In each case a form of biofeedback was used to assist in achieving an isolated muscle contraction. Real-time ultrasound was employed to train TrA, an air-filled pressure sensor (Stabilizer™, Chattanooga Group Inc. USA) was used to train a craniocervical flexion movement which targets the DCF muscles, and a dual-channel surface electromyography biofeedback unit was used to train the VMO relative to the VL muscle. Exercise dosages were quite consistent between studies. Subjects were instructed to perform 3 sets of 10 repetitions of 5–10 s isometric holds with 3–5 s rest between contractions, and 2 min rest between sets. When prescribed as a home exercise this regimne was completed twice daily. Isometric holds were a sub-maximal effort, for example subjects aimed to contract their TrA at 5% of their maximum electromyographic amplitude. This low level of contraction was performed to reflect the low levels of activation in the TrA seen during functional movement (Tsao & Hodges, 2008).

3.4.2. *Instability training*

Instability training prescription parameters were quite diverse, although all studies that used instability training employed some type of unstable surface. These included wobble boards ($n = 4$), swiss balls ($n = 2$), an air-filled balance pad ($n = 2$), and the Biodex stability system ($n = 2$). In one study (Chmielewski et al., 2002) the therapist applied graded levels of external perturbations to challenge the balance of the subject while they stood on an unstable surface such as a rollerboard. Exercise sessions ranged from 12 min to 1 h in length. Frequency ranged from once a week to a daily home exercise program, and training program durations ranged from three to twelve weeks.

3.4.3. *General strength training*

Exercise prescription parameters for general strength training consisted of progressive resistance exercise progressions that were varied between studies. Both isometric holds and movements through range were employed, although no effort was made to isolate the activation of a specific muscle. Exercise frequencies ranged from three sessions a week to twice-daily home exercise programs, and training programs were maintained from 6 to 12 weeks.

4. Discussion

The results of quantitative analysis undertaken in this review suggest that it is possible to use therapeutic exercise to alter muscle onset timing following injury. There were three key modes of exercise identified by the review: instability training, isolated muscle training and general strength training. Isolated muscle training was consistently shown to alter muscle onset timing of TrA in people with chronic low back pain, and was better than a control at doing this after two weeks of training (Tsao et al., 2010). Single-group analyses suggested that isolated muscle training was superior to general strength training at improving TrA onset timing in this population. The exercise dosage prescribed for isolated muscle training was 3 sets of 10 isometric holds of 5–10 s. When performed as a home exercise this routine was performed twice a day.

The mechanisms for changes in the temporal characteristics of muscle activation following isolated muscle activation are still not definitive. It has been proposed that reorganisation of neuronal networks within the motor cortex following isolated muscle training may be an important contributing factor towards changes to the onset timing of TrA in subjects with low back pain (Tsao et al., 2010). Isolated muscle training requires greater levels of precision and attention than the other training modalities identified by this review. It has been suggested that these two characteristics may

Table 3
Standardised mean difference (95% CI) of changes in muscle onset timing: single-group analysis.

Study	Pre-post test results: mean (SD)		Change within groups
	Pre-test	Post-test	Standardised mean difference (95% CI)
Instability training			
Akhbari et al. (2007)			
PL – inversion	71.4 (3.8)	52.9 (2.0)	6.21 (3.14 to 9.28)
TA - inversion	65.5 (6.3)	46.6 (1.0)	4.21 (2.07 to 6.35)
Javed et al. (1999)			
PL – inversion	72.9 (5.3)	63.2 (4.1)	2.03 (0.63 to 3.43)
Osborne et al. (2001)			
PL – inversion	52.3 (45.1)	42.8 (25.2)	0.26 (−0.63 to 1.15)
TA - inversion	67.6 (20.3)	51.7 (17.6)	0.84 (−0.18 to 1.86)
Isolated muscle training			
Tsao and Hodges (2008)			
TrA – arm flexion (immediate)	0.031 (0.02)	0.01 (0.025)	0.74 (0.57 to 0.91)
TrA – arm extension (immediate)	0.067 (0.028)	0.038 (0.027)	1.03 (0.88 to 1.18)
TrA – arm flexion (2 weeks)	0.031 (0.02)	−0.015 (0.022)	2.19 (1.15 to 3.23)
TrA – arm extension (2 weeks)	0.067 (0.028)	0.019 (0.029)	1.7 (1.12 to 2.28)
TrA – arm flexion (4 weeks)	0.031 (0.02)	−0.023 (0.012)	3.16 (1.38 to 4.94)
TrA – arm extension (4 weeks)	0.067 (0.028)	0.012 (0.026)	1.99 (1.19 to 2.79)
TrA – arm flexion (6 months)	0.031 (0.02)	0.001 (0.019)	1.51 (0.66 to 2.36)
TrA – arm extension (6 months)	0.067 (0.028	0.01 (0.023)	2.17 (0.97 to 3.37)
General strength training			
Hall et al. (2009)			
TrA – arm flexion	−0.019 (0.036)	−0.015 (0.052)	−0.08 (−0.54 to 0.38)
TrA – arm extension	0.055 (0.038)	0.044 (0.023)	0.28 (−0.05 to 0.61)
Leinonen et al. (2000)			
GMax – trunk flexion	6.1 (5.3)	11.4 (7.9)	0.79 (0.09 to 1.49)
GMax – trunk extension	59.2 (6.7)	54 (4.9)	0.89 (0.17 to 1.61)
Instability and general strength training			
Boling et al. (2006)			
VMO vs. VL – stair ascent	−22.4 (29.1)	40.8 (50.5)	1.53 (0.49 to 2.57)
VMO vs. VL – stair descent	−50.6 (81.9)	37.3 (45.2)	1.33 (0.37 to 2.29)
Marshall and Murphy (2006)			
TrA/IO – arm flexion (1 month)	59.9 (13.0)	55.4 (23.7)	0.24 (−0.4 to 0.88)
TrA/IO – arm extension (1 month)	−2.2 (17.5)	6.8 (17.9)	−0.5 (−1.17 to 0.17)
TrA/IO – arm flexion (2 months)	59.9 (13.0)	50.5 (20.9)	0.542 (−0.13 to 1.21)
TrA/IO – arm extension (2 months)	−2.2 (17.5)	4.5 (25.2)	−0.31(−0.95 to 0.33)
TrA/IO – arm flexion (3 months)	59.9 (13.0)	46.9 (24.6)	0.66 (−0.03 to 1.35)
TrA/IO – arm extension (3 months)	−2.2 (17.5)	2.1 (23.9)	−0.21 (−0.85 to 0.43)
TrA/IO – arm flexion (6 months)	59.9 (13.0)	49.8 (27.6)	0.47 (−0.19 to 1.13)
TrA/IO – arm extension (6 months)	−2.2 (17.5)	−2.6 (24.4)	0.02 (−0.61 to 0.65)

TrA – transversus abdominus, DCF – deep cervical flexors, PL – peroneus longus, TA = tibialis anterior, VMO = vastus medialis oblique, VL = vastus lateralis, GMax = Gluteus maximus, VMO = Vastus medialis oblique, VL = vastus lateralis, IO = internal oblique, immed. = Immediate.

promote greater changes in the motor cortex when compared with training sessions incorporating the use of multiple muscles at once such as general strength or instability training (Boudreau, Farina, & Falla, 2010). Indeed the motor skill learning literature identifies that novel motor skill training results in an increased representation of the trained muscle in the primary motor cortex when compared to more general exercises (Remple, Bruneau, VandenBerg, Goertzen, & Kleim, 2001; Tsao et al., 2010).

Currently results from controlled trials do not support the individual use of instability or general strength training to improve muscle onset timing. Single-group analyses do however suggest that instability training may have an effect at improving the timing of the peroneus longus and tibialis anterior in people with FAI or an unrehabilitated ankle sprain, and that strength training may improve the onset timing of gluteus maximus in people with chronic low back pain. A combined physiotherapeutic approach incorporating general strength training, with or without the use of isolated muscle training, is also effective at improving the onset timing of VMO relative to VL in people with PFPS after six weeks of training. Due to the multimodal interventions used in these trials however it is not possible to determine which, if any, of the exercise modalities contributed to these effects.

It has been reported that instability training may lead to a reduced reaction time of stabilising muscles by improving the sensitivity of joint position sense and by creating a more synchronised contraction pattern to aid in the correction of excessive positions (Sheth, Bing, Laskowski, & Kai-Nan, 1997). It remains contentious whether possible improvements from instability training might stem from adaptations within the central nervous system (Osborne, Chou, Laskowski, Smith, & Kaufman, 2001) or structures in the periphery (Konradsen, Voigt, & Hojsgaard, 1997).

Interestingly, although a large number of conditions have been identified as involving altered muscle onset timing, only a small number were covered by the review. It is currently unknown whether the effect of exercise on muscle onset timing is the same in different pathologies and subsequently further investigation may be warranted into how muscle onset timing is affected by therapeutic exercise in other conditions where dysfunctional muscle onset timing has been identified.

This systematic review had certain limitations. Foremost, analyses of single-group changes do not account for the effect of time. A review that is limited to RCT's would be of value when sufficient trials exist. Also, studies not published in the English language and grey literature such as university theses and conference proceedings were not included in the review. As a result, publication bias may have influenced the results (Borenstein et al., 2009). Although methodological quality was fairly consistent between studies, the absence of appropriate blinding of subjects and therapists in many of the studies may also have led to an overestimation of effect size of the studies included in this review.

This review has successfully identified that it is possible to change muscle onset timing using therapeutic exercise. Isolated muscle training is effective at achieving these changes in TrA in people with low back pain. The use of instability training to improve muscle onset timing of the peroneus longus and tibialis anterior in FAI lacks evidence from good quality controlled trials. General strength training was found to be ineffective at changing the muscle onset timing of TrA and DCF muscles in people with low back pain and chronic neck pain respectively, although weak evidence was found that this exercise mode may improve the muscle onset timing of gluteus maximus in people with low back pain. Further high quality research is required to establish what exercise prescription parameters are most effective at restoring muscle onset timing in response to both anticipated and unanticipated postural perturbations in conditions known to involve dysfunctional muscle onset timing.

4.1. Practical applications

Following musculoskeletal pathology, where a disorder of muscle onset timing has been identified, practitioners should consider the use of isolated muscle training to restore the timing of muscle onset. It is recommended that a dosage of 3 sets of 10 isometric holds of 5–10 s be performed twice daily to achieve these effects.

Practitioners should exercise caution when prescribing both instability training and general strength training to improve muscle onset timing as research on these two exercise modes is currently limited and inconclusive.

Conflict of interest
None declared.

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Not applicable.

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Appendix 1. Strategy

MEDLINE and EMBASE (inception to March 2010)

1.	Exercise
2.	Exercise Therapy
3.	Rehabilitation
4.	Physical Therapy
5.	1 OR 2 OR 3 OR 4
6.	Electromyography
7.	Activation
8.	Timing
9.	Onset
10.	Peak amplitude
11.	Pattern ADJ2 activation
12.	Duration
13.	Latency
14.	Recruitment
15.	7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14
16.	5 AND 6 AND 15

CINAHL (inception to March 2010)

1.	Exercise
2.	Exercise Therapy
3.	Rehabilitation
4.	Physical Therapy
5.	1 OR 2 OR 3 OR 4
6.	Electromyography
7.	Activation
8.	Timing
9.	Onset
10.	Peak Amplitude
11.	Pattern N2 activation
12.	Duration
13.	Latency
14.	Recruitment
15.	7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14
16.	5 AND 6 AND 15

AUSPORT (Inception to March 2010)

1.	Exercis*
2.	Rehabilitation
3.	Physical ! therapy
4.	Physiotherapy
5.	Conservative
6.	Train*
7.	Stabili*
8.	1 OR 2 OR 3 OR 4 OR 5 OR 6 OR 7
9.	Electromyograph*
10.	EMG
11.	9 OR 10
12.	Activation
13.	Timing
14.	Onset
15.	Peak ! amplitude
16.	Pattern
17.	Duration
18.	Latency
19.	Recruitment
20.	12 OR 13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19
21.	8 AND 11 AND 20

SPORTDISCUS (Inception to March 2010)

1.	Exercise
2.	Exercise therapy
3.	Rehabilitation
4.	Physical therapy
5.	Physical therapists
6.	1 OR 2 OR 3 OR 4 OR 5
7.	Electromyography
8.	Activation
9.	Timing
10.	Onset
11.	Peak amplitude
12.	Pattern N2 activation
13.	Duration
14.	Latency
15.	Recruitment
16.	8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 OR 15
17.	6 AND 7 AND 16

Cochrane Database (Inception to March 2010)

1.	Exercise
2.	Rehabilitation
3.	Physical NEXT therapy
4.	Physiotherapy
5.	Conservative
6.	Train*
7.	Stabili*
8.	1 OR 2 OR 3 OR 4 OR 5 OR 6 OR 7
9.	Electromyograph*
10.	EMG
11.	9 OR 10
12.	Activation
13.	Timing
14.	Onset
15.	Peak NEXT amplitude
16.	Pattern NEAR activation
17.	Duration
18.	Latency
19.	Recruitment
20.	12 OR 13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19
21.	8 AND 11 AND 20

PEDro (Inception to March 2010)

1.	Electromyograph*
2.	Exercis*
3.	Rehabilitation
4.	Physiotherap*
5.	"Physical therapy"
6.	Conservative
7.	Stabili*
8.	Activation
9.	Train*
10.	2 OR 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9
11.	1 AND 10

Appendix 2.
Downs and Black checklist scores of included studies.

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	Total (0–28)
Akhbari, Takamjani, Salatavi, and Sanjari (2007)	1	1	1	0	2	0	1	0	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	1	0	14
Boling et al. (2006)	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	1	1	0	18
Chmielewski et al. (2002)	1	1	1	1	2	0	1	1	1	1	1	0	1	0	0	1	0	1	0	1	0	0	0	0	1	1	0	17
Clark and Burden (2005)	1	1	1	1	2	0	1	1	1	0	0	0	1	0	0	1	1	1	0	1	0	0	0	0	1	1	1	17
Cowan et al. (2002)	1	1	1	1	2	0	1	1	1	0	0	0	1	1	1	1	1	1	0	1	0	0	1	1	0	1	0	19
Eils and Rosenbaum (2001)	1	1	1	1	2	1	1	1	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	1	0	14
Hall et al. (2009)	1	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	1	0	16
Javed et al. (1999)	1	1	1	0	2	1	1	1	1	1	0	0	1	0	0	1	0	1	0	1	0	0	0	0	1	1	1	17
Jull et al. (2009)	1	1	1	1	2	0	1	1	1	0	0	0	1	0	1	1	1	1	0	1	0	0	1	0	0	0	1	17
Leinonen et al. (2000)	1	1	1	0	2	1	1	1	1	0	0	0	1	0	0	1	1	1	0	1	0	0	0	0	1	1	0	16
Marshall and Murphy (2006)	1	1	1	1	1	0	1	1	1	0	0	0	1	0	1	1	1	1	0	1	0	0	0	0	0	1	0	15
Marshall and Murphy (2008)	1	1	1	1	2	0	1	1	1	0	0	0	1	0	1	1	1	1	0	1	0	0	0	0	0	0	1	16
Osborne et al. (2001)	1	1	1	1	2	1	1	0	1	1	0	0	1	0	0	1	1	1	0	1	1	0	0	0	0	1	1	18
Tsao and Hodges (2007)	1	1	1	1	2	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	1	0	1	1	0	19
Tsao and Hodges (2008)	1	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	15
Tsao et al. (2010)	1	1	1	1	2	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	1	1	1	1	1	21

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Chapter Three: Improving Muscle Activation Using Therapeutic Exercise: An Exploration of Clinical Practice

The systematic review completed in the previous chapter provided support for the use of therapeutic exercise to improve muscle activation impairments following injury and also some limited insight into effective exercise prescription parameters. However, it provided no specific evidence relating to exercise selection following hamstring muscle injury. Consequently, it was decided that further information was required to guide the design of a major research project.

The clinical practices in the fields of physiotherapy and strength and conditioning were explored to identify practices relating to the use of exercise prescription to address muscle activation following injury. Current practices and expert opinion in both physiotherapy (Chapter 3.1) and strength and conditioning (Chapter 3.2) are examined below.

3.1 Clinical practice and expert opinion within the field of physiotherapy

To better understand current practice within the field of physiotherapy, expert practitioners were identified and invited to attend a workshop on the topic of 'Muscle activation around the hips and pelvis in the context of Australian Football'. The objective of the workshop was to facilitate discussion and information-sharing between expert practitioners, while allowing the documentation of key findings and trends relevant to this thesis. The workshop was organised by the candidate, who was also the sole author of the workshop booklet, and workshop report.

3.1.1 Method

Leaders in the field of physiotherapy with specific expertise on muscle activation around the hips and pelvis were identified and recruited to attend a half-day workshop hosted by the

Collingwood Football Club on 9th August, 2010 at the Westpac Centre in Melbourne, Australia.

Invited attendees included:

- Professor Shirley Sahrmann (Washington University): Physical therapist renowned for her work on the classification of movement disorders around the hip and pelvis and had recently supervised research publications specifically addressing muscle activation around the hips and pelvis.
- Dr. Alison Grimaldi (University of Queensland): Physiotherapist who completed her PhD on muscle function around the hip and was identified as an expert in the use of real-time ultrasound to address muscle activation impairments.
- Mrs. Leanne Rath: Specialist sports physiotherapist with experience working with the Australian Ballet and at the Australian Institute of Sport. Mrs. Rath has also lectured on the hip/pelvic complex and was known to be an innovative thinker on the workshop topic.
- Mr. Paul Coburn: Specialist sports physiotherapist with 10 years of experience working at the Richmond Football Club in the AFL and had co-authored two recent qualitative analyses on the prevention and management of hamstring injuries and groin pain in the AFL.

Representatives of the host organisation including physiotherapists, club doctor and exercise physiologists also attended the workshop. In advance of the workshop, workshop attendees were provided with a booklet inclusive of an agenda, brief narrative review of the topic which included information on Australian Football for the benefit of the international attendee, case study and short biographies of the workshop participants. The workshop booklet, including the brief narrative review, is contained within **Appendix B**.

The workshop began with each invitee spending twenty minutes speaking about their current research interests and initial thoughts about the topic. A discussion about the potential role of muscle activation exercise during the preparation for an Australian Football match or training session was facilitated next.

The invited guests were then challenged to identify future directions relating to the topic and suggest what they would consider worthy of investment over the next few years. Discussion then moved onto the different effects that surgical and medical management options might have in inhibiting muscle activity.

The workshop concluded with the presentation of a case study which invitees were encouraged to consider. The case presentation described the physical characteristics of a typical Australian Football player.

3.1.2 Results

A full workshop report, including notes from the discussion and key learnings for the host organisation, was produced and is contained within **Appendix C.**

Key findings from the exploration that are relevant to this thesis are listed below:

- Delayed onset of gluteus maximus and multifidus and an earlier onset of biceps femoris has been reported in patients with sacroiliac joint pain (Hungerford et al., 2003). It was postulated that this pattern may also be seen following hamstring muscle injury.
- Isolated muscle activation exercise targeting muscles around the hips and pelvis may be introduced into warm-up routines before football matches and training sessions once quality of exercise can be assured.
- The most common therapeutic exercise prescription used to address muscle activation was 5-10 second isometric holds of isolated muscles repeated 10 times.

- The prescription of voluntary isometric contractions of the gluteus maximus was commonly accompanied by low load hip extension movement in clinical practice.
- There were also specific reports of the use of voluntary isolated muscle exercise targeting the gluteus maximus in conjunction with low load prone hip extension exercises in warm-up protocols for both hamstring injury rehabilitation and hamstring injury prevention.
- Prescription of therapeutic exercise by expert practitioners was also highly dependent on their assessment of the capacity of the patient at any given time. Expert coaching of movement quality was seen as a key to this process.
- Some level of variability in muscle recruitment patterns was considered to be normal and healthy.
- Hip morphology may play a role in activity of the muscles around the hips and pelvis and may be a factor in variation in running gaits.

The findings listed above were used to inform the design of the major research project for this thesis.

3.2 Current practice within the field of strength and conditioning

Strength and conditioning coaches are generally viewed as having expertise in exercise prescription and consequently time was invested in observing expert practitioners and studying current practice in this field. The process culminated in the accreditation of the author as a strength and conditioning coach and publication of the manuscript "The role of the strength and conditioning coach in optimising muscle patterning following injury".

Note that videos that are referred to in the manuscript were available on the journal website at the time of publication. The accreditation process included in-person education modules and assessment of both practical and theoretical competency.

Key findings from the process that are relevant to this thesis are listed below:

- While muscle activation patterns are considered to have high importance by practitioners in the field of strength and conditioning, the equipment required to reliably quantify muscle activation impairment or measure progress, is generally not available in these settings.
- Expert strength and conditioning coaches place high value on visual assessment and coaching of movement quality and posture within the context of a whole functional and sport-specific movement. Video assessment is sometimes used to assist this process.
- In general, more complex and functional movements are prescribed by strength and conditioning coaches post-injury compared to those typically observed in physiotherapy practice.
- It is common for strength and conditioning coaches to prescribe low-load warm-up exercises to be completed immediately before training and competition. These are usually termed 'activation' exercises and aim to illicit an acute improvement in the activation of the targeted muscle during subsequent activity.

Strength and conditioning coaches generally had only minimal involvement in the management of athletes in the early stages of their rehabilitation. This was possibly a result of a limitation in the education provided to strength and conditioning coaches about injury pathology.

Movement quality has been defined as "the way in which human movement is executed with respect to the dimensions of time and space" (Wallbott, 1989). In the manuscript below the optimisation of muscle patterning refers to the utilisation of a muscle activation pattern by an individual that maximises movement quality.

The manuscript is presented below in its peer-reviewed and published format:

Crow, J. (2011). The role of the strength and conditioning coach in optimising muscle patterning following injury. *Journal of Australian Strength and Conditioning,* 19(3), 100-104.

The Role of the Strength and Conditioning Coach in Optimising Muscle Patterning Following Injury.
J. Aust. Strength Cond. 19(3)100-104. 2011 ©ASCA

LEVEL 2 SUBMISSION

THE ROLE OF THE STRENGTH AND CONDITIONING COACH IN OPTIMISING MUSCLE PATTERNING FOLLOWING INJURY.

Justin Crow

ABSTRACT

Following injury muscle recruitment patterns can become altered and persist even once the athlete becomes asymptomatic. Ensuring optimal recruitment patterns in athletes is an important part of both rehabilitation and the prevention of injury recurrence. This article considers the evidence relating to this issue and discusses strategies that strength and conditioning coaches can employ to assist in the optimisation of muscle activation patterns during training. These strategies include training without pain, training in neutral joint postures, encouraging smooth and well-controlled movements, the utilisation of the acute effects of isolated muscle activation, and instability training.

INTRODUCTION

Under normal conditions large variations in muscle recruitment patterns have been observed in healthy individuals (1). Following injury however, pathological muscle patterns can develop (9,17). A new theory on pain adaptation (10) explains that in response to pain or pathology in a joint the muscles around that joint will adapt to protect the joint by either:

a) becoming overactive to splint the joint and therefore reduce movement
b) becoming underactive to reduce movement around the joint
c) redistribute their activity to alter force transfer through the joint

Unfortunately, we can no longer assume that these patterns return to normal once a person becomes asymptomatic, as new research has revealed that these muscle patterns are often persistent even once a person becomes pain-free (12).

Although altered muscle patterning is likely to be of benefit in the short term, persistent changes in muscle activation are potentially detrimental to performance and may expose a person to risk of injury recurrence. For example, the deep fibres of the multifidus muscle in the back have been shown to have persistent altered onset patterning following an episode of acute low back pain. These fibres are expected to contribute two-thirds of the control of the intersegmental motion of the spine (21). This is important because where a person does not have the ability to adequately fine tune their spinal movement, they are more likely to be placing unwanted stress through their spine and may be placing themselves at an elevated risk of injury recurrence. Interestingly, following an acute episode of low back pain that becomes asymptomatic, 34% of people will experience a recurrence within one year (20).

Altered muscle onset timing has been reported following a growing number of musculoskeletal injuries that are listed in Table 1.

Table 1 - Examples of altered muscle onset timing.

Injury	Muscles affected
Shoulder impingement (13)	Scapula stabilisers: serratus anterior and upper, middle and lower trapezius.
Shoulder pain (6)	Subscapularis
Longstanding groin pain (3)	Transversus abdominus
Functional ankle instability (16)	Peroneus longus Peroneus Brevis Tibialis Anterior
Patellofemoral Pain Syndrome (2)	Vastus Medialis Oblique
ACL injury (22)	Quadriceps
Knee osteoarthritis (7)	Vastus lateralis
Hip arthroplasty (19)	Gluteus medius
Low back pain (8)	Transversus abdominus Multifidus
Neck pain (5)	Deep cervical flexors
Sacroiliac joint pain (11)	Transversus Abdominus

HOW THE COACH CAN HELP

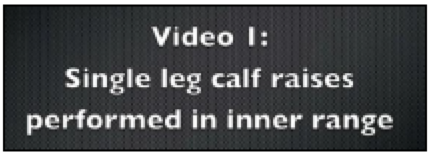
When involved in the rehabilitation and conditioning of an athlete following injury a strength and conditioning coach should be aware of strategies to help optimise muscle patterning in their athletes. Strategies are discussed below:

1. Train pain-free

To give your athlete the best chance of performing a movement with an optimal muscle pattern it needs to be pain-free. Otherwise the neural system is more likely choose to adopt one of its short-term joint protection strategies.

- If necessary modify load to avoid pain.
- Where possible adjust technique to eliminate any painful response.
- Where only one part of the athlete's range of movement is painful, the athlete will still get some benefit from training in their non-painful range.

Example: In insertional achilles tendinopathy athletes get pain in end of range ankle dorsiflexion as the achilles tendon wraps around the calcaneum creating a compressive force. Video 1 shows single leg calf raises being performed so that end of range dorsiflexion is avoided and the exercise remains pain-free. Also, notice that the exercise is performed with a forward trunk lean and some slight knee flexion to replicate the bodies position when accelerating during running.



Video 1 - Single leg calf raises performed in inner range.

2. Train in a neutral posture

Evidence suggests that optimal muscle activation is more likely to occur in neutral joint postures[14,15].

- Educate athlete about the location of neutral joint position.
- Use biofeedback such as mirrors and video.
- Ensure neutral posture can be maintained before progressing exercise.

Example: In upper limb pressing exercises an anterior scapula tilt can alter length-tension relationships around the shoulder and predispose to shoulder impingement syndrome.

Figure 1 - Anterior scapula tilt.

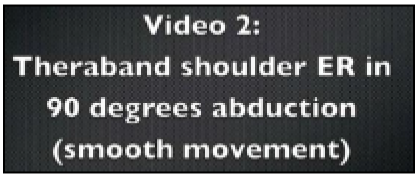
Figure 2 - Neutral scapula tilt.

3. Quality of movement

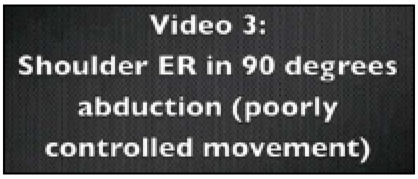
Smooth movement is indicative of good joint control and optimal muscle activation patterns.

- Train movements with controllable levels of complexity and speed.
- Provide biofeedback to athlete to assist their movement quality.
- Ensure good movement quality is achieved before progressing exercise.

Example: Theraband shoulder external rotation is an exercise designed to target two of the rotator cuff muscles: infraspinatus and teres minor. These two muscles are primarily composed of slow-twitch muscle fibres that control and fine-tune shoulder movement. It is a reasonable assumption that during a smooth, well-controlled external rotation movement that they would demonstrate good activation (**Video 2**). However, in the absence of good rotator cuff activation it is possible to rely on the posterior portion of deltoid, a primarily fast-twitch muscle, to externally rotate the shoulder. In which case you might expect to see a grosser, less well-controlled external rotation movement (**Video 3**).



Video 2 - Theraband shoulder ER in 90° abduction (smooth movement).



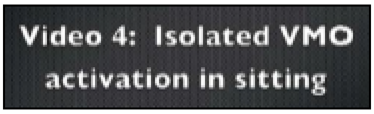
Video 3 - Theraband shoulder ER in 90° abduction (poorly controlled movement).

4. Isolated muscle activation

Where possible it may be worthwhile incorporating some isolated muscle activation training into an athlete's warm-up. Low load isometric holds of isolated muscles have the acute effect of improving muscle onset timing during functional movements (4). Importantly, these effects are observed immediately after completion of the exercise (18).

- Where possible use biofeedback to ensure precision of the isolated exercise.
- The literature recommends 3 x 10 holds of 5-10 seconds (4).
- Consider also prompting the athlete to engage the targeted muscle at the start of a training movement to encourage its activation during the exercise.

Example: Isolated activation of the vastus medialis oblique (VMO) muscle of the knee may be indicated following knee pain or injury. In the presence of knee pain, swelling or instability the VMO can become delayed or weaker in its activation during movement. VMO activation during knee extension is important in maintaining good patella tracking and reducing the likelihood of any anterior knee pain. The athlete or coach can easily use palpation to provide biofeedback about this particular muscle's activation, as when it is activated the athlete will be able to feel the VMO contract under their fingertips **(Video 4)**. A useful cue to encourage activation of the VMO in sitting is to get the athlete to gently press their heel into the ground. This exercise may be an appropriate inclusion to a warm-up in athletes who have had anterior knee pain or other knee injury



Video 4 - Isolated VMO activation in sitting.

5. Instability training

Training on an unstable surface has been suggested as a way of improving muscle reaction times and although there is only mixed evidence to support its use (4) it may be worthy of consideration for inclusion in the warm-ups of athletes following injury. Another similar training option is perturbation training during which external perturbations are provided by the coach to the athlete with varying degrees of force and random timing to simulate a competitive environment.

- Consider instability training in the context of the whole body.
- Start with low levels of instability, low force perturbations and eyes open.
- Progress to eyes closed, greater instability and higher forces with multidirectional components.

Example: Instability training using an unstable surface such as a wobble-board or foam mat is well documented. Internal and external perturbations to balance can be provided by the coach by including tasks such as bouncing a ball (**Video 5**) or gently pushing the athlete with their eyes closed.

Video 5 - Single leg stance on a foam mat with an additional ball-bouncing task.

Practical Applications

1. When managing an athlete following injury, even once they become asymptomatic, a coach should be aware that optimal muscle patterning may not have returned.
2. In these situations a coach should ensure that their athlete trains pain-free, trains in a neutral posture wherever possible, and performs exercises with a good quality of movement.
3. The coach may also consider the use of isolated muscle training or instability training to optimise muscle patterning following injury.

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Chapter Four: Examining the Practicalities of Running an Investigation Into the Use of Targeted Therapeutic Exercise in a Professional Australian Football Setting

Exercise utilising low loads may activate the central nervous system to create a favourable environment for the performance of explosive movements (Verkoshansky, 1986). The gluteal muscle group is involved in the production of force during fast, powerful movements such as sprinting and jumping (Lieberman, Raichlen, Pontzer, Bramble, & Cutright-Smith, 2006) and low load exercises targeting the gluteal muscle group may be prescribed to improve the activation of these muscles before the introduction of more complex and explosive movements (Saez de Villarreal, Gonzalez-Badillo, & Izquierdo, 2007). In Chapter Three it was observed that the low-load gluteal muscle activation exercises typically used to target improvements in explosive movement are very similar to those commonly used to address the temporal characteristics of muscle activation following injury.

A research study was designed to assess the practicality and potential efficacy of using a low-load activation warm-up exercise protocol in a professional Australian Football setting. It was intended that the completion of this study would provide insight and direction to guide the design of the major research project. The use of a WBV training group was to satisfy other research interests within the professional football environment and maximise the use of the time of the professional football players who were recruited into the study. The research study investigated the effect of a warm-up exercise protocol, consisting of a series of seven low-load exercises targeting the gluteal muscle group, on peak power production during a CMJ in professional Australian Football players. The exercises selected were based on EMG data reported in previous literature (Ekstrom, Donatelli, & Carp, 2007) and are detailed in Table 1 within the published manuscript. The trial was conducted in a practical gym setting. As well as using a control intervention (no warm-up), the trial also compared the effect of weight-bearing vibration intervention on peak power production, which was of interest to the host organisation at the time. No warm-up was conducted prior to any of the interventions as part of the study design as this may have created an interference effect for the interventions.

Practical findings relevant to the design of the major research project are listed below:

- An acute improvement in power output was observed following the series of low load exercises targeting the gluteal muscle group.
- Pre-season is a good time for research of this nature to be conducted as it allows for greater access to professional players and improved likelihood of endorsement from coaching staff.
- The two exercises that were observed to be completed with the highest quality of movement were the prone single leg hip extension and the double leg bridge.
- While a dosage of 1 x 10 repetitions was effective practically, when repeated over 7 different exercises, some decrease in quality of exercise performance was observed.
- Time allocated to warm-ups competes with the time allocated for actual training both in the gym and on the field. Consequently, in this setting, shorter warm-up protocols are highly desirable.
- Training related soreness and absence due to illness are both factors that affect the ability to do practical research within a professional football setting.
- It was still unclear if it was just a general warm-up effect that improved peak power and it may be better in future to look at a specific exercise rather than a collection of exercises that may just have a general warm-up effect.

Since muscle activation was not specifically measured in this research study, the role of low load muscle activation exercises in improving muscle activation, and in turn contributing to improved power output on CMJ, is hypothetical only.**The manuscript is presented below in its peer-reviewed and published format:**

Crow, J., Buttifant, D., Kearney, S., & Hrysomallis, C. (2012). Low load exercises targeting the gluteal muscle group acutely enhance explosive power output in elite athletes. *Journal of Strength and Conditioning Research,* 26(2), 438-442.

Low Load Exercises Targeting the Gluteal Muscle Group Acutely Enhance Explosive Power Output in Elite Athletes

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Abstract

Crow, JF, Buttifant, D, Kearny, SG, and Hrysomallis, C. Low load exercises targeting the gluteal muscle group acutely enhance explosive power output in elite athletes. *J Strength Cond Res* 26(2): 438–442, 2012—The purpose of this study was to investigate the acute effect of 3 warm-up protocols on peak power production during countermovement jump (CMJ) testing. The intention was to devise and compare practical protocols that could be applied as a warm-up immediately before competition matches or weight training sessions. A group of 22 elite Australian Rules Football players performed 3 different warm-up protocols over 3 testing sessions in a randomized order. The protocols included a series of low load exercises targeting the gluteal muscle group (GM-P), a whole-body vibration (WBV) protocol (WBV-P) wherein the subjects stood on a platform vibrating at 30 Hz for 45 seconds, and a no-warm-up condition (CON). The CMJ testing was performed within 5 minutes of each warm-up protocol on an unloaded Smith machine using a linear encoder to measure peak power output. Peak power production was significantly greater after the GM-P than after both the CON ($p < 0.05$) and WBV-P ($p < 0.01$). No significant differences in peak power production were detected between the WBV-P and CON. These results have demonstrated that a low load exercise protocol targeting the gluteal muscle group is effective at acutely enhancing peak power output in elite athletes. The mechanisms for the observed improvements are unclear and warrant further investigation. Coaches may consider incorporating low load exercises targeting the gluteal muscle group into the warm-up of athletes competing in sports requiring explosive power output of the lower limbs.

Key Words vertical jump, warm-up

Introduction

Explosive power output of the lower limbs is one of the key determinants of performance in many elite sports (10) and is required to perform jumping, sprinting, and many weightlifting activities (15). Consequently, warm-up protocols are often used in an attempt to optimize power production during explosive movements (18) for both competition and weight training purposes. One common test of the peak power output of the lower limbs is the countermovement jump (CMJ). Warm-ups incorporating both high (4,25) and low load (20) exercises, usually involving the squat exercise, have both been reported to be effective at improving CMJ performance. It is possible that, if they could be shown to improve explosive power characteristics in athletes, low load warm-up exercises may be of value to coaches because they are less likely to induce athlete fatigue before competition or weight training sessions.

It has been suggested that performing exercise with low loads may activate the central nervous system to create a favorable environment for the performance of explosive movements (24). The gluteal muscle group is a key contributor to explosive movements of the lower limb including sprinting and jumping (13). During a CMJ, the gluteus maximus, medius, and minimus are all highly activated (10,14). Modeling suggests that although the gluteus maximus generates large force and work output in the sagittal plane, the gluteus medius and minimus also play substantial roles in the generation of a jumping motion by stabilizing the movement of the hip joint (15). Low load isometric exercises of the transversus abdominus have been demonstrated to acutely improve the activation of this muscle during functional movement (23). It is currently unknown whether this acute carryover effect might be transferrable to muscles involved in lower limb power production such as the gluteal muscle group.

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It has also been suggested that the exposure to mechanical vibrations, often referred to as whole-body vibration (WBV) training, may be of use when preparing an athlete for explosive athletic events (11). Research into the acute effects of WBV on the explosive characteristics of elite athletes, however, shows mixed results. Cochrane and Stannard (5) reported improved vertical jump height after a WBV warm-up protocol in elite athletes when compared with that in control conditions ($p < 0.001$). However, another study found that WBV had no acute effect on any CMJ parameters, including peak velocity and acceleration in elite athletes, and that after WBV, the subjects had a decreased total vertical distance traveled in an unloaded squat jump when compared with a control condition ($p = 0.006$) (3).

The intention of the study was to devise and compare practical protocols that could readily be applied as a warm-up immediately before competition or weight training sessions with consideration given to the minimization of fatigue. The specific purpose of this study was to investigate and compare the acute effect of a warm-up protocol incorporating low load exercises targeting the gluteal muscle group (GM-P), a WBV warm-up protocol (WBV-P), and a control group (CON) on peak power production during CMJ testing. Consequently, the study attempted to address the research question: "Which is the most effective warm-up protocol in terms of its effect on peak power production during CMJ testing: GM-P, WBV-P, or CON?"

Methods

Experimental Approach to the Problem

Two warm-up protocols were devised that could be easily applied as a warm-up either precompetition or before weight training sessions with a minimal risk of fatigue. The first used low load exercises targeting the gluteal muscle group (GM-P), whereas the second incorporated the use of WBV (WBV-P). A third protocol designed to act as a control was also incorporated (CON). To address the research question, and establish which of the 3 warm-up protocols was the most effective, the subjects were randomly allocated into 3 separate groups with each completing all 3 warm-up protocols: WBV-P, GM-P, and CON. Testing was conducted over 3 different sessions in a randomized order. This randomized, counterbalanced, repeated measures design was employed to analyze differences in peak power production during CMJ testing (dependent variable) among the 3 different warm-up protocols (independent variables). The CMJ testing was performed using a Smith machine so that peak power could be measured using a linear encoder.

Subjects

Thirty elite Australian Rules Football players were recruited in the study. All the players were healthy at the commencement of the study. All the players provided informed consent to participate in the study, and institutional ethics approval was granted to retrieve and analyze deidentified data after the completion of the testing.

Procedures

Three testing sessions were held on training days over a 10-day period during the team's preseason training phase. No 2 sessions were conducted on consecutive days to avoid the effects of fatigue from training or testing. All the training sessions were of a similar intensity and volume. The testing sessions were performed in the late morning 1 hour after the completion of a field training session. Given this consistent time of testing and the professional environment, it could be expected that players' arousal levels would have remained consistent for the duration of the study. The WBV-P consisted of subjects standing with 10–30° knee flexion in an unloaded static squat stance with feet shoulder width apart for 45 seconds on a side-alternating platform vibrating at 30 Hz and an amplitude of 6.4 mm. The protocol was conducted on a commercially available Galileo Sport machine (Novotec, Pforzheim, Germany). Enhanced electromyographic (EMG) activity has been reported with increasing frequencies on side-alternating platforms up to 30 Hz (17).

The GM-P consisted of 7 exercises performed in sequence. One set of 10 repetitions was performed for each exercise. The subjects were familiar with all the exercises before the study and were encouraged to maintain a neutral spinal posture. The use of a verbal cue to engage the gluteal muscles before movement may be of benefit in improving gluteal muscle activation during exercise (12). The subjects were consequently instructed to engage their gluteal muscle group before and during the exercise movements. The exercise

Table 1. Electromyographic muscle activation levels for gluteus maximus and gluteus medius during GM-P exercises (mean ± *SD*).*

Exercise	Gluteus maximus (% MVIC)	Gluteus medius (% MVIC)
Double leg bridge (9)	25 ± 14	28 ± 17
Quadruped lower extremity lift (9)	42 ± 17	56 ± 22
Quadruped hip abduction (2)	N/A	N/A
Side lying clam in 60° hip flexion (7)	39 ± 34	38 ± 29
Side lying hip abduction (9)	21 ± 16	39 ± 17
Prone single leg hip extension (12)	22 ± 10	N/A
Double leg stability ball squat (2)	N/A	N/A

*GM-P = warm-up protocol targeting the gluteal muscle group; MVIC = maximum voluntary isometric contraction; N/A = appropriate electromyographic data not available.

Table 2. Player characteristics and previous maximal VJ height values (mean ± *SD*).*†

Group	Age (y)	Height (cm)	Body mass (kg)	Previous maximal VJ height (cm)
Group 1 ($n = 8$)	22.6 ± 4.2	184.2 ± 8.8	84.1 ± 9.9	68.0 ± 4.3
Group 2 ($n = 7$)	21.6 ± 3.6	190.0 ± 10.2	90.8 ± 11.3	68.9 ± 6.7
Group 3 ($n = 7$)	23.0 ± 3.5	187.4 ± 5.6	84.1 ± 6.2	70.1 ± 5.2

*VJ = vertical jump test.
†No statistical differences between groups ($p > 0.05$).

protocol was performed under supervision and took approximately 5–7 minutes to complete.

The 7 exercises in the GM-P included a double leg bridge, side lying hip abduction exercise, and quadruped lower extremity lift that were performed as described by Ekstrom et al. (9) except in the case of the quadruped lower extremity lift where, in this study, no arm movement was involved. A side lying gluteal clam in 60° hip flexion was performed as described by Distefano et al (7). A prone single leg hip extension exercise was performed using verbal cues according to a protocol described by Lewis and Sahrmann (12). The remaining 2 exercises, stability ball wall squats and hip abduction in quadruped or "dirty dog," were performed according to the instructions in the American Council on Exercise online library of exercises (2). Where available, previous data on EMG recordings of gluteus maximus and gluteus medius muscle activation during these exercises are listed in Table 1. The CON group performed no specific preparation before CMJ peak power testing.

Testing of peak power was undertaken within 5 minutes of the performance of each warm-up protocol. The subjects performed 5 consecutive CMJs using a Smith machine with a bar mass of 20 kg, and no additional weight was added. The players jumped off and landed on a thin foam mat. Peak power was measured using a Gymaware linear encoder (Kinetic, Mitchell, Australia), which was secured to the floor directly below the Smith machine bar at one end. An infrared receiver enabled data captured by the encoder to be saved on a palm top and subsequently downloaded to a computer. The use of a linear encoder has been shown to be valid and reliable (6,8). Jump technique was closely monitored to ensure consistency of testing. In particular, the subjects were not allowed any upward movement of the bar before commencing their countermovement. The highest peak power achieved during the 5 jumps was used for analysis.

Statistical Analyses

A Shapiro-Wilk's (<50 subjects) test was found to have an alpha level of $p > 0.05$ indicating that all data were normally distributed. A repeated measures analysis of variance (ANOVA) was used to investigate any differences between conditions. After the ANOVA, a pairwise comparison post hoc test was performed with a Bonferroni adjustment. Baseline comparability was established using a Student's *t*-test to assess any differences in age, body mass, height, or previous vertical jumping performance between groups. Statistical analysis was conducted using SPSS (SPSS Inc, Chicago, IL, USA). In all cases, the alpha level was set at 0.05.

Results

Twenty-two of the subjects completed all the 3 testing conditions. Eight subjects each missed 1 testing session because of training-related soreness ($n = 7$) or absence because of illness ($n = 1$) and were consequently excluded from the analysis. No subjects were injured during the testing. No differences were found between the baseline characteristics of the 3 testing group's height, body mass, age, and previous best vertical jumping height ($p > 0.05$). Baseline characteristics are reported in Table 2.

Table 3 shows the differences in peak power production during CMJ testing between the 3 warm-up protocols. Repeated measures ANOVA showed a significant difference in peak power production between warm-up protocols during CMJ testing ($F = 6.376$, effect size = 0.233, $p < 0.01$). Pairwise comparisons found that the subjects performed 4.2% better after the GM-P than after the CON condition ($p < 0.05$), and 6.6% better than in the WBV-P condition ($p < 0.01$). A 2.4% decreased performance for the WBV-P compared with that of the CON was found to be nonsignificant ($p > 0.05$).

Table 3. Peak power during CMJ testing ($n = 22$) after different warm-up protocols (mean ± *SD*).*

Warm-up protocol	Peak power (W)
GM-P	4,565 ± 634†‡
WBV-P	4,267 ± 658†
CON	4,374 ± 659‡

*WBV-P = whole body vibration warm-up protocol; GM-P = warm-up protocol targeting gluteal muscle group; CON = control group; CMJ = countermovement jump.
†Significant difference between GM-P and WBV-P ($p \leq 0.05$).
‡Significant difference between GM-P and CON ($p \leq 0.05$).

Discussion

The results demonstrate improved peak power production during CMJ testing after the GM-P when compared with that of both CON and WBV-P and suggest that the low load warm-up protocol described in this article may be a useful tool for coaches who desire to enhance the explosive power of their athletes before either competition or training. This protocol would be most applicable for athletes competing in sports with high demands for explosive power output from the lower limbs and has the obvious advantage, because of the low loads involved in the protocol, of minimizing any risks of fatigue or injury before performance. The other advantage is that no equipment is required and makes the protocol suitable for a large portion of athletes at various levels of competition.

The results of this study are consistent with those of other research in healthy active men, which demonstrated that improved CMJ height and mean power output can be achieved with a warm-up incorporating light loads (25–35% 1RM) (20). Interestingly however another study in highly trained subjects reported that a warm-up involving low loads (30% 1RM) was inferior to one involving high loads (80–95% 1RM) at improving CMJ performance (18). Neither of these 2 other studies however specifically targeted the gluteal muscle group and instead used 5 minutes of generalized cardiovascular warm-up followed by loaded half squats. It is possible that a series of low load exercises targeting the gluteal muscle group may influence explosive characteristics differently to the protocols undertaken in the 2 previous studies.

Postactivation potentiation has been proposed as a mechanism for improved power production following a voluntary contraction of a muscle (21). However, this contraction is typically performed at maximal or near-maximal intensity and many of the proposed mechanisms, which include phosphorylation of myosin regulatory light chains and a possible change in pennation angle (21), are unlikely to be applicable after low-intensity exercise (19). The enhancement in power production after low-intensity exercise that was observed in this study is likely to be because of other mechanisms. It has been reported that low-level isometric contractions of the transversus abdominus muscle have the acute effect of increasing activation levels of this muscle during functional tasks (23). These increases are accompanied by altered motor cortical activity measured with transcranial magnetic stimulation (22). It is possible that exercises eliciting low to moderate levels of activation of the gluteal muscle group such as those contained in the GM-P may also lead to a transfer of increased muscle activation within the gluteal muscle group to functional movements such as countermovement jumping. Future research could validate the findings of this study with EMG recordings of the gluteal muscle group during CMJ testing and other measures of explosive power output both before and after the performance of the GM-P.

The results also demonstrate that the WBV-P used in this study was not effective at improving peak power production during CMJ testing when compared with control. This result is consistent with the findings of Bullock et al. (3) who reported no changes in any CMJ performance parameters after 3 × 1 minutes of vibration exposure when compared with a control protocol. One other study that reported improved vertical jump heights postvibration in elite athletes applied a vibration exposure that lasted for 5 minutes and included dynamic exercises (5). It is possible that the differences in vibration exposure times and the inclusion of dynamic exercises on the WBV machine might explain the difference in results. The WBV-P in this study was dictated by a number of practical considerations: It was intended as a warm-up immediately before matches and at half-time, and given the limitations of the number of WBV machines available and warm-up time required for a team of 22 players, the exposure time was set at 45 seconds and WBV dynamic exercises were avoided to minimize fatigue. Another reason, which may have contributed to the WBV-P not being effective, is the knee flexion range used by the players. Pilot work revealed that WBV with the knees extended frequently resulted in discomfort to the lower back and head regions. The players were instructed to bend their knees slightly and hold the self-selected position, which ranged from 10 to 30°. It is now acknowledged that having a 10–30° range of knee flexion can influence the level of transmissibility, but it is unclear as to what the difference in the magnitude of the transmissibility is to the gluteal region. It has been reported that head acceleration decreased by about 50% by increasing the knee flexion angle from 10 to 30° (1). Whether transmissibility to the gluteal muscles is influenced by the same magnitude is unknown given that gluteal EMG data were not reported and the gluteal region is significantly closer in proximity to the knees than to the head. It is not only the distance that varies but also the number of joints and other structures capable of dissipation such as the intervertebral joints and discs. The WBV can be performed with the feet flat or with the heels raised. Enhanced activation of the knee extensors (rectus femoris and vastus medialis) and the hip extensor (biceps femoris) was found for normal stance with the feet on the platform compared with raising the heels off the platform (16). Although the gluteals were not directly monitored, it could be expected that the normal stance position would be more favorable for not only the biceps femoris but also the other hip extensors such as the gluteal maximus.

Despite some players dropping out because of non-experimental condition factors, training-related soreness ($n = 7$) and absence because of illness ($n = 1$), an even spread of subjects across testing groups was present, and a sufficient number of subjects were included in the analysis to ascertain any differences between warm-up protocols. No control for hydration status was undertaken in the study, and it is possible that mild variations in hydration levels may have existed between the groups. However, it was considered unlikely that, except in cases of severe dehydration, this variation would have affected explosive output during a single set of jumps. There was no indication that any of the athletes were dehydrated during any of the testing.

This study has investigated the specific research question, "Which is the most effective warm-up protocol in terms of its effect on peak power production during CMJ testing: WBV-P, GM-P, or CON?" It has demonstrated that improved peak power production during CMJ testing is possible by undertaking a low load warm-up protocol that targets the gluteal muscle group. It has also found that a short-duration WBV protocol was no better than control at improving peak power production in highly trained elite Australian Rules Football players.

Practical Applications

A warm-up protocol involving low load exercises targeting the gluteal muscles is effective at acutely enhancing explosive power output in the lower limbs. Coaches may consider this protocol when preparing athletes for competition or training in sports involving explosive lower limb movements such as jumping, sprinting, and some weightlifting movements. Low load exercises of this nature are likely to be more acceptable to the athlete and coach than are protocols incorporating heavier loads because of a lower risk of athlete fatigue and no equipment requirement. Coaches of athletes in sports involving explosive lower limb movements should also exercise some caution when deciding how best to use WBV in the lead up to competition or training sessions because the WBV-P used in this study did not acutely enhance jumping performance in elite athletes.

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Chapter Five: Does a Recent Hamstring Muscle Injury Affect the Timing of Muscle Activation During High-Speed Overground Running in Professional Australian Football Players?

5.1 Background

Changes to the timing of muscle activity have been reported following injury (Hodges & Moseley, 2003) and may persist after the individual becomes asymptomatic and symptoms have resolved (MacDonald et al., 2009). There is evidence to specifically support the proposition that hamstring muscle activation timing is altered following injury. Sole et al. (2012) reported earlier onset timing of the biceps femoris and medial hamstrings during transition from double leg to single leg stance following hamstring muscle injury. In contrast, another study compared the injured and uninjured limbs of a group of athletes following hamstring muscle injury and reported no differences in the temporal characteristics of hamstring muscle activation during high-speed treadmill running (Silder et al. 2010).

Differences in running kinematics and also muscle activity exist between treadmill and overground running (van Hooren et al., 2020), and the majority of hamstring muscle injuries sustained in professional football occur during overground high-speed running (Ekstrand et al., 2016). Consequently, it was decided that an overground high-speed running protocol would be the most practically relevant task to use to assess muscle activation, and also the task with the greatest potential of identifying deficits should they exist.

The focus of this thesis is the temporal aspects of muscular activation and a conscious decision was made to consider EMG amplitude measurements outside the scope of this research. Key factors in this decision included the error associated with the measurement of EMG amplitude using surface electrodes in running, challenges with the normalization of EMG amplitude, and poor between-subject reliability (Subbu, Weiler, & Whyte, 2015).

Prior to this investigation, no study had investigated the effect of a hamstring muscle injury on the muscle onset and offset timing of the gluteus maximus and hamstring muscles specifically during high-speed overground running.

5.2 Research design

A research study was designed to address two separate questions:

1. What is the impact of a hamstring muscle injury on the muscle onset and offset timing of the gluteus maximus and hamstring muscles during high-speed overground running?

2. Can a targeted exercise protocol acutely alter the temporal aspects of muscle activation of the gluteus maximus and hamstring muscles during high speed overground running?

This chapter, and the associated research publication, relate to the first question only. The second question, which was also a focus of this research study, is addressed in Chapter Six.

The ethics application relevant to this research is contained in **Appendix A**.

The participant information sheet is contained in **Appendix D.**

The participant questionnaire form is contained in **Appendix E.**

The major project recording sheet is contained in **Appendix F.**

For completeness, the research design is outlined below in **Figure 2.**

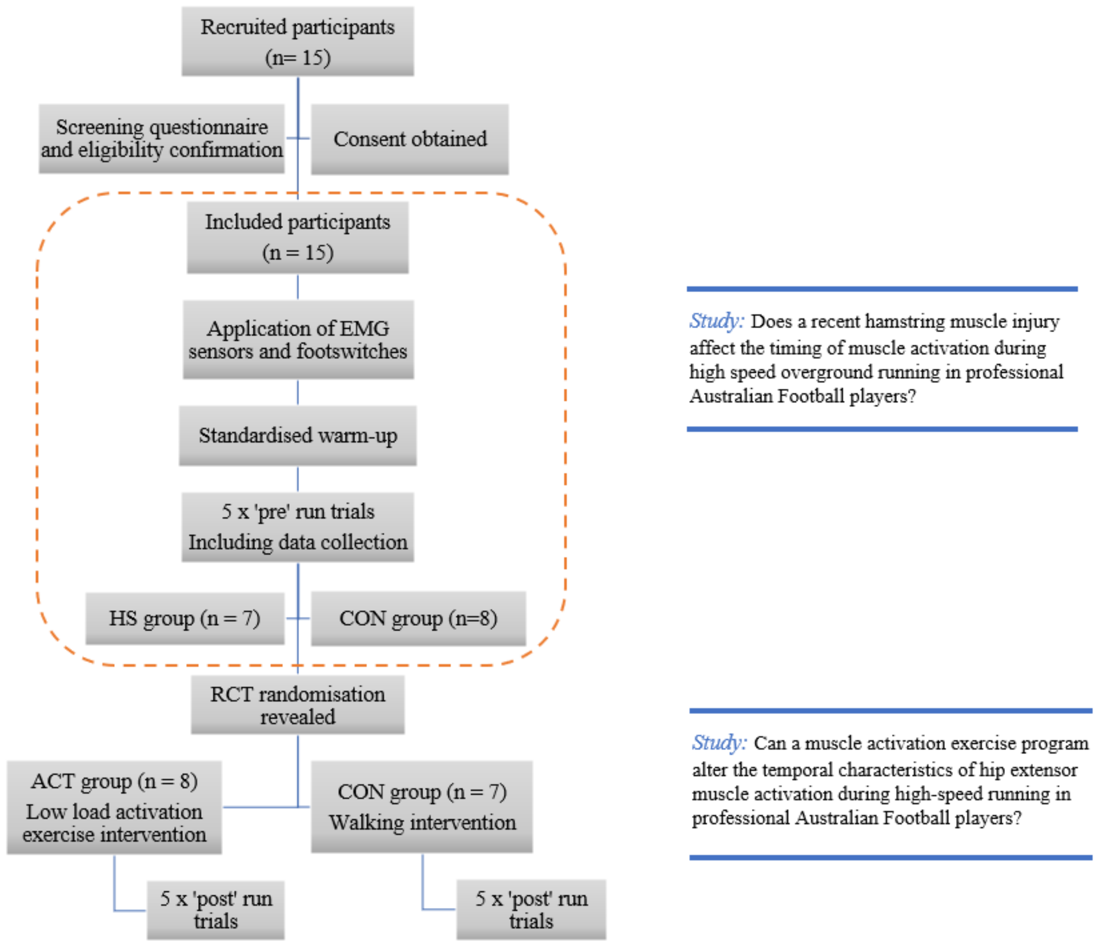

Figure 5.1: Major project research design. EMG = Electromyography; RCT = Randomised Controlled Trial; HS group = hamstring group; CON group = control group; ACT group = Activation group.

All participants included in the research design were free of complaints at the time of testing and those players with a history of HSI had been fully rehabilitated and were undertaking a full training workload at the time of the study. After RCT randomisation, the intervention group (ACT) included 4 players with a history of hamstring muscle injury, and the control group (CON) included 3 players with a history of hamstring muscle injury.

It is noted that the modest sample size in the present study (N = 15) may have played a role in limiting the significance of some of the statistical comparisons conducted. A post hoc power analysis revealed that on the basis of the mean time of muscle onset, and the effect size observed in the present study, a sample of approximately 24 would be needed to obtain a statistical power of 80% (Cohen, 1988).

The research publication that details the first component of this research study is presented below in its peer reviewed and published format:

Crow, J., Semciw, A., Couch, J., & Pizzari, T. (2020). Does a recent hamstring muscle injury affect the timing of muscle activation during high speed overground running in professional Australian Football players? *Physical Therapy in Sport,* 43, 188-194.

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Original Research

Does a recent hamstring muscle injury affect the timing of muscle activation during high speed overground running in professional Australian Football players?

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ABSTRACT

Objectives: To investigate if the temporal characteristics of hamstring and gluteal muscle activation are altered during high speed overground running in professional Australian Football players following hamstring muscle injury.
Design: Cohort study.
Setting: Field-based testing.
Participants: Elite professional Australian Football players who had sustained a hamstring muscle injury in the six months prior to testing (n = 7) and a group of players from the same club who had no history of hamstring muscle injury (n = 8).
Main outcome measures: Muscle onset timing, muscle offset timing and muscle onset duration of the medial hamstrings, biceps femoris and gluteus maximus muscles during high-speed running using electromyographic data.
Results: No significant differences in any of the temporal aspects of muscle activation were found between groups for any of the muscles tested ($p > 0.05$).
Conclusions: Persistent alterations to the timing of muscle activation following hamstring muscle injury that have been reported in recreational athletes were not observed during high speed running in professional athletes who have completed comprehensive rehabilitation programs.

1. Introduction

Hamstring muscle injuries are the most prevalent injury in professional men's football (Ekstrand, Waldén, & Hägglund, 2016). These injuries lead to significant player unavailability (Woods et al., 2004), decreased performance levels (Hägglund et al., 2013) and place a significant financial burden on clubs (Hickey, Shield, Williams, & Opar, 2014). Despite ongoing efforts at improving rehabilitation and prevention protocols there remains a high rate of injury recurrence (van Heumen et al., 2017).

The risk of injury recurrence is influenced by factors such as how recently and the number of times a previous hamstring injury was sustained by an individual (Green, Bourne, van Dyk, & Pizzari, 2020). Hamstring muscle injuries can lead to structural changes within the muscle such as local atrophy (Sanfilippo, Silder, Sherry, Tuite, & Heiderscheit, 2013) and scar tissue formation (Silder, Heiderscheit, Thelen, Enright, & Tuite, 2008). These factors may contribute to persistent physical strength deficits (Croisier, Forthomme, Namurois, Vanderthommen, & Crielaard, 2002), reduced tissue extensibility (De Vos et al., 2014), and shortened muscle fascicles (Timmins et al., 2016), which have been proposed to influence hamstring injury recurrence.

Neuromuscular inhibition is one sequelae to hamstring muscle injury that has been proposed to contribute to an increased risk of re-injury (Fyfe, Opar, Morgan, & Shield, 2013). Following pain or injury, neuromuscular inhibition in the form of aberrant muscle timing may develop (Clark & Burden, 2005; Falla, 2004; Tucker & Hodges, 2009) resulting in changes to the control and function of the affected area (Hodges & Tucker, 2011). Changes to the temporal characteristics of muscle activity have been found to exist following

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injury, even after symptoms are resolved (Crow, Pizzari, & Buttifant, 2011). It has been proposed that following hamstring injury, neural inhibitory mechanisms are most evident during maximal eccentric contractions (Fyfe et al., 2013), which corresponds to the activity of the hamstring and gluteal muscles during the late swing phase of gait when the hamstring is most vulnerable to injury (Chumanov, Schache, Heiderscheit, & Thelen, 2012).

Evidence for the value of assessing neuromuscular activation for predicting index strains is variable. It has been reported that healthy athletes with delayed onset of their hamstring muscle in a prone hip extension exercise (Schuermans, van Tiggelen, & Witvrouw, 2017a), or who have lower amounts of gluteal muscle activity during overground maximal acceleration (Schuermans, Danneels, van Tiggelen, Palmans, & Witvrouw, 2017b), were more likely to suffer a hamstring strain in the following 18 months. In contrast, another study found that onset timing of the biceps femoris and medial hamstrings during isokinetic strength testing in healthy athletes was unrelated to risk of hamstring muscle injury in the following season (van Dyk et al., 2018). Another study reported that professional Australian Football players were more likely to sustain a hamstring muscle injury during the season if they had higher gluteus medius muscle activity during treadmill running prior to the season (Franettovich Smith et al., 2017). The same study found no association between activity levels of gluteus maximus during treadmill running and future hamstring muscle injury.

There is mixed evidence that the muscle activation of the hamstring and gluteal muscles may be altered following injury. One recent study of collegiate sprinters with a history of hamstring muscle injury found reduced biceps femoris activation during late swing phase in the previously injured side compared to the uninjured side during maximal overground acceleration, but not during other phases of the running cycle, or in the gluteus maximus (Higashihara et al., 2019). Altered ratios of biceps femoris to gluteus maximus EMG activity have been reported as being isolated to the late swing phase of fast treadmill running in athletes with a history of hamstring muscle injury (Daly, McCarthy Persson, Twycross-Lewis, Woledge, & Morrissey, 2016). However, another study found no changes in the activation patterns of biceps femoris and medial hamstrings during fast treadmill running in athletes with a history of hamstring muscle injury (Silder, Thelen, & Heiderscheit, 2010).

Altered muscle activation in tasks other than running have also been investigated. Earlier onset timing of the biceps femoris and medial hamstrings has been reported during transition from double leg to single leg stance in males with a history of hamstring muscle injury (Sole, Milosavljevic, Nicholson, & Sullivan, 2012) and a lower rate of torque development of the biceps femoris has been reported during isokinetic testing in recreational athletes with a history of hamstring muscle injury (Opar, Williams, Timmins, Dear, & Shield, 2013).

The specific effects of hamstring muscle injury on the temporal characteristics of the hamstring and gluteal muscles during fast overground running remains unclear. Although previous studies have isolated changes in muscle activation levels to certain parts of the running cycle (Daly et al., 2016; Higashihara et al., 2019) there have been no studies to date that consider the specific temporal characteristics of hamstring and gluteal muscles activation during fast overground running.

The objective of this study was to investigate whether the muscle onset time, muscle offset time or duration of muscle activation in the biceps femoris, medial hamstrings or gluteus maximus are altered in high speed running following hamstring muscle injury in professional Australian Football players compared to those with no hamstring muscle injury history. The study also aimed to provide a graphical representation of muscular activity throughout the gait cycle to assist in the interpretation and understanding of the results.

2. Materials and methods

2.1. Participants

Professional male Australian Football players from a single AFL club were recruited. In total, 15 players were included in the study; seven players with a history of hamstring muscle injury within the preceding six months (HS group) and eight control participants (CON group). All previous hamstring injuries were diagnosed by medical staff at the AFL club and confirmed by magnetic resonance imaging (MRI). The most recent strain injury occurred seven weeks prior to testing. All control participants had no recorded history of a hamstring injury while contracted to play in the AFL and reported having never sustained a hamstring injury prior to the study. All participants were in full pre-season training at the time of the study, reported having no history of lower limb surgery, and had no recorded lower limb surgery while contracted to play in the AFL.

The study protocol was approved by the Faculty Human Ethics Committee (FHEC11/170), and all participants provided written informed consent.

2.2. Injury questionnaire

Participants completed a short questionnaire, which included demographic information as well as information about their injury history. Collected data were cross-referenced with comprehensive injury data maintained by the club to confirm the accuracy of self-reported injury histories.

2.3. Instrumentation and electrode placement

Surface EMG electrodes consisted of Trigno (Delsys Inc., Boston, USA) wireless sensors with a single differential configuration and a 4 bar (99.9% silver) contact area, with an inter-electrode distance of 10 mm.

Skin preparation and electrode placement were consistent with recommended SENIAM guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Gluteus maximus electrode placement was midway along a line between the greater trochanter and the sacral vertebrae. The biceps femoris electrode placement was midway along a line between the ischial tuberosity and the lateral epicondyle of the tibia, and medial hamstring electrode placement was midway along a line between the ischial tuberosity and the medial epicondyle of the tibia.

Footswitches (Model: 402, Interlink Electronics, USA) were positioned bilaterally on the plantar aspect of the heel and interphalangeal joint of the hallux, and used to record temporal aspects of the gait cycle (Semciw, Pizzari, Murley, & Green, 2013).

A Delsys Trigno Wireless 16-Channel EMG system was used to collect raw EMG signals (Delsys Inc., Boston, USA; CMRR > 80 dB @60 Hz; gain of 1000; band pass filtered at 20–450 Hz) and sampled at 2000 Hz.

Players wore a 5Hz Global Positioning System (GPS) unit (MinimaxX, Team 2.5, Catapult Innovations, Australia) in a specifically tailored garment during the testing protocol to assess maximum running speed during each trial (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010).

Ambient temperature was recorded using a portable weather metre (Kestrel 2500; Kestrel Instruments, PA, USA) during the warm-up that preceded each trial.

2.4. Study procedure

The testing procedure was conducted on a 100m stretch of grass within an outdoor field at La Trobe University, Melbourne, Australia. To negate any possible effects of fatigue or muscle soreness, participants did not engage in any intensive training within the 48 h prior to testing. Following EMG electrodes, footswitch and GPS application, the participant completed a standardised warm-up protocol consisting of 200 m of jogging followed by 100 m walk recovery. The participants next completed 100 m runs at 60%, 70%, and 80% of their perceived maximum speed consecutively with 100 m walk recovery between each effort. Participants then completed one practice trial of the testing procedure before commencing testing.

The running trial protocol was adapted from a graded running protocol developed for hamstring rehabilitation (Reid, 1993). Participant running trials were divided into a 40 m acceleration section where players commenced from a standing start and were instructed to steadily build up their speed to 90% of their perceived maximum, a 20 m middle-section where players were instructed to hold their speed at 90% of their perceived maximum, and a 40 m deceleration section where players were instructed to steadily reduce their speed so that they were walking by the end of the run. Participants then walked back the full 100 m before commencing their next trial.

Two sessions of testing were undertaken within a seven-day period and participants were randomly assigned to one of the two testing sessions.

2.5. EMG data processing and analysis

All EMG data were processed using a customised adaptation of the Biosignal EMG package (2.1.0) from R statistical software (https://www.r-project.org/, version 3.6.1). Raw EMG signals for each running trial were high pass filtered (Butterworth, 4th order, zero phase lag, 20Hz cut-off) to remove movement artefact. Data were full wave rectified and further filtered using a moving average (20 ms window). Two consecutive strides from the middle 20m of each running trial were further processed for analysis (two strides x five trials = ten strides per participant). These particular strides were chosen to decrease the likelihood that participants were accelerating or decelerating during the stride, and increase the likelihood that participants were at their highest speed at the point of analysis. In the HS group the most recently injured side was chosen for analysis. In the CON group the players preferred kicking leg (skill leg) was chosen for analysis. Individual strides were considered to start at heel contact, detected using the heel footswitch, and end at the next consecutive heel contact on the same side. The data from the gait cycle were time-normalised to 101 points (representing the gait cycle from 0 to 100% in 1% increments) enabling time-dependant analysis between groups (Schuermans, Danneels, van Tiggelen, Palmans, & Witvrouw, 2017a). Data were amplitude normalised to peak activity recorded through the running cycle.

For each muscle and participant, an ensemble average was generated from the ten strides. All participants' ensemble averages were summed and averaged to produce a grand ensemble for gluteus maximus, biceps femoris and medial hamstrings in both the HS group and the CON group. This allowed an EMG profile to be established for each muscle in each group across the high-speed running gait cycle. For each muscle and participant, the muscle onset time, muscle offset time and duration of muscle activation were calculated as a percentage of gait cycle. Muscle onset time was calculated using a customised algorithm in the R Statistical software package (version 3.6.1) and determined as the time when EMG amplitude was increased above baseline by a level of ≥15% of peak amplitude for a period of ≥10% of the gait cycle. The time of muscle offset was determined as the point when EMG amplitude returned to baseline or remained below 15% of the maximum EMG amplitude for ≥10% of the gait cycle (Chapman et al., 2006; Franettovich, Chapman, & Vicenzino, 2008); . Duration of muscle activation was the percentage of the gait cycle contained between the muscle onset and muscle offset.

Descriptive statistics (means, medians, interquartile range and standard deviations) were calculated and data reviewed for normality using boxplots and the Kolmogorov-Smirnoff (K–S) test. To compare each temporal variable for each muscle between groups, a Mann-Whitney *U* test was used, since data were not normally distributed. The comparison between demographic data was done by independent groups *t*-test.

To determine the magnitude of any differences between groups, a standardised effect size was calculated by dividing the *z*-score of the Mann–Whitney *U* test by the square root of the total sample size (Field, 2009). Effect sizes were categorised as small (0.2), medium (0.5) and large (≥0.8) (Sullivan & Feinn, 2012). All statistical comparisons were performed using the SPSS statistical software package (Version 19, IBM SPSS Inc., Chicago, IL, USA).

3. Results

Participant demographic information, environmental conditions during testing, and running speeds, are displayed in Table 1. There was no statistical difference between HS and CON groups on any of these measures.

The footswitch data of one participant (HS group) was discovered to be corrupted after testing was completed and consequently that participant's gait was unable to be analysed. Consequently, after that participant's data was discarded, analysis was conducted on the gluteus maximus, medial hamstrings and biceps femoris of remaining six participants in the HS group. With the exception of one electrode on one participant's medial hamstrings (CON group), which dislodged during testing, electrodes remained in place during the testing sessions. The biceps femoris and gluteus maximus were analysed for all eight participants from the CON group, and the medial hamstrings were analysed for seven of the eight participants in the CON group.

3.1. Gait

Fig. 1 contrasts the grand ensemble curves between the HS group and the CON group for the gluteus maximus, biceps femoris and medial hamstrings.

3.2. Temporal characteristics

No statistically significant differences were observed between HS and CON groups for muscle onset, muscle offset or the duration of muscle activation for gluteus maximus, biceps femoris or medial hamstrings between the HS group and CON group (Table 2).

4. Discussion

This study did not find any differences in the temporal characteristics of muscle activation during high speed overground running between professional Australian Football players with a recent history of hamstring muscle injury and those with no prior history of hamstring injury.

The findings of this study support the findings of previous research that reported no differences in muscle onset time, muscle offset time or the duration of muscle activity between injured and

Table 1
Participant demographic and testing information.

Variable	HS group ($n = 7$) Mean (SD)	CON group ($n = 8$) Mean (SD)	p value
Age (years)	22.3 ± 1.6	21.9 ± 1.6	0.651
Height (centimetres)	189.1 ± 4.3	187.1 ± 3.4	0.362
Weight (kilograms)	90.6 ± 3.8	88.6 ± 2.8	0.306
Average running speed (m.sec^{-1})	7.3 ± 0.3	7.2 ± 0.4	0.848
Ambient temperature (°C) at testing	20.5 ± 2.2	23.4 ± 3.4	0.095
Time since HS strain (days)	108 ± 46	–	–

Abbreviations: SD, standard deviation; °C, degrees celsius.

uninjured limbs during fast treadmill running following hamstring muscle injury (Silder et al., 2010). Changes to the temporal characteristics of muscle activation have been reported to occur during isokinetic testing (Opar et al., 2013) and a double-leg to single-leg stance task (Sole et al., 2012) following hamstring muscle injury. Given that most hamstring muscle strains occur during high-speed running (Woods et al., 2004), and any neural inhibitory mechanisms are most likely to be present during strong eccentric contractions (Fyfe et al., 2013; Sole, Milosavljevic, Nicholson, & Sullivan, 2011), it is proposed that due to its specificity, high-speed running is the most appropriate task to assess motor patterning as a risk factor for future injury risk.

Other studies have reported altered levels of muscle activation in specific phases of the gait cycle during fast running (Daly et al., 2016; Higashihara et al., 2019). However, our study chose not to focus on muscle activation levels or use maximal voluntary isometric contractions in the analysis as we wanted to evaluate running patterns as opposed to strength or muscle activation levels. It is acknowledged that other parameters of muscle activation such as normalised amplitude or pattern of activity may have yielded different results. Timing of events in the gait cycle may be influenced by which threshold is used to determine onset and offset. This study used an onset and offset threshold of 15% of peak amplitude, an approach that has been used previously to assess changes in the temporal characteristics of muscle activity between groups (Chapman et al., 2006; Franettovich Smith, Honeywill, Wyndow, Crossley, & Creaby, 2014).

All participants in this trial were professional athletes who received a comprehensive hamstring rehabilitation program following their hamstring muscle injury. It is possible that any changes to the temporal characteristics of hamstring or gluteal muscle activation that may have been present following injury ceased either when pain related to the injury resolved or as a result of a comprehensive rehabilitation process. Both previous studies identifying residual adaptations in muscle onset time following hamstring muscle injury were in recreational athletes that may not have completed a comprehensive rehabilitation program (Opar et al., 2013; Sole et al., 2012).

This study was conducted in an environment designed to closely simulate that of a professional football match. Differences in muscle activation have been observed between treadmill and overground gait (Anders, Patenge, Sander, Layher, & Kinne, 2019) and consequently overground gait was investigated in this trial. The high-speed running was conducted outdoors on a grass field to replicate the surface encountered by players on matchday. However, as the trial was conducted over two testing sessions, for practical reasons, environmental conditions such as temperature, wind and ground hardness were not able to be controlled as well as they might have been in a laboratory setting. For example, the CON group ran in slightly hotter conditions, although the difference did not reach statistical significance.

4.1. Limitations

As professional players from one club were available for recruitment, a small sample resulted, and should be considered a limitation of this study. Although we ensured that participants completed no strenuous exercise or training in the 48 h before testing, we were unable to control for the amount of training that a player may have completed in the week leading into their testing session. This is one limitation of running research in a professional sporting setting. In high speed running and other fast movements there is an increased likelihood of an EMG sensor becoming dislodged and in this trial we missed data from the medial hamstrings of one participant as a result. This is a limitation of studying high speed running as opposed to a more controlled task.

Surface electromyography using telemetry allows for a non-invasive insight into muscle activity during overground activity. The measurements in this study were recorded using SENIAM guidelines from electrodes placed on a specific part of the muscles investigated. However, separate functional compartments within both of the hamstring muscles (Woodley & Mercer, 2005) and also gluteus maximus (Lyons, Perry, Gronley, Barnes, & Antonelli, 1983) have been identified. Consequently, the signal recorded may be biased towards one of these functional compartments and could potentially miss a change to the neuromuscular activity of the other compartments. It is also acknowledged that the use of surface EMG during high speed running in the field is unlikely to be as reliable as it might be at lower speeds of locomotion.

It has been suggested that hamstring muscle injuries are more likely to occur when an athlete is in a fatigued state (Woods et al., 2004). The testing procedure used in this study involved participants walking back between trials and was designed to keep players relatively fresh for each running effort. It is possible that due to the relatively fresh state of the athletes in this study that changes to the temporal characteristics of neuromuscular activation may have been harder to detect.

4.2. Future direction

The running in this study was confirmed using GPS to be 7.3 m s^{-1}.Typically any speed above 5.56 m s^{-1} is considered to be very high-speed running (Rampinini et al., 2015) and at speeds above 7 m s^{-1}, the strategy to increase running speed has been reported to shift from increasing stride length to increasing stride frequency, which requires increased muscle activation of the hip flexors, gluteus maximus and hamstring muscles (Dorn, Schache, & Pandy, 2012). Significantly, as running speed increases above 7 m s^{-1}, and approaches maximum speed, the gluteus maximus and hamstring muscles demonstrate the most dramatic increases in mechanical load and therefore increases in demands for muscular activation (Schache et al., 2011). Future research might consider assessing the temporal characteristics of muscular activation during overground running during maximum speed

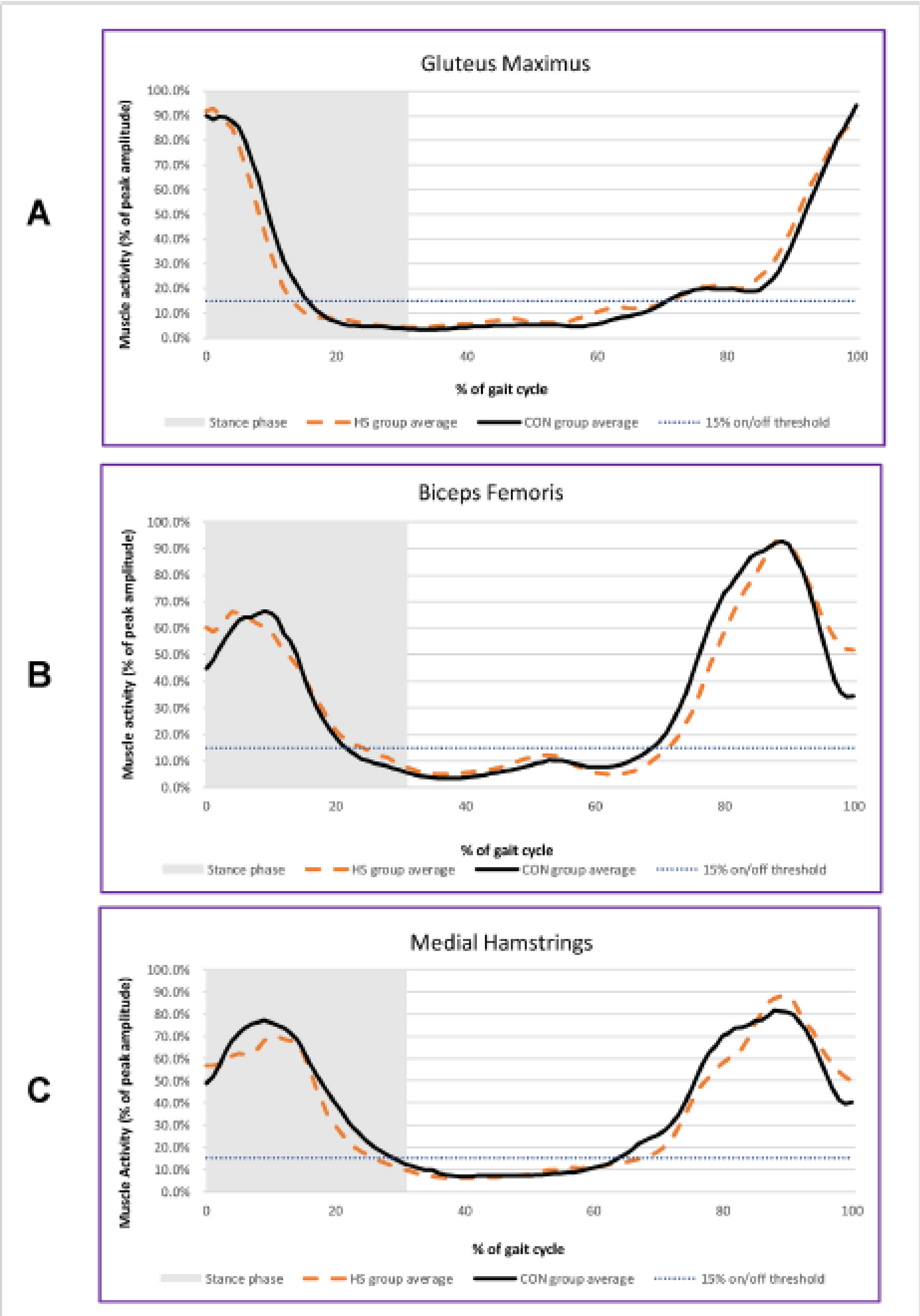

Fig. 1. Muscle activation pattern during high speed running: HS vs. CON group.
A – Gluteus Maximus muscle activation pattern; **B** – Biceps Femoris muscle activation pattern; **C** – Medial Hamstrings muscle activation pattern.

Table 2
Temporal characteristics of muscle activation during high speed running (% of gait cycle).

		HS Group Median (IQR)	CON group Median (IQR)	Effect Size	p
Gluteus maximus	onset	83.4 (5.2)	84.6 (6.4)	0.24	0.41
	offset	11.4 (2.7)	13.5 (2.8)	0.24	0.41
	duration	28.2 (4.6)	28.4 (3.7)	−0.03	0.95
Biceps Femoris	onset	70.0 (4.9)	68.8 (5.2)	−0.24	0.41
	offset	21.4 (8.8)	23.7 (8.6)	−0.07	0.85
	duration	52.8 (7.2)	56.5 (6.4)	0.24	0.41
Medial hamstrings	onset	71.0 (9.6)	64.4 (7.5)	−0.52	0.73
	offset	24.0 (9.1)	27.1 (9.1)	0.08	0.84
	duration	53.3 (8.9)	60.1 (11.2)	0.44	0.14

Abbreviation: IQR, Interquartile range.

running, or when athletes are in a more fatigued state, to determine if any neural inhibitory mechanisms are present when even greater demands are placed on the muscles involved. Given the results of this study we would not currently recommend assessment of muscle onset and offset times using EMG during overground running for the purpose of assessing re-injury risk following hamstring muscle injury. Practitioners may instead consider EMG assessment in protocols that have been reported to discriminate between injured and uninjured athletes such as isokinetic testing or a double leg to single leg stance task.

5. Conclusion

Following hamstring muscle injury no changes to the muscle onset time, offset time or duration of activity of the hamstring muscles or gluteus maximus were observed in professional Australian Football players during high-speed overground running.

Ethical approval

The study protocol was approved by the Faculty Human Ethics Committee (FHEC11/170), and all participants provided written informed consent.

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Declaration of competing interest

The authors declare no conflicts of interest. There was no grant aid, or manufacturers' aid, received to complete this study. The authors do not have any affiliations, or financial involvement, to declare with any company or organisation in the content or equipment discussed in the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2020.03.005.

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Chapter Six: Can Activation Exercise Alter Muscle Activation Timing During High-Speed Running in Professional Australian Football Players?

6.1 Background

The neuromuscular activation pattern of the gluteus maximus and hamstring muscles may be associated with the risk of sustaining a hamstring muscle injury (Edouard et al., 2018; Schuermans et al., 2017a; Schuermans et al., 2017c;), and should be a consideration in injury prevention protocols (Heiderscheit et al., 2010; Schuermans et al., 2017c).

The systematic review completed in Chapter One supported the use of targeted therapeutic exercise to improve muscle onset timing. One study included in the systematic review specifically reported that repeated voluntary isometric contractions can acutely improve muscle activation timing in the transversus abdominus muscle, likely through a mechanism of motor cortical reorganisation (Tsao et al., 2010). However, no research has been published that investigates whether this acute effect occurs following the use targeted therapeutic exercise in the gluteus maximus or hamstring muscles.

As high-load exercise protocols may increase injury risk by exacerbating muscular fatigue low-load muscle activation exercises are preferable for use in professional athletes (Marshall, Lovell, Jeppesen, Andersen, & Siegler, 2014). It has also been established in the earlier chapters of this thesis that low-load muscle activation exercises have become increasingly prevalent in pre-exercise warm-up protocols. There is also evidence that a low-load exercise protocol targeting the gluteus maximus can improve muscle activation timing during a prone hip extension exercise after nine-weeks of training (Rainsford, 2015). However, the acute effect of an exercise protocol targeting the gluteus maximus and hamstring muscles on muscle activation timing during high-speed running has not been investigated.

6.2 Research design

The research study outlined in Chapter Five found that no changes to muscle activation timing were present following hamstring muscle injury during high-speed overground running. This finding pertained to the first component of a research study that was completed to address two separate but related questions. The second component used the same recruited participants to investigate the acute effects of a targeted therapeutic exercise protocol on the temporal characteristics of muscle activation during high-speed running.

Participants were randomised into one of two groups: a control group (CON) and a group that received a muscle activation exercise protocol targeting the gluteal and hamstring muscles (ACT). Following an initial running protocol, which was outlined in Chapter Five, participants in the CON group completed a 6-minute walking protocol, and the participants in the ACT group completed a low-load activation exercise protocol targeting the gluteal and hamstring muscles. Both groups then repeated the high-speed running protocol which allowed for muscle activation timing to be compared before and after the ACT and CON interventions. There was a random and even spread of participants in the ACT and CON group over the two testing days.

The exercise protocol that was used in the research study was designed based on the accumulated information and knowledge compiled in the earlier chapters of this thesis. The protocol incorporated a voluntary isolated contraction of the gluteus maximus followed by a prone hip extension exercise. Factors taken into consideration during the development of the protocol included practicality, evidence-base and current practice. The novel exercise protocol that was selected consisted of two related exercises that were intended to be executed as a pair with the first isolated muscle activation contraction designed to improve the activation of the muscle during the following movement exercise. The protocol is outlined in detail within the methods section of the attached manuscript.

The data collection in this study was undertaken by researchers who were experienced in the collection of EMG data, and the processing of the EMG data was undertaken by the candidate. In order to improve consistency and to reduce bias, the candidate was responsible for the instruction of each participant during both the exercise intervention and also the execution of the running trials. After testing was completed, the footswitch data of one participant in the ACT group was discovered to be corrupted, and that participant's data were discarded since their gait was unable to be analysed. All electrodes remained in place for the duration of the testing sessions, with the exception of the medial hamstring muscle electrode of one participant in the CON group that dislodged during testing. The medial hamstring muscle data for this participant was discarded. Aside from this one set of medial hamstring data, all available data from all participants in the CON group were analysed. The data of all participants in the ACT group, except for the participant whose footswitch data was discarded, were analysed.

The decision to study the acute effects of exercise were justified based on a number of factors. A single bout of exercise has been shown to acutely alter muscle activation timing in people with nonspecific low back pain (Tsao & Hodges, 2007). The study that was published and outlined in Chapter Four further supports this finding and demonstrated an acute effect of a series of low load exercises targeting the gluteal muscle group. It is also relevant to consider that in a professional sporting environment, interventions that can take effect quickly and be implemented into a warm-up, are of high practical value.

The use of the same group of participants in the studies contained within Chapter 5 and Chapter 6 was practically useful in minimising the disruption on the training of the professional athletes involved in the research. Although it is unclear whether a history of hamstring muscle strain injury might have had any impact on individual athlete's response to exercise. Given that no difference was found between the groups in terms of muscle activation timing it was considered reasonable to analyse these two categories of athletes together in this study.

The research publication that details the methods, results and implications of the second component of this study is presented below in the format it has been submitted to Science and Medicine in Football:

Crow, J., Semciw, A., Couch, J., & Pizzari, T. (Submitted). Can activation exercise alter muscle activation timing during high-speed running in professional Australian Football players? *Science and Medicine in Football,* Submitted.

Can activation exercise alter muscle activation timing during high-speed running in professional Australian Football players?

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Running Title:

Activation exercise effects on muscle timing in high-speed running

Type of Article:

Original Research

Keywords:

Running; Gait cycle; Electromyography; Neuromuscular inhibition

Abstract

Objective: To assess whether a targeted exercise protocol including repeated voluntary contractions, and a low-load hip extension exercise targeting the gluteus maximus and hamstring muscles, leads to an acute change in temporal characteristics of muscle activity during high-speed overground running.

Methods: Fifteen professional Australian Football players were recruited and randomised into an 'activation' (ACT) intervention group (n=8) and a control (CON) group (n=7). The ACT group completed 10 x 10 second unilateral isolated gluteus maximus contractions followed by 10 repetitions of a prone unilateral hip extension exercise. The CON group completed six-minutes of self-paced walking. Differences in muscle onset timing, offset timing and onset duration of the gluteus maximus and hamstring muscles during the high-speed running gait cycle were analysed using electromyographic data.

Results: No significant differences in any of the temporal aspects of muscle activation were found between groups for any of the muscles tested ($p > .05$).

Conclusions: The completion of a targeted low-load muscle activation exercise protocol does not alter the temporal characteristics of the gluteus maximus and hamstring muscles during high-speed overground running. Practitioners should reconsider the inclusion of low-load muscle activation exercises in cases where acute improvement of muscle activation timing is a desired outcome.

Introduction

Changes to the timing of muscle activity can develop in the presence of pain (Hodges & Moseley, 2003), or joint pathology (Stokes & Young, 1984), and may persist after an individual becomes asymptomatic (MacDonald, Moseley, & Hodges, 2009). The activation timing of the gluteus maximus and hamstring muscles is considered to be an important factor in both hamstring muscle injury prevention and rehabilitation (Heiderscheit, Sherry, Silder, Chumanov, & Thelen, 2010; Schuermans, Danneels, van Tiggelen, Palmans, & Witvrouw, 2017b) as the existence of dysfunctional muscle activation timing may impact the control and function of the affected area (Hodges & Tucker, 2011).

The delayed onset of the hamstring muscles during a prone hip extension task has been reported as a risk-factor for hamstring injury in football players (Schuermans, van Tiggelen, & Witvrouw, 2017a), and persistent neuromuscular deficits in the hamstring muscles have been proposed as a contributing factor to injury recurrence (Fyfe, Opar, Morgan, & Shield, 2013). The gluteus maximus is also considered to be susceptible to inhibition (Tyler, Nicholas, Mullaney, & McHugh, 2006) and, even in apparently healthy people, may present with delayed onset during functional tasks, which could increase susceptibility to injury (Buckthorpe, Stride, & Della Villa, 2019).

The majority of hamstring muscle injuries sustained in professional football occur during high-speed running (Ekstrand, Waldén & Hägglund, 2016), during which the gluteus maximus and hamstring muscles work as hip extensors in the late swing phase of the gait cycle to control knee and hip extension (Dorn, Schache, & Pandy, 2012). Consequently, strategies to optimise the neuromuscular activation of the gluteus maximus and hamstring muscles during running are utilised in professional football.

Targeted low-load exercises are one intervention shown to be effective for improving the temporal characteristics of muscle activation (Crow, Pizzari, & Buttifant, 2011). Repeated voluntary isometric contractions can also acutely shift the motor cortical representation of targeted muscle (Cohen, Gerloff, Ikoma, & Hallett, 1995), and through this mechanism of motor cortical reorganisation, improve the timing of muscle activation during functional activity (Tsao, Galea, & Hodges, 2010).

This study assessed whether a muscle activation exercise protocol including repeated voluntary contractions and a low load hip extension exercise targeting the gluteus maximus and hamstring muscles, led to any acute change to the muscle onset timing, muscle offset timing or duration of gluteus maximus and hamstring muscle activity during high-speed overground running in a group of professional Australian Football players.

Methods

Participants

Fifteen professional male, Australian Football players were recruited from a single Australian Football League club. Participants were randomly allocated into one of two groups using a computer-generated randomisation sequence by a person not involved in the intervention: a control group (CON), and an "activation" intervention group (ACT). A total of seven participants were randomised to the CON group, and eight randomised to the ACT group. The allocation of participants was revealed to testers on the day of testing. All participants were engaged in full pre-season training at the time of the study and had no reported history of lower limb surgery. Seven participants had a history of hamstring strain, four were allocated to the ACT group and three were allocated to the CON group following randomisation. A research study that was run in parallel to this investigation using the same participants confirmed that there were no differences in muscle activation timing during high speed running between participants with and without a history of hamstring muscle injury (Crow, Semciw, Couch, & Pizzari, 2020). The study was approved by the Faculty Human Ethics Committee (FHEC11/170) and all participants provided written informed consent.

Procedures

The study utilised a randomised controlled trial design.

A questionnaire was completed by all participants to collect demographic information, as well as information about each player's injury history. The accuracy of self-reported injury history was confirmed using comprehensive injury data maintained by the club.

The testing procedure was conducted on a 100m stretch of grass on an outdoor field. To negate any possible effects of fatigue or muscle soreness on the testing protocol, participants did not engage in any intensive training within the 48 hours prior to testing.

Electromyographic (EMG) measurement of the gluteus maximus, biceps femoris and medial hamstring muscles was performed using surface EMG electrodes consisting of Trigno (Delsys Inc., Boston, USA) wireless sensors with a single differential configuration and a four bar (99.9% silver) contact area, with an inter-electrode distance of 10 mm.

Skin preparation and electrode placement were consistent with recommended SENIAM guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Gluteus maximus electrode placement was midway along a line between the greater trochanter and the sacral vertebrae. The biceps femoris electrode placement was midway along a line between the ischial tuberosity and the lateral epicondyle of the tibia, and medial hamstring electrode placement was midway along a line between the ischial tuberosity and the medial epicondyle of the tibia. Footswitches (Model: 402, Interlink Electronics, USA) were positioned bilaterally to record temporal aspects of the gait cycle.

A Delsys Trigno Wireless 16-Channel EMG system was used to collect raw EMG signals (Delsys Inc., Boston, USA; CMRR > 80 dB @60 Hz; gain of 1000; band pass filtered at 20–450 Hz) and sampled at 2000 Hz.

Players wore a 5Hz Global Positioning System (GPS) unit (MinimaxX, Team 2.5, Catapult Innovations, Australia) in a specifically tailored garment during the testing protocol to assess maximum running speed during each trial. Ambient temperature was recorded using a portable weather meter (Kestrel 2500; Kestrel Instruments, PA, USA) during the warm-up that preceded each trial.

The running trial protocol was adapted from a graded running protocol developed for hamstring rehabilitation (Reid, 1993). Participant running trials were divided into a 40-metre acceleration section where players commenced from a standing start and were instructed to steadily build up their speed, a 20-metre middle-section where players were instructed to hold their speed at 90% of their perceived maximum, and a 40-metre deceleration section where players were instructed to steadily reduce their speed. Participants then walked back the full 100 metres before commencing their next trial. Five trials were completed during testing. At the conclusion of the pre-intervention trials, each player underwent their allocated intervention. Following the completion of the CON or ACT intervention, participants were given two minutes of rest while investigators checked that electrodes remained in place. Each participant then repeated the series of five running trials again.

Intervention

ACT group

Participants in the ACT group completed a supervised exercise program in the prone position. The first exercise was adapted from research demonstrating an acute effect on muscle activation timing (Tsao & Hodges, 2007) and involved the completion of 10 x 10 second unilateral isolated gluteus maximus contractions. The second exercise was 1 x 10 repetitions of a prone unilateral hip extension exercise adapted from the work of Lewis and Sahrmann (2009). The exercise protocol was expected to take six minutes.

CON group

Participants in the CON group were instructed to walk for six minutes at a comfortable pace around the testing field. Participants were supervised during this walking protocol.

Data processing

Following testing, all EMG data were processed using a customised adaptation of the Biosignal EMG package (2.1.0) from R statistical software (https://www.r-project.org/ , version 3.6.1). Raw EMG signals for each running trial were high pass filtered (Butterworth, 4th order, zero phase lag, 20Hz cut-off) to remove movement artefact. Data were full wave rectified and further filtered using a moving average (20 ms window). Two consecutive strides from the middle 20 metres of each running trial were further processed for analysis. These particular strides were chosen to decrease the likelihood that participants were accelerating or decelerating during the stride, and increase the likelihood that participants were at their highest speed at the point of analysis. In all participants, the preferred kicking leg was chosen for analysis. The data from the gait cycle were time-normalised to 101 points (representing the gait cycle from 0 to 100% in 1% increments) enabling time-dependant analysis between groups. Data were amplitude normalised to the peak activity recorded through the running cycle.

An ensemble average was generated for each muscle and each participant both before and after the intervention. Pre- and post-intervention ensemble averages were summed and averaged to produce a grand ensemble for gluteus maximus, biceps femoris and medial hamstrings for all participants in the CON and ACT groups. This allowed an EMG profile to be established for each muscle in each group across the high-speed running gait cycle both before and after the intervention.

For each muscle and participant, the muscle onset time, muscle offset time and duration of muscle activation were calculated as a percentage of gait cycle. Muscle onset time was determined as the time when EMG amplitude was increased above baseline by a level of $\geq$ 15% of peak amplitude for a period of $\geq$ 10% of the gait cycle, and the time of muscle offset was determined as the point when EMG amplitude returned to baseline or remained below 15% of the maximum EMG amplitude for > 10% of the gait cycle. Duration of muscle activation was the percentage of the gait cycle contained between the muscle onset and muscle offset (Franettovich, Chapman, & Vicenzino, 2008).

For each participant, the difference between the pre- and post-intervention measurements of muscle onset time (muscle onset diff), muscle offset time (muscle offset diff) and the duration of muscle activation (muscle duration diff) was calculated and used for statistical analysis.

Statistical Analyses

Descriptive statistics (means, medians, interquartile range and standard deviations) were calculated and data reviewed for normality using boxplots and the Kolmogorov-Smirnoff (K-S) test. To compare muscle onset diff, muscle offset diff and muscle duration diff, for each muscle between groups, a Mann-Whitney U test was used, since data were not normally distributed. An independent groups t-test was used to compare demographic data between groups.

To determine the magnitude of any differences between CON and ACT groups, a standardised effect size was calculated by dividing the z-score of the Mann–Whitney U test by the square root of the total sample size. All statistical comparisons were performed using the SPSS statistical software package (Version 19, IBM SPSS Inc., Chicago, IL, USA).

Results

No statistical difference was evident between ACT and CON groups for demographic information, running speed, and ambient temperature recorded during testing (**Table 1**).

Table 1. Demographic information and testing conditions.

Variable	**ACT group (n=7) Mean (SD)**	**CON group (*n*=7) Mean (SD)**	***p* value**
Age (years)	22.0 ± 1.9	21.7 ± 0.9	0.738
Height (centimetres)	186.0 ± 4.0	189.7 ± 3.1	0.097
Weight (kilograms)	90.1 ± 3.2	90.1 ± 3.2	0.628
Average running speed ($m.sec^{-1}$)	7.2 ± 0.2	7.4 ± 0.3	0.243
Ambient temperature (°C) at testing	21.0 ± 2.3	22.6 ± 3.8	0.741

Abbreviations: SD = standard deviation; °C = degrees Celsius, ACT = Activation group, CON = Control group

After testing was completed, the footswitch data of one participant in the ACT group was discovered to be corrupted, and that participant's data were discarded since their gait was unable to be analysed. All electrodes remained in place for the duration of the testing sessions, with the exception of the medial hamstrings electrode of one participant in the CON group that dislodged during testing. The medial hamstrings data for this participant was discarded (**Figure 6.1**)

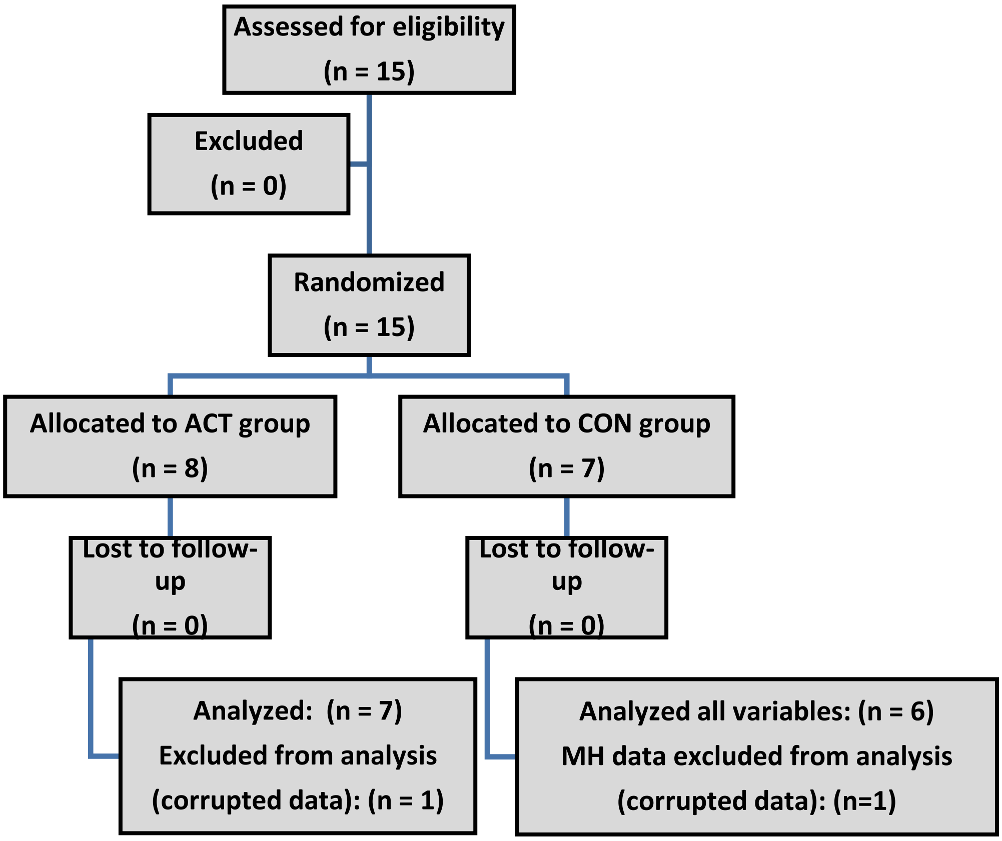


Figure 6.1. Flow diagram for parallel randomised trials comparing groups (CONSORT)

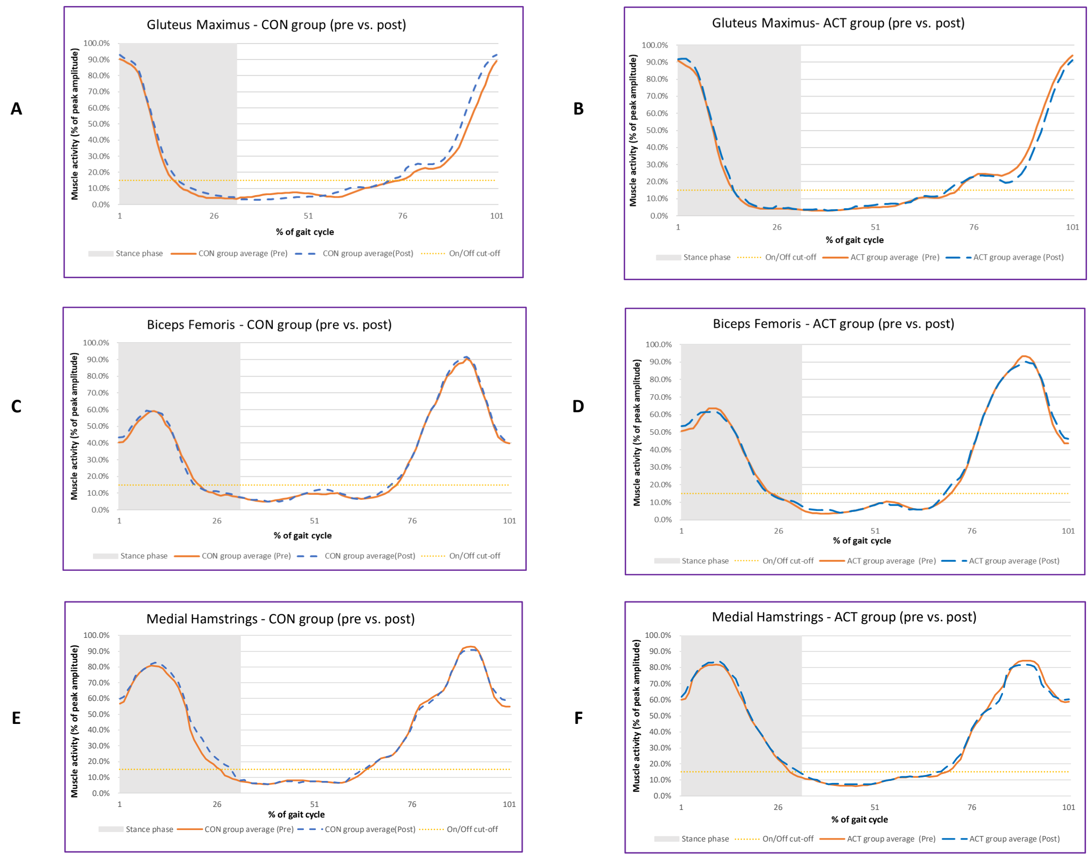
No statistically significant differences were observed between ACT and CON groups on any of the temporal comparisons (muscle onset diff, muscle offset diff and muscle duration diff) for gluteus maximus, biceps femoris or the medial hamstrings (**Table 2**).

Figure 6.2. contrasts the pre- and post-intervention grand ensemble curves for the gluteus maximus, biceps femoris and medial hamstrings in both the CON and ACT groups.

Table 2. Pre-post differences in temporal characteristics of muscle activation during high speed running (% of gait cycle).

		ACT MEDIAN (IQR)	CON MEDIAN (IQR)	EFFECT SIZE	P
GLUTEUS MAXIMUS	Onset diff	-0.81 (2.9)	-0.96 (3.8)	0.09	0.81
	Offset diff	0.04 (2.4)	0.34 (2.4)	-0.19	0.54
	Duration diff	-0.27 (5.3)	1.39 (3.1)	-0.15	0.62
BICEPS FEMORIS	Onset diff	-1.2 (5.2)	-1.30 (3.6)	0.19	0.54
	Offset diff	0.2 (3.1)	-0.46 (5.7)	0.15	0.62
	Duration diff	0.5 (3.4)	2.25 (4.1)	-0.15	0.62
MEDIAL HAMSTRINGS	Onset diff	-0.9 (1.9)	-1.24 (7.5)	0.04	0.90
	Offset diff	1.1 (6.2)	3.06 (6.7)	-0.19	0.53
	Duration diff	2.0 (7.4)	3.19 (11.5)	-0.12	0.73

Abbreviations: IQR = Interquartile range, ACT = Activation group, CON = Control group



A = Gluteus maximus muscle activation pattern (CON group average); **B** = Gluteus maximus muscle activation pattern (ACT group average); **C** = Biceps femoris muscle activation pattern (CON group average); **D** = Biceps femoris muscle activation pattern (ACT group average); **E** = Medial Hamstrings muscle activation pattern (CON group average); **F** = Medial Hamstrings muscle activation pattern (ACT group average)

Figure 6.2. Muscle activation pattern during high speed running: pre vs. post

Discussion

This study found that a muscle activation exercise program targeting the hip extensor muscles does not acutely impact the temporal components of muscle activation during high-speed running in a group of professional Australian Football players.

Previous studies into acute changes in muscle activation timing following targeted low-load exercise protocols investigated muscle onset during an arm perturbation movement in standing (Tsao & Hodges, 2007). It is possible that any motor cortical reorganisation achieved through the completion of a low load exercise is insufficient, or not specific enough, to transfer to complex or explosive functional movements such as high-speed running.

The single bout of activation exercises might also be insufficient to elicit changes in muscle timing. Altered gluteus maximus timing during a prone hip extension test has been reported following a targeted low-load exercise protocol conducted over a period of weeks (Rainsford, 2015). Improved muscle activation timing has also been reported from low load targeted exercise programs lasting between two to six weeks in the transversus abdominus (Tsao & Hodges, 2007; Tsao et al., 2010). Future research may consider investigating the effects of a targeted low-load exercise protocol that is implemented over an extended prescription period.

This study chose to investigate only the temporal characteristics of muscle activation. The relationship between electromyographic (EMG) signal intensity and muscular force production is influenced by various factors including muscle shortening velocity and can be difficult to determine. It has been suggested that the best use of the EMG signal is to describe the onset and offset timing of muscle activation (Maniar, Schache, Heiderscheit, & Opar, 2020). It must be acknowledged that an investigation using normalised amplitude or other parameters of muscle activation may have produced different results. This study used a threshold of 15% peak amplitude to determine onset and offset timing. The timing of events in the gait cycle may also be influenced by the threshold utilised.

There are several limitations of our study. As we recruited professional players from one club, a small sample size was the result. The sample size recruited for this study (ACT = 8; CON = 7) was comparable to a previous RCT that reported a difference in gluteus maximus muscle onset timing between a group of athletes that undertook a targeted exercise intervention (7 participants) and a control group (3 participants) (Rainsford, 2015). However, the risk of type II error must be acknowledged. Future research with a larger sample size would help verify the findings of this study.

Conclusion

This study was the first to analyse the acute effects of targeted muscle activation exercise on muscle activation timing during high-speed running. Previous research into the acute effects of muscle activation exercise investigated less dynamic and functional movement.

The muscle onset time, muscle offset time, and duration of muscle activity of gluteus maximus and the hamstring muscles, are all unaffected during high speed running following the completion of a low load targeted muscle activation exercise. Practitioners should reconsider the inclusion of low load targeted muscle activation exercises in cases where acute improvement of muscle activation timing is a desired outcome.

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Chapter Seven: Grand Discussion and Conclusion

7.1 Discussion

The overall aim of this thesis was to investigate the temporal characteristics of muscle activation following hamstring muscle injury and explore the potential use of exercise to acutely improve the timing of muscle activation in professional Australian Football players. This was achieved by completing a systematic review, examining current practice in professional sport through a narrative review and workshop, and conducting a preliminary research study to explore practical considerations within a professional sport setting. Information gathered in these preliminary investigations was used to guide the design and completion of prospective research studies using a group of professional Australian Football players.

The systematic review identified 16 studies (and 19 therapeutic groups) that used muscle onset timing as an outcome measure following the application of therapeutic exercise. The review concluded that it is possible to use therapeutic exercise to alter the timing of muscle activation following injury. The quantitative analysis determined that isolated muscle training is the most effective modality at achieving this outcome and did not support the use of general strength training or instability training to achieve this effect. The data supporting isolated muscle exercise were limited to exercise targeting the transversus abdominus, deep cervical flexors and vastus medialis muscles. Only one study looked at the acute effects of exercise on muscle timing (Tsao & Hodges, 2007), while the others investigated exercise programs over a period of weeks.

None of the studies included in the systematic review studied an athletic population and there were no studies that considered the effect of exercise on muscle timing following hamstring muscle injury. There were, however, studies that reported on gluteus maximus targeted using general strength training in subjects with chronic low back pain (Leinonen, Kankaanpaa, Airaksinen & Hanninen, 2000), and biceps femoris targeted using instability training following ACL rupture (Chmielewski, Rudolph, & Snyder-Mackler, 2002). In both of these studies the prescribed exercise was ineffective for altering muscle activation timing.

The results from the systematic review offered support for the use of therapeutic exercise to improve muscle onset timing but also indicated that further information was needed about exercise prescription before proceeding with a research study in professional athletes. It was also important to ascertain which muscles might be most appropriate to target, with which particular exercises, and how to best run such an investigation in a professional athletic performance setting. Consequently, we used targeted projects to gather expert information from practitioners within the fields of physiotherapy and strength and conditioning.

A workshop of physiotherapists with expertise in muscle activation was convened and a narrative review on muscle activation around the hips and pelvis in the context of Australian Football was completed to assist in the planning of the workshop. Discussion was facilitated to explore current concepts, best practice, and case studies applicable to this topic. Key findings relevant to this thesis included the corroboration of the theory that altered muscle timing of the gluteus maximus and hamstring muscles may occur following hamstring muscle injury. Anecdotal reports of the use of voluntary isolated muscle exercise targeting the gluteus maximus in conjunction with low load prone hip extension exercises for both hamstring injury rehabilitation and hamstring injury prevention were noted.

To gather further information on current practice and expert opinion, a strength and conditioning accreditation program was undertaken. The manuscript “The role of the strength and conditioning coach in optimising muscle patterning following injury” was published as a part of this accreditation process. The main finding relevant to this thesis was that anecdotally, the use of activation exercise during warm-up protocols in strength and conditioning practice was common, and that these exercises were prescribed with the objective of eliciting an acute improvement in muscle activation in the subsequent activity. This process also reinforced the importance of maintaining good postures when completing exercise and ensuring smooth and controlled movement quality.

It was important to ascertain the practicality of conducting a prospective major research study into muscle activation in a professional football setting and consequently a research study was designed in conjunction with an AFL club to address questions of interest to both the researchers and the club. This research study found that a warm-up protocol inclusive of low-load muscle activation exercises targeting the gluteal muscle group can acutely enhance peak power output in professional Australian Football players. The study results supported the proposition that low-load muscle activation exercises may have an acute effect on characteristics of muscle activation. Important practical findings were noted while conducting this research that were relevant to the design of the major research studies conducted for this thesis. For example, as there are a number of competing demands on players time within a professional football environment, and these demands are heightened during the competitive season, the pre-season training phase was the most appropriate time to gain access to players for research.

There are differences between professional and amateur football players that are important to understand when interpreting the findings of this thesis. Injury recurrence rates are lower in professional football compared to amateur football and it is more likely that a professional player will have completed a comprehensive HSI rehabilitation protocol than an amateur player (Hägglund, Waldén, & Ekstrand, 2016). The maximum velocity, and volume of high speed running completed during a competitive match are also higher in a professional player when compared to a player at the amateur level (Kaplan, Erkman, & Taskin, 2009).

Prior to this thesis no research had been published that specifically investigated the muscle activation timing of the gluteus maximus or hamstring muscles during high-speed overground running in athletes with a recent hamstring strain. Utilising the practical information collated through the earlier components of this thesis, research was undertaken to evaluate muscle timing in a group of professional Australian Football players. We found no differences in the muscle activation timing of the gluteus maximus or hamstring muscles between players who had sustained a hamstring muscle injury within the last six months, and players who had never sustained a hamstring muscle injury. This outcome supports the findings of Silder et al. (2010) who found no differences in muscle activation timing between injured and uninjured limbs during high-speed treadmill running. The only study that has reported altered timing of muscle activation following hamstring muscle injury examined muscle activity during a double leg to single leg stance task (Sole et al., 2012). It is also worth noting that this study investigated recreational athletes who, unlike professional Australian Football players, may not have completed a comprehensive hamstring rehabilitation protocol, and consequently may have been more likely to carry a residual impairment.

The major project research design provided the opportunity to test whether therapeutic exercise targeted at the gluteus maximus and hamstring muscles can acutely improve the muscle activation timing of these muscles during high-speed running. The data and practical knowledge accumulated through the earlier components of this thesis guided the development of a novel exercise protocol that we believed would be most likely to have an acute effect on the temporal aspects of muscle activation. The exercise protocol included a set of voluntary isometric holds of the gluteus maximus muscle followed by set of low-load prone hip extension repetitions that focused on voluntarily activating the gluteus maximus muscle immediately prior to the movement and then focused on keeping the muscle engaged for the duration of the movement. No difference was observed between this novel exercise protocol, and a control protocol that consisted of six-minutes of walking, in the muscle onset or offset timing of the gluteus maximus or hamstring muscles during high-speed overground running.

It was the intention of this thesis to study the acute effects of a muscle activation exercise protocol that might be used as part of a warm-up. It remains unclear whether the exercise protocol would have led to any changes in muscle activation timing if it had been repeated over a period of weeks or months. A change in gluteus maximus timing after the prescription of a low-load gluteal muscle activation program conducted over a period of nine-weeks has been reported in netball players, although this change was only observed in a prone hip extension test and was not observed in more functional or sport-specific movement (Rainsford, 2015). In fact, there are no documented reports of improved muscle activation timing following low-load activation exercise protocols during running. While acute improvement in the muscle onset timing of the transversus abdominus during a standing arm perturbation movement have been reported following voluntary isolated muscle contractions (Tsao & Hodges, 2007), it is possible that the same effect was not observed in this thesis because low-load exercises may not transfer well to high-load activities like high-speed overground running. Given that the acute effects have been reported in postural muscles that typically perform low-load contractions, it is also possible that low-load exercises may be less effective at altering the muscle activation of muscles such as the gluteus maximus and hamstring muscles that typically perform greater work during movement.

7.2 Strengths and clinical implications of this thesis

The applied nature of the research conducted is a strength of this thesis. All of the research studies in this thesis were conducted in an applied professional sporting setting with professional Australian Football players as research subjects. The research was directly related to the environment where the findings were to be applied, and all testing was conducted during sport-specific movements that are highly relevant to the sport of Australian Football.

This thesis examined muscle activation timing during high-speed overground running instead of another less sport-specific task. High-speed overground running is an appropriate activity to assess muscle activation as it is highly specific to Australian Football (Saw et al., 2018), and is also the activity in which hamstring muscle injuries most commonly occur (Ekstrand et al., 2016). The results reported in this thesis are a reminder that effects observed in the lab during less-functional and sport-specific movement may not necessarily translate to the sporting field.

The research conducted in this thesis used EMG telemetry and is the first research study of its kind to assess muscle activation timing following hamstring muscle injury during high-speed overground running. The major research study was also the first to investigate the acute effects of exercise on muscle activation timing during high-speed running.

This thesis sought to compare muscle activation timing between athletes, instead of comparing injured and uninjured limbs. This approach eliminated any potential error created due to a crossover effect between limbs in the same athlete, which can be a limitation of the published research in this area.

Conflicting reports exist about whether muscle activation intensity is altered during running following hamstring muscle injury (Daly et al., 2016; Higashihara et al., 2019; Silder et al., 2010). This thesis chose to focus only on the temporal characteristics of muscle activation. The relationship between EMG signal intensity and muscular force production is influenced by various factors including muscle shortening velocity and can be difficult to determine. The measurement of muscle activation intensity also relies on the use of a reference point. Maximum voluntary contraction is one reference point that can be used for this purpose but is a potentially confounding factor that may lead to error and inaccuracy during analysis (Marras & Davis, 2001). Peak signal intensity is another reference point that can be used for normalisation, and while it is less prone to error than maximum voluntary contraction, this benefit may come at the expense of interpretability (Allison, Marshall & Singer, 1993). Where the objective is to evaluate muscle activation patterns it is better to measure muscle onset and offset timing, independently to activation intensity, as this method is not reliant on a normalisation process to determine intensity and therefore less prone to error.

In the absence of sufficient empirical research evidence, it can be worthwhile listening to experts in the field and giving consideration to practice-based evidence. The thesis sought information from a mix of sources to guide the development of the research protocol tested in the major research study. Due to barriers to accessing professional athletes for research, many of the practices undertaken in professional sporting environments are based on theory and assumption. This thesis has provided evidence to oppose some of the assumptions underlying common warm-up and rehabilitation practices in professional sport and provided clinicians with extra information to inform their decision making about hamstring muscle injury prevention and rehabilitation.

While this thesis does offer some support for the use of low-load activation exercise to acutely improve peak power output, it does not support the use of this type of exercise to improve the muscle activation timing of the gluteus maximus and hamstring muscles in professional athletes. Consequently, clinicians may decide to omit low-load activation exercises from warm-up protocols where acute changes in peak power output are not a primary focus.

7.3 Limitations of this thesis and directions for future research

An observed limitation of practical research in a professional sporting environment is that the needs of the club where the research is being conducted are often a factor in both research design and implementation. For example, weight bearing vibration was included as an experimental group in Chapter 4, as it was of interest to the club, even though this was not of interest to the overall thesis. Practical considerations are also present in sport-specific settings, as opposed to a laboratory. For example, participants in our studies were completing pre-season training at the time of the research. While measures were taken to ensure that participants were "fresh", it was not feasible to control for training loads outside of the 48-hours prior to testing.

Environmental conditions are also a notable limitation of field-based research. One example of this was a trend for the control group in the major research study to run in hotter conditions than the HS group. Fortunately, the difference did not reach statistical significance and none of the environmental conditions that we measured had a significantly greater impact on one testing group compared to another.

There are limitations to the use of EMG in high-speed running that must be acknowledged. In particular, the risk of an EMG or foot contact sensor becoming dislodged is elevated compared to more controlled activities. The ambient temperature is also relevant and in cases where an athlete is sweating there is an increased risk of sensor movement or dislodgement. It was due to these factors that the data of one participant was corrupted and lost to analysis and one additional set of data from the medial hamstrings was lost for one participant. The reliability of surface EMG in high speed running is also not well known and may be lower than for lower speeds of locomotion, consequently the degree to which this may have influenced the results is unknown.

The quality of the studies included in the systematic review was not strong. Conclusions about the effect of isolated muscle training must be made with care, and given the non-athletic populations examined by the included studies, it was difficult to extrapolate the results to professional football players with a history of hamstring strain injury.

Another limitation of this thesis is statistical power. This thesis may have benefited from larger sample sizes to minimise the risk of type II error. A larger sample would have also enabled the use of a mixed ANCOVA, or a linear mixed effects model to analyse two aims with one test. Specifically, we could have investigated whether there was a difference between groups in muscle activation during high speed running, and also whether the effect of the intervention depends on the presence of hamstring muscle injury. As this was not possible due to the limited sample, we separated these questions into separate studies.

Due to the variability that exists in measuring muscle onset timing using surface EMG in overground running during overground running, and based on the post hoc power analysis taken as a part of this thesis, it is recommended that future research of this type recruit 24 or more participants to ensure sufficient statistical power.

Chapter 4 assessed the effect of a low-load exercise protocol targeting the gluteal muscle group on peak power output used a control group that did no warm-up, and another that completed a weight bearing vibration protocol before testing. The results of this study would have greater practical application if one of the control groups had have completed a general warm-up protocol. It remains unclear if the improved peak power output seen after the low load exercise protocol was the result of a general warm-up effect or from another mechanism.

This research found no differences in muscle activation timing during high-speed overground running in professional Australian Football players with a recent hamstring strain who had completed a comprehensive rehabilitation protocol. Future research may seek to identify if this is also the case in community-level athletes who have not been rehabilitated in a professional environment.

A decision was made to investigate only the acute effect of an activation exercise protocol on muscle activation timing and future research may seek to investigate the effects of targeted low-load muscle activation exercise following an extended prescription period of 2-6 weeks.

The high-speed running protocol used in this research involved athletes running at 90% of their maximum speed. It is likely that running at 100% maximum speed places increased demands on the hamstring and gluteal muscles and future research may consider whether these increased demands can discriminate between previously injured and uninjured subjects.

7.4 Conclusion

Following hamstring muscle injury in professional Australian Football players the muscle activation timing of the gluteus maximus and hamstring muscles is no different to players who have never sustained a hamstring strain during high-speed overground running.

Low-load exercises targeting the gluteal muscles are used in warm-up protocols in professional sport, and while this thesis provides some support for their use to acutely improve peak power production, this thesis also concludes that it is unlikely that they have any effect on the temporal characteristics of gluteus maximus or hamstring muscle activation during high-speed overground running in professional Australian Football players.

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Appendices

Appendix A:

Ethics approval

La Trobe University
Faculty of Health Sciences
MEMORANDUM

TO: Dr Tania Pizzari
School of Physiotherapy

SUBJECT: *Reference:* **FHEC11/170**

Student or Other Investigator: Justin Crow

Title: **The motor patterning of the hamstring and gluteus maximus muscle in Australian football players following injury: Is it altered and can it be changed?**

DATE: 7 February, 2012

The Faculty Human Ethics Committee's (FHEC) reviewers have considered and approved the above project.

Please note that the Informed Consent forms need to be retained for a minimum of 5 years. Please ensure that each participant retains a copy of the Informed Consent form. Researchers are also required to retain a copy of all Informed Consent forms separately from the data. The data must be retained for a period of 5 years.

Please note that any modification to the project must be submitted in writing to FHEC for approval. You are required to provide an annual report (where applicable) and/or a final report on completion of the project. A copy of the progress/final report can be downloaded from the following website: http://www.latrobe.edu.au/research-services/ethics/HEC-application.htm

Please return the completed form to The Secretary, FHEC, Faculty of Health Sciences Office, La Trobe University, Victoria 3086.

If you have a student/s involved in this project, a copy of this memorandum is enclosed for you to forward to the student(s) concerned.

Timothy M Bach, PhD
Acting Chair
Faculty Human Ethics Committee
Faculty of Health Sciences

Appendix B:

Workshop booklet including narrative review

Muscle activation around the hips and pelvis in the context of Australian Football

Monday 9th august 2010
Westpac centre
Melbourne

SCHEDULE

11.30 – 12.00	Arrival of guests. Possible tour of facilities.
12.00 – 12.15	**Introductions**: Aims of workshop and schedule of the day.
12.15 – 1.15	Each of our guests will have an opportunity to introduce themselves and touch on their background and philosophies. Approx. 15-20 min.
1.15 – 1.30	LUNCH SERVED
1.30 – 2.45	**Specific topics for discussion**.

Justin Crow: Exercise prescription in muscle activation.

David Francis: Use of muscle activation as a preventive and warm-up protocol.

David Buttifant: Muscle activation in performance enhancement and future directions.

Ruben Branson: The role of medical interventions in managing conditions of the hips and pelvis.

2.45 – 3.00	COFFEE BREAK
3.00 – 3.45	Gary Nicholls: Broad **case studies** are to be opened for discussion by the group.
3.45 – 4.00	Thank you's and departures.

Invited guests

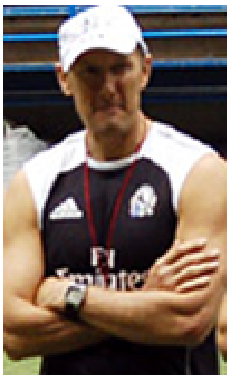
Dr. Shirley Sahrmann is Professor of Physical Therapy/ Neurology/ Cell Biology and Physiology at Washington University School of Medicine, St. Louis, Missouri. She received her bachelors degree in Physical Therapy, masters and doctorate degrees in Neurobiology from Washington University. She is a Catherine Worthingham Fellow of the American Physical Therapy Association and is a recipient of the Association's Marion Williams Research Award, the Lucy Blair Service Award, and the Kendall Practice award, the John H.P. Maley Lecture and Mary McMillan Lecture awards. Dr. Sahrmann has also received Washington University's Distinguished Faculty Award, the School of Medicine's Excellence in Clinical Practice Award and an honorary doctorate from the University of Indianapolis. She has served on the APTA Board of Directors. In addition to her numerous national and international presentations, Dr. Sahrmann has been a keynote speaker at the 3rd International Conference on Movement Dysfunction, World Confederation of Physical Therapy, and at the Canadian, Australian, and New Zealand national congresses. Dr. Sahrmann's research interests are in development and validation of classification schemes for movement impairment syndromes as well as in exercise based interventions for these syndromes. Her book Diagnosis and Treatment of Movement Impairment Syndromes describes the syndromes and methods of treatment. She maintains an active clinical practice specialising in patients with musculoskeletal pain syndromes.

Dr. Alison Grimaldi is a sports physiotherapist who has completed a PhD on muscle function around the hips and pelvis. Alison presents courses throughout Australia on muscle function around the hips and pelvis, and the use of real-time ultrasound. Alison also currently practices at a private practice in Brisbane. Alison's practical experience includes work in swimming and athletics at the elite level. Recently Alison was invited to be keynote speaker at the 3rd International Conference on Movement Dysfunction in Edinburgh, Scotland.

Mrs. Leanne Rath is a sports physiotherapist. She was one of the first in Victoria to successfully achieve clinical specialisation (FACP). Leanne is currently practicing at a physiotherapy practice in Melbourne and has conducted lectures on topics relating to the hips and pelvis. Leanne's extensive practical experience includes work with The Australian Ballet, the Australian Institute of Sport, the Australian gymnastics team (including work at the Olympics) and other national teams including the Australian netball and athletics teams.

Mr. Paul Coburn is a sports physiotherapist currently managing a busy private practice in Melbourne's northern suburbs. Paul's practical experience includes ten years as head physiotherapist with the Richmond Football Club, as well as work with the Victorian Institute of Sport rowing squad. Paul has coordinated the Master of Sports Physiotherapy program at La Trobe, worked as a clinical leader with the Victorian Workcover Authority for the last seven years and acted as medical advisor to the Professional Footballers Association. Paul has also contributed to two recent qualitative analyses for the AFL Research Board reporting on the prevention and management of hamstring injury and groin pain in the Australian Football League.

Collingwood staff



Dr. David Buttifant is a sports physiologist who has been employed as Director of Sport Science at the Collingwood Football Club for the last ten years. David has previous experience as Head of Conditioning at the North Melbourne Football Club and also with the New South Wales Institute of Sport in the lead up to the Sydney Olympics. In addition to being an ex-AFL player with the Richmond Football Club, David has completed his PhD at Victoria University, and currently sits on the AFL research board. David recently presented a study on the effects of gluteal muscle activation exercise on peak power output at the National Strength Conditioning Association National Conference in Orlando, Florida.

Mr. Justin Crow is a physiotherapist currently employed as rehabilitation coordinator with the Collingwood Football Club. Justin has completed a Master of Applied Science (Exercise Rehabilitation) and is currently enrolled in a Doctor of physiotherapy program at La Trobe University. Justin has contributed to a report to the AFL research board on prevention and management of groin pain in the AFL, and published research relating to the screening of adductor strength in elite junior Australian football players.

Mr. Gary Nicholls is a sports physiotherapist who has worked at Collingwood Football Club since 1999. Gary has also practiced at Olympic Park Sports Medicine Centre for the last 14 years. Gary has acted as chairman of the Sports Physiotherapy Association and is currently president of the AFL physiotherapists association.

Mr. David Francis is an experienced musculoskeletal physiotherapist who has recently achieved his clinical specialisation (FACP). David has worked as a physiotherapist with the Collingwood Football Club since 1996, and currently also manages and practices at a large private practice in Melbourne's south east growth corridor.

Dr. Ruben Branson is currently employed as team doctor at the Collingwood Football Club. Ruben also practices at Olympic Park Sports Medicine Centre, Alphington Sports Medicine Centre and other sports medicine centres throughout Melbourne. Ruben's past experience includes working with the Melbourne Storm and as team doctor at the 2008 Paralympics in Beijing, and world university games in Thailand. Ruben has contributed to research relating to the prevention of hamstring injuries in community-level Australian football.

Introduction

Muscle activation is a growing area of research in both the community and sporting populations. The understanding of how pathology can affect muscle activation is improving. For example, delayed muscle activation of gluteus maximus and multifidus in combination with an earlier onset of biceps femoris have been reported in sacroiliac joint pain (Hungerford, Gilleard & Hodges 2003), and a delayed onset of transversus abdominus is seen in low back pain (Hodges, 2001), and longstanding groin pain (Cowan et al., 2004). Suboptimal muscle activation levels and patterns may also exist in asymptomatic individuals (MacDonald, Hodges & Mosely, 2009) and may be implicated in the pathogenesis of injuries around the hips and pelvis, which make up the majority of injuries seen in Australian rules football (Orchard & Seward, 2010). Consequently, an understanding about the assessment and management of issues relating to muscle activation in this area of the body is considered to be of high importance in the management of elite Australian football players (Pizzari, Coburn & Crow, 2008).

The Collingwood Football Club prides itself on providing best practice in the management of its playing list. Consequently, a workshop has been organised to facilitate discussion with world leaders in the field of muscle activation about how best to apply recent progress in the field and share new ideas to assist in injury prevention, injury management and performance enhancement at the Collingwood Football Club.

This literature review attempts to summarise some of the key points and recent literature published relating to the topic: Muscle activation around the hips and pelvis in the context of Australian Football. It is intended to provide some background information to the invited guests about Australian football and also give Collingwood-based staff some background information on the research undertaken by our invited speakers as well as a brief summary of some key literature relating to the topic.

A schedule of proceedings, biographies of attendees and some supplementary information are also included in the booklet in addition to this review.

Australian Football

Australian football is currently the most popular football code in Australia (Gray & Jenkins, 2010) and is played at the elite level in the Australian Football League (AFL). Two teams of 22 players contest four 20-minute quarters of match play. Only 18 of these players may be one the field at any one time while the other four players remain on the interchange bench. Team players are generally classified into three groups: forwards (offensive players), backs (defensive players) and nomadic players who traverse the entire field. Australian football is a running game combining athleticism with speed that requires skilful foot and hand passing to score goals which are worth six points. It is also a contact game that typically can involve a player sustaining collisions during a match.

Player characteristics in the AFL: Mean (SD) (Gray & Jenkins, 2010)

- Age = 22.6 (2.9) years
- Height = 188 (9.0) cm
- Weight = 86.8 (8.9) kg
- Skinfolds = 47 (7.8)
- Vertical jump = 62.3 (3.7)
- 3RM bench press = 97.9 (11.9) kg
- 3RM leg press = 399 (48) kg

Sprinting

Acceleration is an important part of the game and the ability of players to recover from high intensity exercise is a defining quality of 'better' players at elite AFL level (Young et al., 2005). For all positions there are more than 150 high intensity efforts a match (fast run or sprint) that typically last less than 6 seconds each (Dawson et al., 2004).

Overall distances travelled in matches are typically 12 310m for nomadic players, 11 920m for forwards and 11 880m for backline players (Wisbey, Rattray & Pyne, 2008).

Change of direction

Agility and the ability to change direction are key characteristics of Australian football. In particular, the ability to change direction at speed is important as more than half of all high intensity efforts involve at least one change of direction (Dawson et al., 2004).

Kicking

Typically in an AFL game an individual player might kick the ball up to 20 times, not including the warm-up. During a typical training session however a player is likely to kick the ball approximately 40 times.

In the kicking leg the greatest muscle activity, as viewed in MRI, occurs in the adductor longus and Tensor Fascia Lata (TFL) muscles. In the stance leg the semitendinosis and TFL muscle show the highest signal changes. (Baczkowski et al., 2007)

Injury characteristics

Australian football typically sees a wide variety of injuries each year. On average a team with a player list of 46 players will have over eight players missing through injury every week (Orchard & Seward, 2010). A breakdown of injuries to the hips and pelvis during the 2009 season is summarised below in Table 1. (adapted from Orchard & Seward, 2010):

Table 1.

Injury classification	Incidence	Prevalence	Recurrence
Hamstring strain	6.0	21.2	38%
Quadriceps strain	1.9	5.7	35%
Groin strain/Osteitis Pubis	3.3	13.1	36%
Other hip/groin/thigh including hip joint	0.5	2.6	
Thigh/Hip Haematoma	0.8	1.2	
Buttock/SIJ	0.6	1.6	
Lumbar/thoracic spine	1.5	5.1	
All Injuries	**35.5**	**136.7**	**20%**

Note: Incidence refers to average new injuries per club for the 2009 season (a player must miss a match during the season for the injury to be captured by the survey), recurrence refers to the percentage of new injuries that are a recurrence of an old injury, while prevalence is a product of incidence x severity (matches missed).

Hamstring Injury

Hamstring injury is the most common injury in Australian football. A trend for reduced recurrence and increased prevalence might be explained by a move within the league towards increasingly conservative management of this injury (Orchard & Best, 2002). Known risk factors for hamstring injury are player age, past history of hamstring injury, strength deficits, indigenous race and a past history of other injury (Prior, Guerin & Grimmer, 2009). Although injury risk is highest for the first eight weeks following return to sport, a significantly increased risk is maintained so that football players are approximately three times more likely to suffer a recurrence a year after their initial injury (Hagglund, Walden & Ekstrand, 2006; Gabbe, Bennell, Finch, Wajeswelner & Orchard, 2006).

It has been suggested that a high rate of recurrence may be attributed to the persistence of a shorter optimum musculotendon length for active tension in the injured muscle (Brockett, Morgan & Proske, 2004). Interestingly, testing during different stages of match-play in soccer players reveals a significant change in angle of peak torque and peak eccentric torque at the end of each half when compared to pre-exercise testing (Small, McNaughton, Greig & Lovell, 2010). These changes could explain an increased hamstring injury risk that is seen during the later stages of match play.

Hamstring strain injuries sustained during high-speed running are believed to occur during the terminal swing phase, or possibly the initial contact phase of the gait cycle during which phase the hamstrings are lengthening and actively absorbing energy from the decelerating limb (Heiderscheit et al., 2010). A tight iliopsoas has also been implicated in hamstring injury risk as it may place the hamstrings at a mechanical disadvantage at the end of the swing phase in running by increasing relative anterior pelvic tilt (Thelen, Chmanov & Sherry, 2006). Similarly, it has been hypothesised that impaired coordination and muscular control of the lumbopelvic region may not allow the hamstrings to function at optimal lengths and loads during running (Sherry & Best, 2004). For example, it has been suggested that an early activation of the hamstrings and erector spinae muscles relative to the gluteal muscles may be indicative of faulty muscle activation (Lewis & Sahrmann, 2009). This was also reported in a survey of AFL medical and physiotherapy staff who considered both the strength and recruitment of the gluteal and hamstring muscles to be key modifiable risk factors for hamstring injury in their playing list (Pizzari, Wilde & Coburn, 2009).

<u>Groin injury</u>

In the AFL injury report, groin injuries include a number of overlapping diagnoses including adductor muscle strains, tendinopathy, osteitis pubis and sports hernias. Using this classification a high rate of recurrence and chronicity is seen in the AFL, especially in first year players (Orchard & Seward, 2010). Interestingly, it has recently been reported that players who have had a hip or groin injury in their elite junior years are over six times more likely to sustain a hip or groin injury in the AFL (Gabbe et al., in-press). It has been suggested that an imbalance between pelvic integrity and training load may be central to the development of chronic groin injuries (Pizzari, Coburn & Crow, 2008). However, the complex interaction between the hip, abdominal and adductor regions means that diagnosis and classification of injuries in this region can be difficult.

Altered muscle onset patterns in transversus abdominus have been identified in Australian football players with longstanding groin pain (Cowan et al., 2004) suggesting that the correction of muscle activation patterns has a role to play in the rehabilitation, and perhaps prevention, of this condition. Successful retraining of transversus abdominus timing and activation level has been demonstrated in patients with chronic nonspecific low back pain (Tsao & Hodges, 2008;Tsao, Galea & Hodges; in-press). However, it is currently unknown whether this approach would also be effective in conditions such as longstanding groin pain. The resting thickness of the transversus abdominus as measured on ultrasound has also been found to be decreased in athletes with longstanding groin pain (Jansen et al., 2010). Interestingly, improvements in self-reported sports restriction and pain during the squeeze test following a training program incorporating both motor control of the transversus abdominus and global strength exercises were found not to be associated with changes in transversus abdominus thickness in athletes with longstanding groin pain (Jansen, Mens, Backx & Stam, 2009).

One prospective study investigating risk factors for the development of chronic hip and groin pain in Australian football players found that reduced total hip joint range of movement (ROM) and a lower body weight were related to the development of chronic groin injury. Of all of the measures of hip ROM, dominant side external rotation (ER) ROM appeared to be the least predictive measure, although all of these results should be interpreted with some caution as only four players in a group of 29 actually developed groin pain (Verrall et al., 2007). It has been postulated that a restriction of hip joint ROM may result in greater stress across the superior pubic ramus and pubic symphysis and thereby contribute to the development of a pubic overload injury (Verrall et al., 2005). Interestingly though, another study of elite junior Australian football players found that despite acceptable reliability of testing, no measures of hip rotation ROM differed among players with or without groin pain (Malliaras, Hogan, Nawrocki, Crossley & Schache, 2009).

Assessment of hip joint ROM appears to have a role in the screening of players in Australian football. Although normal hip joint ROM has been reported to be 30-40° for IR and 40-60° for ER, a group of 29 elite Australian football players were found to average 20° for IR and 30° for ER (measured at 90° of hip flexion) (Verrall et al., 2007). Although it is still uncertain why this might be the case, it has been suggested that it might be possible for this restriction to develop secondary to joint stressors in a similar way to the shoulder joint capsule in throwing (Verrall et al., 2005). In Australian football players that developed longstanding groin pain displayed an average hip IR ROM of 15° (Verrall et al., 2007). Another study of athletic patients diagnosed with longstanding adductor-related groin pain found the average hip IR ROM to be 22° (Weir et al., 2010).

<u>Hip injury</u>

A study of 218 consecutive subjects with groin pain presenting to a primary care sports clinic demonstrated that the most prevalent condition was hip joint pathology, with common diagnoses including acute labral tears and impingement syndromes. These patients also had an elevated likelihood of not returning to their pre-injury level (Bradshaw, Bundy & Falvey, 2008).

FAI refers to abnormal contact between the acetabulum and the femoral head or neck, and can result from either a non-spherical femoral head or overhang of the acetabular rim (Laude, Boyer & Nogier, 2007). The two main variants are pincer impingements where the acetabular rim impinges on the femoral neck at the limits of its ROM, and cam impingements where the non-spherical femoral head contacts the anterior rim when the hip is flexed. Structural abnormalities are obviously a key factor in the aetiology of this condition although increased pelvic tilt is likely to promote the occurrence of FAI (Siebenrock, Schoeniger & Ganz, 2003), and other factors such as muscle activation and tightness that may also contribute to dynamic impingement should also be considered.

The relationship between femoroacetabular impingement (FAI) and long-standing groin pain appears strong with one study reporting that 64 out of 68 hips in patients with longstanding adductor-related groin pain had radiological signs of femoroacetabular impingement (Weir, de Vos, Moen, Holmich & Tol, in-press). Despite a high prevalence of radiological signs however the FADIR test for anterior hip impingement was positive in only nine of these cases (14%), and there was no relationship between the number of radiological signs of FAI within a hip and either total hip ROM or a positive anterior impingement test (Weir et al., in-press).

There have been eight different radiological signs for FAI reported in the literature, and it would follow that as the number of possible signs continues to increase that the prevalence of the disorder will also increase. However at present there is no clear consensus about how a diagnosis of FAI should be made and a gold standard is lacking (Weir et al., 2010).

FAI has also been suggested as a possible factor in the aetiology of hip joint degeneration. Changes to the muscles of the hip have been reported in patients with either hip osteoarthritis or degenerative labral pathology and may be worth noting to assist management in the early stages of FAI. Grimaldi et al., (2009a;2009b) reported that piriformis, lower gluteus maximus, upper gluteus maximus, and gluteus medius were all smaller in size on the affected side in patients with advanced hip pathology. Gluteus minimus also showed a trend (p=0.1) for reduced size in the affected side of this patient group. It is uncertain whether these differences between sides were the result of muscle atrophy on the affected side or muscle hypertrophy on the unaffected side due to increased load bearing. Interestingly gluteus medius was shown to be increased in size on the affected side compared to matched controls in patients with mild hip pathology. It has been suggested that this hypertrophy of the gluteus medius in the early stages of hip pathology may be the result of increases in relative hip adduction, and also that different responses of the three fascially different layers of the gluteus medius muscle to hip joint pathology might warrant further investigation (Grimaldi et al., 2009a).

During hip extension, when gluteal force is decreased, modelling suggests that an increased anterior hip joint force will be present. Likewise, anterior hip joint force is expected to increase with decreased activation of the iliopsoas during hip flexion (Lewis, Sahrmann & Moran, 2007). Accordingly, the correction of a movement pattern that involves delayed gluteal muscle activation during hip extension is recommended to reduce stress to the anterior hip (Lewis & Sahrmann, 2009), and it would be follow that assessment of iliopsoas muscle function would be warranted in football players with hip pain. It has also been suggested that when assessing and rehabilitating the lateral stability mechanism of the hips and pelvis three anatomical layers should be considered. The upper gluteus maximus and TFL, along with their attachments to the iliotibial band make up the superficial layer. The intermediate layer consists of the piriformis and the gluteus medius, with the gluteus minimus forming the deepest layer (Grimaldi, 2009c).

Diagnosis and classification of injury to the hips and pelvis

Diagnosis of conditions in the areas of the groin and hips is typically difficult. Consequently, a number of systems of classification have been proposed to aid the decision making of clinicians when managing problems in this area of the body. For example, it has been proposed that groin pain be classified into one of three broad groupings using a "clinical entity" approach: Adductor-related/osteitis pubis, hernia and lower abdominal, and iliopsoas related pain (Holmich, 2007). This classification however is challenged by another case series that reported a high prevalence of hip-related pathology in patients presenting with groin pain (46%), and cases not clearly covered by the above groupings such as external iliac artery endofibrosis and obturator neuropathy (Bradshaw et al., 2008).

Another system of classification, advocated by Sahrmann (2000), involves the diagnosis of musculoskeletal pain syndromes according to the directions of motion or stress that are accompanied by pain. In other words, the name of the syndrome is the name of the movement or postural alignment during which a person experiences pain or during which the motion is performed in a suboptimal manner. For example, femoral anterior glide syndrome occurs due to an inadequate posterior glide of the femoral head during hip flexion, presents with groin and generalised hip pain, and can be associated with both iliopsoas tendinopathy and bursitis (Sahrmann, 2000). Classifications such as these can be useful to guide a therapist in their assessment, management and clinical decision making.

Injury prevention

Screening

Decreased hip adductor strength has been identified as occurring both during and preceding the onset of groin pain in elite junior Australian football players (Crow, Pearce, Veale, Coburn & Pizzari, 2009). This supports the suggestion that the onset of pain in the groin may be part of a continuum of pathology in cases of pubic overload. It then follows that frequent screening of player adductor strength might be an effective way of monitoring the response of a player to their training load and allow for early management of their condition.

Research in professional dancers shows that altered lumbopelvic movement control as measured on two movement control tests (knee lift abdominal test and standing bow) are predictive of musculoskeletal injury (Roussel et al., 2009). Poor lumbopelvic control has also been identified as being a key perceived risk factor for hamstring injury in the Australian football league, along with sacroiliac joint and pelvic dysfunction (Pizzari et al., 2009).

Initial research suggests that there may be an association between playing sports involving lateral movement and the presence of pelvic asymmetry (Bussey, 2010). However, this research was conducted in women playing laterally dominant sports such as ice hockey and it is uncertain whether it could be generalisable to Australian football. It is known however that the size of the psoas is increased in the dominant kicking leg, while quadratus lumborum size is greater in the stance leg in elite Australian football players (Hides et al., 2010). The importance of addressing these asymmetries is still unknown.

Targeted exercise

Exercises targeting neuromuscular control of the lumbopelvic region have been suggested for inclusion in hamstring injury prevention programs for Australian football players (Cameron, Adams, Maher & Missen, 2009). As eccentric hamstring training is known to facilitate a shift in peak force development to longer musculotendon lengths it is also commonly used as a rehabilitative and preventive measure in this condition (Heiderschit et al., 2010). For example, nordic hamstring exercises have been advocated for use in athletes to reduce hamstring injury risk, possibly by facilitating a shift in the length of optimal muscular tension (Mjolsnes, Amason & Osthagen, 2004).

A progressive retraining program for gluteus maximus in a triathlete has been reported to achieve reduced EMG activation of the hamstrings during terminal swing and the first half of stance phase, as well as improving hip extension strength (Wagner et al., 2010). This approach used exercises and progressions recommended by Sahrmann (2002). Although only level four evidence, it is possible that a training program of this type that may reduce the activity of the hamstring muscles during running gait could prove to be a useful tool in reducing the risk of hamstring cramping and hamstring strain in Australian football players. It may also be of value to differentiate between the difference in function of the upper and lower portions of gluteus maximus. During both walking and stair climbing for example, the lower portion of gluteus maximus functions as the main hip extensor, whereas the upper portion functions more like the gluteus medius muscle as a lateral stabiliser (Lyons, Perry, Gronley, Barnes & Antonelli, 1983).

The development of a 'stable core' is often recommended to assist in injury prevention. While the core is generally considered to be the lumbo-pelvic complex, stability has been explained as a dynamic state in which the body has sufficient stiffness to resist displacement from both internal and external perturbations, and involves an interplay between movement and stiffness without being a simple rigidification of the body (Saunders, 2007). Core stability during locomotion is believed to be dependent on a high degree of neuromuscular control of intersegmental shear and torsion (Saunders, 2007) and the assessment and retraining of local spinal and pelvic stabilisers to facilitate this may be an important component in an injury prevention strategy at an Australian football club.

<u>Posture</u>

Postural education and correction may form an important role in injury prevention of Australian football players. For example, it has been observed that different upright sitting postures result in different muscle activation in the muscles of the trunk (O'Sullivan et al., 2006; Reeve & Dilley, 2009). For this reason posture should be considered when retraining muscle activation around the trunk, hips and pelvis. Biomechanical modelling has also suggested that an exaggerated anterior pelvic tilt posture could lead to a predisposition to have an excessively internally rotated hip joint (Neumann, 2010). This may be of importance in players with FAI and reduced hip IR ROM.

Management of injury to the hips and pelvis

<u>Exercise prescription to improve muscle activation</u>

Exercises to improve muscle onset timing have been used with success in other areas of the body. Isolated muscle retraining of transversus abdominus appears effective subjects with low back pain (Tsao, Galea & Hodges, in-press), wobble-board and other instability training methods appear effective at retraining muscle onset times of the peroneal muscles in functional ankle instability (Clark & Burden, 2005; Akhbari, Takamjani, Salatavi & Sanjari, 2007), and general strengthening with or without isolated muscle retraining of the VMO appears effective in patellofemoral pain syndrome (Cowan et al., 2002; Boling et al., 2006). Currently little is still known about whether any of these training modes might be effective in retraining muscle onset timing and patterning in conditions of the hips and pelvis. It has however been demonstrated that both gluteal muscle timing and activation can be altered with verbal cues (Lewis & Sahrmann, 2009) and abdominal hollowing (Chance-Larsen, Littlewood & Garth, 2010; Oh et al., 2007) during a prone hip extension exercise in healthy subjects.

Although measures of muscle activation were not recorded, a functional rehabilitation program for acute hamstring injuries, incorporating trunk stabilisation exercise and agility training, has been found to be more effective at reducing injury recurrence that traditional rehabilitation involving strengthening and stretching (Sherry & Best, 2004). Any 'motor control dysfunction' identified following acute hamstring injury has been reported to become a focus of management starting immediately after the injury had occurred (Pizzari et al., 2009). Core stability exercises incorporating real-time ultrasound to assess and attempt to improve the functioning of transversus abdominus, multifidus and the deep hip rotators have also been reported to be currently used in the rehabilitation of hamstring injuries in the AFL (Pizzari et al., 2009).

Retraining of the transversus abdominus taught using real-time ultrasound has been shown to correlate with improvements in function and pain in people with low back pain (Ferreira et al., in-press), while stabilisation training of multifidus also incorporating real-time ultrasound has been demonstrated to improve cross-sectional area of multifidus and reductions in pain in elite cricketers with low back pain when high-resistance exercise is ceased (Hides, Stanton, McMahon, Sims & Richardson, 2008).

Although the functioning of the transversus abdominus and multifidus have been shown to be important in spinal and pelvic stability, less is known about the role of the deep hip rotators. The composition of these muscles (large cross-sectional area and short fibre length) would suggest that they play a stabilising role for the hips and pelvis (Ward, Winters & Blemker, 2010). Lee (1999) also promotes consideration of the activity of the deep muscles of the hip to assist in the achievement of optimum load transfer between the spine and the lower limbs.

Medical and surgical management and muscle activation

It has been suggested that in cases where deficient stability of the sacroiliac joint has been established, then specific exercise programs designed to improve lumbopelvic stability may not be sufficient to improve pain and function (Cusi et al., 2010). This may be because deficient ligament strength in the posterior aspect of the joint may not be providing a sufficiently stable base to permit an effective muscle recruitment strategy (Pool-Goudzwaard, Vleeming, Stoeckart, Snijders & Mens, 1998). Prolotherapy treatment, usually involving an injection of hypertonic dextrose solution, aims to induce the proliferation of new cells and encourage the production of dense fibrous tissue to strengthen incompetent structures at their fibro-osseous junctions (Cusi et al., 2010). Prolotherapy injections into the dorsal interosseous ligament of the sacroiliac joint in combination with exercise therapy have shown positive clinical outcomes for 76% of patients at their 3-month follow up in a study of 25 patients with sacroiliac joint pain (Cusi et al., 2010). These results contrast with the results of a controlled trial reporting no difference in effect between prolotherapy and the injection of normal saline (Yelland, Glasziou, Bogduk, Schluter & McKernon, 2004). The application of prolotherapy during the preseason has also been mentioned as a possible tool in assisting in the prevention of hamstring strain injuries by improving sacroiliac joint stability (Pizzari et al., 2009).

Corticosteroid injections have been listed as a management option for the treatment of bursitis or synovitis around the hip. Injections of local anaesthetic may also be applied to painful structures around the hips and pelvis such as the iliolumbar ligament and posterior sacral ligaments (Fricker, 1997).

A qualitative report into the use of injections in the management of hamstring injuries in the Australian football league reported that the use of epidurals, lumbar facet joint blocks and nerve root injections are not uncommon where an injured player has concurrent low back issues (Pizzari et al., 2009). Some clubs also mentioned using local anaesthetic injections into trigger points proximal to the hamstring, and injections into the iliolumbar ligament as required. Although local injections into the hamstrings were avoided by most clubs, a few clubs reported routine injection of Traumeel. Traumeel is a homeopathic remedy possessing anti-inflammatory and analgesic properties that is sometimes injected into the hamstring following a strain. Clubs differed on whether the injection went directly into the injury site or into another area of the muscle, and two clubs reported that they have stopped using the method as they felt that it "made no difference to recovery or slowed down rehabilitation"(Pizzari et al., 2009). The effects on these various injection options on muscle activation levels and patterns are currently uncertain, although it might be hypothesised that a reduction in pain from an injection could facilitate an improvement in the activation of any muscles that may have been inhibited by the painful structure.

It is thought that in some patients with adductor related groin pain that their pain may emanate form the adductor enthesis. Where adductor enthesopathy is confirmed on MRI it may be treated with entheseal pubic cleft injections. A procedure that has been reported to provide pain relief at one year follow-up in competitive athletes with adductor enthesopathy (Schilders et al., 2007).

A recent review into the role of muscle imbalance in sports-related pain and dysfunction outlined the potential for the use of intramuscular injections of botulinum toxin (botox) in the sporting population (Cullen, Boyle, Silbert, Singer & Singer, 2007). This review suggested that as botox injections provide short term reductions in focal muscle overactivity, their use in overactive muscles might facilitate the reactivation of relatively inhibited muscles and assist in the restoration of optimal motor patterns (Cullen et al., 2007).

FAI can be managed arthroscopically with a variety of procedures available to surgeons. Commonly the femoral head and neck are smoothed and any labral lesions repaired or removed (Laude et al., 2007). Hip arthroscopes have been reported to lead to good success rates in terms of return to sport in professional athletes with FAI (Phillippon, Schenker, Briggs & Kuppersmith, 2007) and are become increasingly utilised in Australian football.

Adductor tenotomy refers to a surgical procedure where the superficial fibres of the adductor longus tendon are cut 2-4cm below the tendon insertion that has been shown to have good clinical success, possibly by transferring tensile stress from the superficial component of the tendon to the deep portion of the tendon which still remains intact (Orchard, Cook & Halpin, 2004).

Surgical repair of the abdominal wall or fascia near the inguinal ligament may be undertaken in the management of athletes considered to have a 'sports hernia' or 'conjoint tendon tear'. It has been suggested that surgery may lead to more successful outcomes than conservative management in this condition, which like other diagnoses of groin pain lacks consensus about what specifically constitutes a diagnosis (Caudill, Nyland, Smith, Yerasimides & Lach, 2008). This condition is less frequently diagnosed in Australian football players than in football players in other codes. It is worth noting that it has been contended that proper evidence does not exist for the theory that a sports hernia constitutes a credible explanation for groin pain, and that greater restraint should be observed before surgical intervention (Fredberg & Kissmeyer-Nielsen, 1996). Another similar procedure is the inguinal release. This is a laparoscopic procedure that is combined with a mesh repair of the posterior abdominal wall that is hypothesised to alleviate groin pain symptoms in patients with tenderness over the inguinal ligament. One study of 73 consecutive patients (sportsmen/women) reported that following the procedure patients returned to full training at two to three weeks and 74% considered themselves 'match-fit' by four weeks. This study also reported improvements in pain severity, pain frequency and functional limitation in the cohort (Mann, Sutton, Garcea & Lloyd, 2009).

Surgery to the symphysis pubis can also be undertaken in players diagnosed with osteitis pubis, a painful inflammatory process involving the symphysis pubis and surrounding structures. Options described in the literature include pubic symphysis stabilisation, pubic symphysis curettage and polypropylene mesh placement into the preperitoneal retropubic space (Choi, McCartney & Best, in-press).

The reason why surgical and medical intervention including those listed above are effective is contentious. It has been suggested that that the efficacy of many of these treatments may often be attributed to the fact that they buy rehabilitation time, and that coaches and managers may be more amiable towards conservative rehabilitation when a player has had an 'exotic' intervention first (Cook, 2010). The role that surgery may have in 'resetting' a patient's muscle activation pattern has not been investigated, and it is often unfeasible for surgical studies to use a control group to control for the effects of time or rehabilitation.

<u>Other management techniques</u>

Exercise is not the only conservative treatment modality to influence muscle activation. Spinal manipulation has been reported to increase the activity of the internal and external oblique muscles in people with low back pain, although it does not appear to have any effect on the activation or timing of onset of transversus abdominus (Ferreira, Ferreira & Hodges, 2007). The use of a pelvic belt also appears to alter muscle activation around the pelvis and trunk although actual changes appear to be inconsistent between individuals (Beales, O'Sullivan & Briffa, 2010). Similarly, taping may also be useful in facilitating changes in muscle activation around the hips and pelvis (McConnell, 2010).

Summary

A high prevalence of injuries around the hips and pelvis continue to be seen in Australian football. Understanding is growing about the role of muscle activation in many of these injuries, although a lack of clear diagnostic criteria for many of these conditions makes both research and clinical practice difficult. Assessment of muscle activation patterns and the prescription of interventions to improve them when appropriate should be considered in both the screening of Australian football players and the management of existing injuries. The role of muscle activation in performance enhancement is still in preliminary stages and warrants further investigation.

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Case Study

Classic 20 year old elite professional Australian football player with a grade 1 hamstring muscle strain

- Increased anterior pelvic tilt
- Stiff in both hip joints
- ‘Overactive’ hamstrings and ‘underactive glutes’
- Stiff into ankle dorsiflexion
- Overactive TFL
- Stiff and kyphotic thoracic spine

Case specific questions:

1. What would you do first to prevent future injury?
2. What is worth fixing and what isn’t?
3. General thoughts relating to specific rehabilitation?

Appendix C:

Workshop report for host organisation

Muscle activation around the hips and pelvis
Workshop report

Introduction

Muscle activation around the hips and pelvis has been identified as an area of physiotherapy practice that is advancing rapidly in terms of its clinical application within an Australian football club. The majority of Australian football injuries are to this area of the body, and issues with injury incidence and recurrence may be able to be attributed to the development of suboptimal muscle activation patterns in football players. Consequently, it was proposed that a workshop be conducted at the Collingwood Football Club to explore the role of muscle activation around the hips and pelvis in the context of Australian football.

On Monday 9th August, 2010 leaders in the field of physiotherapy met with club physiotherapists, exercise physiologists and a physician from the Collingwood football club. A half-day workshop was undertaken which allowed for the sharing of ideas and discussion of key points relating to the workshop topic. Details about the organisation, budgeting and a summary of key outcomes from the workshop are detailed within this report.

Organisation

After brainstorming was undertaken to identify key figures in the field of physiotherapy with experience relevant to the topic it was decided that within any potential group of contributors a mix of research and clinical experience was desirable. It was also decided that a group larger than ten people might dilute the effectiveness of the group. As six Collingwood staff were listed to attend, this left up to four places for invited guests.

Dr. Alison Grimaldi was identified as a key researcher on the workshop topic, having completed her PhD on muscle function around the hips, and was recruited to attend. Dr. Grimaldi also teaches popular courses on the use of real-time ultrasound to assess and manage conditions of the hips and pelvis. To balance Dr. Grimaldi's research experience, an experienced clinician was targeted next. Mrs. Leanne Rath is a specialist sports physiotherapist with experience working with the Australian Ballet and at the Australian Institute of Sport. Mrs. Rath has also lectured on the hip/pelvic complex over a twelve-year period and was known to be an innovative thinker on the workshop topic. Mrs. Rath was also contacted and recruited for the workshop.

A quick scan of potential international contributors found that Dr. Shirley Sahrmann would be completing a national tour in August 2010. Dr. Sahrmann is

Professor of physical therapy at Washington University and world renowned for her work on the classification of movement impairment syndromes around the hips and pelvis. Dr. Sahrmann has also supervised a couple of recent papers that model muscle activation patterns around the hip. Dr. Sahrmann was contacted and accepted her invitation to attend the workshop as long as the Australian Physiotherapy Association (APA) was happy for her to attend and the course fitted into her schedule. Upon contacting the APA, it was agreed that Dr. Sahrmann's flights could be rescheduled to later in the day on Monday 9th August to enable her attendance at the workshop. Fortunately, the date for the workshop also coincided with a course that Dr. Grimaldi, who lives in Queensland, was presenting in Melbourne. It was agreed that the Collingwood Football Club would cover her accommodation for one night to allow her to stay in Melbourne for the workshop.

Given that none of the invited contributors to the workshop had any Australian football experience it was considered important to recruit an experienced physiotherapist who might be able to shed light on issues specific to Australian football. Mr. Paul Coburn has ten years experience working at the Richmond Football Club and has recently co-authored qualitative investigations on the management of injuries to the groin and hamstrings in Australian football. Consequently, Mr. Coburn was also recruited to attend the workshop. The list of invitees was ratified by Mr. Coburn, and my supervisors Dr. Tania Pizzari and Dr. David Buttifant.

In the lead up to the workshop a summary of recent literature relating to the workshop topic was prepared. This summary was designed to familiarise Collingwood staff with recent developments in research relating to the workshop topic and help them prepare for the workshop. A workshop schedule was drafted which would allow Collingwood staff to take ownership of a small component of the workshop and facilitate discussion on a topic that they considered to be of importance and interest. For example, given my particular interest is in exercise prescription, I had time allocated to ask the invited contributors about what prescription parameters they use in practice and facilitate discussion on future directions relating to this topic. The schedule of the workshop, biographies of presenters, and the literature summary are contained in a booklet which was provided to all workshop attendees in advance of the workshop.

Workshop outcomes

The workshop began with each invitee spending twenty minutes speaking about their current research interests and initial thoughts about the topic. Mr. Coburn started proceedings by explaining that he had noticed a pattern in the management of injuries around the hips and pelvis. Mr. Coburn reported that since the 1980's a new surgical method for the treatment of groin or hip pain has become popular approximately every five years, and that although these treatments all appear to be better than rest alone, none of them offer good long-term outcomes. Mr. Coburn suggested that it might be time for everyone to stop following these surgical trends and look at using new conservative management options such as optimising muscle activation. He also suggested that new conservative methods of optimising muscle activation may be paramount in the management of groin and hip injuries. This generated discussion about concerns over a new trend for the use of hip arthroscopy to manage hip impingement. It was explained that the hip joint has a natural vacuum that is important to its function, and that any arthroscopic technique would break this vacuum seal and may therefore be detrimental to future hip joint function. Also, any removal of hip labrum might also be detrimental due to its role in helping create a hip joint negative pressure.

Dr. Grimaldi led a discussion on the role of the deep lateral stabilisers of the hip in normal movement. In particular the role of gluteus minimus was seen as important due to its relationship with the joint capsule, and its tendency to become underactive in the presence of pain. Methods of assessing and improving the function of gluteus minimus and also the iliacus muscle were discussed. It was generally agreed that the iliopsoas muscle is a vital component in good hip function and very relevant in Australian football, especially given its role in hip flexion movements such as kicking. Both Dr. Sahrmann and Dr. Grimaldi agreed that this muscle was commonly underactive in conditions such as hip impingement syndromes and that clients benefited greatly from exercise that facilitate the improvement of its function.

Dr. Grimaldi also described research that she is currently undertaking on the role of hip morphology on muscle function. She explained that the angle of the femoral head and neck can show quite large variability and influence optimal length tension relationships in the hip rotators. This was considered an interesting point as it had been observed that players at the Collingwood football club run with their hips in an externally rotated position yet remain asymptomatic. Dr. Grimaldi suggested that due to variability in hip morphology this position can actually be the neutral position in some people and the one where they may get optimal muscle activation. The implication of this suggestion was that caution should be employed when changing a player's hip range of movement or running gait, particularly if they are asymptomatic.

Dr. Sahrmann presented information about her approach to classifying common patterns of hip dysfunction and also one particular management technique that she considered to be useful for the management of anterior hip impingement. Dr. Sahrmann also explained that she believes that problems and pain around the hips and pelvis are the result of poor movement, as opposed to other schools of thought which suggest that poor movement patterns generally result from pain or pathology. Dr. Sahrmann also described recent research from her university that found that increased hip hyperextension during movement can put increased stress on the anterior structures of the hip joint. For example, she suggested that a 2° overstriding in hip extension during walking correlated with a 20% increase in anterior hip joint force. It was extrapolated from this that players who overstride during running are likely to receive large forces to the structures of their anterior hip joint.

The next topic considered in the workshop was a guided discussion about exercise prescription in improving muscle activation around the hips and pelvis. Dr. Grimaldi explained that once she has identified an underactive muscle she gets a client to perform 5-10 second isolated and isometric holds of that muscle. She continues these holds until their quality of activation starts to deteriorate. She encourages clients to practice this exercise dosage up to five times a day until good activation is achieved. The next phase of her management involves the incorporation of the isolated muscle activation into functional movements. Dr. Grimaldi also raised the importance of exercising specific to muscle fibre type. For example, doing long endurance holds at low loads for muscles with predominately type II fibres, and quick and strong movements to train muscles with predominately type I muscle fibres.

Dr. Sahrmann uses a very different approach to exercise which involves the inducement of a hypertrophic response within a lengthened muscle to allow it to rest at a shorter length and thereby facilitate the return to an improved posture and movement pattern. Dr. Sahrmann uses a strength/hypertrophy dosage to achieve this. Dr. Sahrmann also believes it is important to not get too caught up in isolated muscle function as she considers the whole movement itself to be what is important and not the specific activation level of a single muscle. Although Dr. Grimaldi and Mr. Coburn agreed that the performance of a movement might be able to be restored by changing muscle balance, they both expressed concern that when a movement is performed without the use of deep postural muscles, simply practicing the movement may reinforce the dysfunctional muscle activation pattern that is already present.

Dr. Sahrmann also spoke about the importance of variability in muscle recruitment patterns. She explained that muscles do not normally fire in exactly the same way every time and it therefore does not make sense to train one specific activation pattern. It was generally agreed however that the literature was particularly lacking in its reporting of normal muscle activation patterns around the hips and pelvis and that the collection of this information was an important step in the management of conditions of the hips and pelvis.

The potential role of muscle activation exercise during a team's preparation for an Australian football match or training session was discussed next. There were specific reports of the use of voluntary isolated muscle exercise targeting the gluteus maximus in conjunction with low load prone hip extension exercises in warm-up protocols for both hamstring injury rehabilitation and hamstring injury prevention. It was proposed that players perform isometric holds of important deep stabilising muscles around the hips and pelvis during their warm-up routine. The idea was generally approved of in theory by the invited contributors, although the number of repetitions required to achieve the desired effect without creating fatigue of a player's deep muscle system was queried. Dr. Grimaldi suggested that as few as five repetitions might be appropriate, while Mr. Coburn and members of the Collingwood staff were more confident that a player may be able to perform higher repetitions of isolated muscle exercise without creating fatigue. The importance of quality of exercise was also stressed as the performance of these exercises with incorrect technique might reinforce poor patterns of movement and have adverse effects on injury risk and performance.

The invited guests were next challenged to identify future directions relating to the topic and suggest what they would be consider worthy of investment over the next few years. Mr. Coburn spoke about methods of load monitoring and ways of identifying that a player is not coping with their training load as he considers these to be paramount to injury prevention. Mr. Coburn also made reference to the idea that injuries to the hips and pelvis may often be the result of an imbalance between pelvic stress from training load and pelvic integrity. It was generally agreed that due to the complexity of the pelvic ring it was rare to get any one problem in this area in isolation and any approach which offered the opportunity to prevent a disruption to the optimal function of any of these structures was a good idea.

Dr. Grimaldi also made suggestions relating to the use of technology in the assessment and retraining of muscle activation and joint posture. She encouraged the use of real time ultrasound to assess muscle function, in particular as computer programs are being developed to offer opportunities to assess muscle onset timing using this device. She also described the use of a strain gauge that can be worn during daily activities that provides feedback to players about their posture. This could be useful as uneven postures can lead to altered length tension relationships in muscles around the hips and pelvis. For example, standing with one side in hip adduction will, due the force of gravity during the day, strengthen the adductor muscle in this position so that its length-tension curve will shift which might create a muscular imbalance between sides. Dr. Sahrmann also supports this idea in terms of creating increased passive tension on one side and thereby influencing movement patterns. Dr. Grimaldi also suggested that the development of a reliable and sensitive test may be useful in screening players who needed closer attention to the activity of the muscles around their hips and pelvis. She offered the example of the Star Balance Test which is a test that can be used to assess hip and pelvic control in a functional position.

The role of surgery and medical management options in inhibiting muscle activity was discussed next. It was suggested that the inhibition of overactive muscles may be as important in restoring good movement patterns and muscle function as increasing the activity of the underactive muscles. Treatment techniques with a role in reducing superficial muscle overactivity were discussed, such as botox, dry needling, and surgical techniques which involve the cutting of superficial structures, such as in adductor tenotomy. It was generally agreed that these techniques were of more value than simply providing time for conservative management techniques, but were also only of value when coinciding with conservative management that encouraged a return to a normal muscle activation and movement pattern.

The workshop concluded with the presentation of a case study which invitees were encouraged to comment on. The case presentation is included in the workshop booklet and described the physical characteristics of a typical Australian Football player. It was agreed that it was difficult to know what to do first with this player without assessing them in person. Dr. Grimaldi however suggested that she would address postural awareness as a first point of call, followed by isolated muscle assessment and treatment as needed. Other invitees suggested performing gait analysis and described the need to watch how the player moved before making any further decisions about their management.

Key ideas to be considered for introduction by Collingwood Football Club:

- The increased use of real time ultrasound to assess and train the muscles around the hips and pelvis, in particular the gluteus minimus muscle.
- An increased awareness of the importance of the iliopsoas muscle in allowing optimal hip movement and preventing the development of impingement syndromes.
- Caution should be exercised when attempting to change an asymptomatic players hip range of movement or hip position when running as their particular movement pattern may actually be optimal for their individual hip morphology.
- Overstriding during running can place increased stress on the anterior hip joint and benefit may be gained from addressing this technique fault in players with or without hip impingement.
- Isolated muscle activation exercise of key muscles around the hips and pelvis may be able to be introduced into warm-up routines before football matches and training sessions once quality of exercise can be assured, and an appropriate exercise prescription agreed upon.
- The consideration of the Star Balance Test for inclusion in player screening protocols.
- Increased caution when sending a player for arthroscopic hip surgery in the light of potential implication of a broken vacuum within the hip joint.
- The use of a strain gauge to measure pelvic and hip position throughout the day. Possibly with auditory feedback.

Conclusion:

A workshop on the topic "muscle activation around the hips and pelvis in the context of Australian football" was conducted at the Collingwood Football Club. The workshop ran smoothly and to plan. The workshop attendees are expected to all have gained ideas and knowledge relating to the topic, and some key ideas are proposed for introduction at the Collingwood Football Club.

Appendix D:

Participant Information Sheet

LA TROBE UNIVERSITY

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Faculty of Health Sciences

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Information Form

Project title: The motor patterning of the hamstrings and gluteus maximus in Australian football players following injury: Is it altered and can it be changed?

Who are the researchers?

Dr. Tania Pizzari

- Physiotherapist
- Lecturer, School of Physiotherapy, La Trobe University (supervisor)

Mr. Justin Crow

- Physiotherapist and Exercise Physiologist
- Professional Doctorate student, School of Physiotherapy, La Trobe university

What is this study about?

This project aims to determine whether muscle patterning of the gluteal and hamstring muscles is altered following injury in elite Australian football players, and whether a simple low-level exercise program can change it.

Why am I being asked to be in this project?

We are asking you to take part in this project because you participate in Australian Football at the elite level. Participation in this project is on a voluntary basis.

What does the project involve?

The project involves attending two testing sessions during the pre-season where the muscle activation pattern of your gluteal and hamstring muscles will be assessed using surface electromyography during two movements:

- Prone hip extension: During this movement you will be asked to lie on your front and lift your knee up while keeping your leg straight.
- Box step-up: During this movement you will be asked to step up and over a small box.

Testing is non-invasive and your muscle pattern will be measured by electrodes that will be taped to your skin using hypo-allergenic tape. The testing protocol will be conducted in a laboratory at La Trobe University and is expected to take up to half an hour of your time. Upon consenting to participate in the study you will also be asked to complete a short questionnaire detailing basic demographic information.

Following the initial testing sessions your club physiotherapist will be contacted on a weekly basis to determine if any injuries have occurred. If you sustain a hamstring injury, ankle sprain injury or an episode of low back pain over either the 2012 pre-season, or 2012 football season you may be requested by the researchers to attend the laboratory within 4-10 days of the injury to re-test your muscle patterning using the protocol outlined above.

In addition to the testing protocol, at the post-injury session you will also be taught a simple exercise program incorporating isolated muscle activation. Immediately after which you will be re-tested once more to establish whether the exercise has altered your muscle patterning. Neither the testing protocol or the exercise program are expected to be in any way painful or detrimental to your injury and have been designed so that this is the case. Nevertheless if any movement or position is painful then testing or exercise will cease. You will also have the opportunity to withdraw from the study at any time without consequence. The post-injury session is expected to take an hour of your time.

What are the benefits of participating?

Your participation will assist in determining whether muscle patterning is altered following injury in elite Australian football players, and whether a simple exercise program can alter it. This knowledge may lead to better prevention and management of hamstring injuries in Australian Football.

What are the risks of the study?

The risks involved in this study are minimal due to the testing and exercise protocols using minimal force and speed and being conducted in the presence of experienced physiotherapists using a safe and reliable procedure.

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What happens to the results?
Results from your assessment and testing procedures will be kept confidential. The results of your testing procedures will be entered into a computer utilising a number system so that no-one will be able to identify you. Only Dr. Pizzari and Mr Crow will have access to this information. During the project the hard copy of questionnaire results will be kept in a locked filing cabinet in the office of Dr Pizzari. At the conclusion of the project, these results will be archived in a locked archive room at La Trobe University, School of Physiotherapy.

The results of the project will appear in a thesis to be written by Mr. Justin Crow, in journal publications, and in presentations at conferences, but you will not be able to be identified in any of these reports.

Can I withdraw from the study?
Participation in this research project is voluntary and therefore you are not obliged to take part. You are also free to withdraw from the project at any stage if you change your mind. If you choose not to participate, or withdraw from the project at a later stage, there will be no consequences or penalties for this decision.

In addition, you can withdraw consent for your data to be used up to four weeks following the completion of your participation. In this case, you are asked to complete the "Withdrawal of Consent Form" or to notify one of the researchers by e-mail or telephone.

Who can I contact if I have any questions?
Any further question you may have regarding this project may be directed to the Senior Investigator, Dr. Tania Pizzari, School of Physiotherapy, La Trobe University, on the telephone number (03) 9479 5872.

If you have any complaints or queries that the investigator has not been able to answer to your satisfaction, you may contact the Secretary, Faculty Human Ethics Committee, Faculty of Health Sciences, La Trobe University, Victoria, 3086 (ph: (03) 9479-2357, e-mail: n.mcdonald@latrobe.edu.au).

What do I do now?
If you decide that you would like to participate in this research study then you are encouraged to contact Dr. Tania Pizzari at the School of Physiotherapy on (03) 9479 5872 and advise her that you wish to participate in the study.

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Consent form

Project title: The motor patterning of the hamstrings and gluteus maximus in Australian football players following injury: Is it altered and can it be changed?

Statement of Agreement - Participant's Copy

I, ……………………………………………, have read and understood the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this project, realizing that we may withdraw at any time and withdraw consent for my data to be used up to four weeks following completion of participation. I agree that research data collected during the project may be included in a thesis, presented at conferences and published in journals, on condition that neither my name nor any other identifying information is used.

NAME OF PARTICIPANT (in block letters):……………………………………………

Signature: ………………………………………………… Date: ……………………

SENIOR INVESTIGATOR (in block letters): DR. TANIA PIZZARI

Signature: ………………………………………………… Date: ……………………

RESEARCHER (in block letters): MR. JUSTIN CROW

Signature: ………………………………………………… Date: ……………………

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Consent form

Project title: The motor patterning of the hamstrings and gluteus maximus in Australian football players following injury: Is it altered and can it be changed?

Statement of Agreement - Investigators' Copy

I, …………………………………………, have read and understood the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this project, realizing that we may withdraw at any time and withdraw consent for my data to be used up to four weeks following completion of participation. I agree that research data collected during the project may be included in a thesis, presented at conferences and published in journals, on condition that neither my name nor any other identifying information is used.

NAME OF PARTICIPANT (in block letters):……………………………………….

Signature: ………………………………………………… Date: ……………………

SENIOR INVESTIGATOR (in block letters): DR. TANIA PIZZARI

Signature: ………………………………………………… Date: ……………………

RESEARCHER (in block letters): MR. JUSTIN CROW

Signature: ………………………………………………... Date: ……………………

Appendix E:

Participant questionnaire

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THE MOTOR PATTERNING OF THE HAMSTRINGS AND GLUTEUS MAXIMUS IN AUSTRALIAN FOOTBALL PLAYERS FOLLOWING INJURY: IS IT ALTERED AND CAN IT BE CHANGED?

Please complete the following information and bring with you to your initial testing session.

Name: ____

DOB: ________/________/_________

Weight: ___________________________

Number of years on an AFL list: ________________________

Are you on any medication? YES / NO

Please List: ____

INJURY HISTORY: (Please circle)

Have you ever had hamstring or hamstring tendon surgery? YES / NO

Do you currently have any injuries that are preventing you from completing all of your prescribed training sessions? YES / NO

Please provide detail:

____

____

____

____

Have you ever had a hamstring strain injury that caused you to miss a match or training session due to the injury? YES / NO

If yes, please detail which side and in which year each injury occurred:

____

____

____

____

____

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Have you ever had an ankle sprain injury that caused you to miss a match or training session due to the injury? YES / NO

If yes, please detail which side and in which year each injury occurred:

____

____

____

____

____

Have you ever had an episode of low back pain that has caused you to miss a match or training session due to the injury? YES / NO

If yes, please detail which side (if applicable) and in which year each injury occurred:

____

____

____

____

____

Appendix F:

Major project recording sheet

Name: ______________________________

ID Number: _______________ **GPS**: __________ **Control** / **Rx**

Date: ___________ **Time**: __________ **Wind**: ________ **Temp**: ________

Item	Record
Preparation	
Sign indemnity form	
Baggy shorts on	
GPS and vest on	
Electrode sites prepared: shave, sand, swab	
Electrode placements: GMax	
Electrode placements: Biceps femoris	
Electrode placements: Medial HS	
Footswitches inserted: big toe, MTPJ and heel	
Warm-up: 200m, 100@60%, 100@70%, 100@80%, 100@gradual build to 90%	
Testing	
40:20:40 Trial 1	
40:20:40 Trial 2	
40:20:40 Trial 3	
40:20:40 Trial 4	
40:20:40 Trial 5	
Intervention	
Intervention (Control): Walking x 6 min	
Intervention (Rx): Prone - neutral spine	
10 x 10 sec Gmax squeezes L + R	
1 x 10 reps Gmax PHE L + R	
Testing	
40:20:40 Trial 1	
40:20:40 Trial 2	
40:20:40 Trial 3	
40:20:40 Trial 4	
40:20:40 Trial 5	
Post-testing	
Take off electrodes and footswitches	

Appendix G:

Publications not forming part of this thesis but published during the candidature

International Journal of Computer Science in Sport

Volume 15, Issue 2, 2016

DE GRUYTER OPEN

Journal homepage: http://iacss.org/index.php?id=30

DOI: 10.1515/ijcss-2016-0005

Predicting ratings of perceived exertion in Australian football players: methods for live estimation

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[3]Essendon Football Club, Melbourne, Australia

Abstract

The ability of machine learning techniques to predict athlete ratings of perceived exertion (RPE) was investigated in professional Australian football players. RPE is commonly used to quantifying internal training loads and manage injury risk in team sports. Data from global positioning systems, heart-rate monitors, accelerometers and wellness questionnaires were recorded for each training session (n=3398) from 45 professional Australian football players across a full season. A variety of modelling approaches were considered to investigate the ability of objective data to predict RPE. Models were compared using nested cross validation and root mean square error (RMSE) on RPE predictions. A random forest model using player normalised running and heart rate variables provided the most accurate predictions (RMSE ± SD = 0.96 ± 0.08 au). A simplification of the model using only total distance, distance covered at speeds between 18-24 km·h^{-1}, and the product of total distance and mean speed provided similarly accurate predictions (RMSE ± SD = 1.09 ± 0.05 au), suggesting that running distances and speeds are the strongest predictors of RPE in Australian football players. The ability of non-linear machine learning models to accurately predict athlete RPE has applications in live player monitoring and training load planning.

KEYWORDS: GPS, RPE, MACHINE LEARNING, TRAINING LOAD

Introduction

A rating of perceived exertion (RPE) is a subjective numerical value reported by an athlete following physical activity (Foster et al., 2001). The rating represents the perceived amount of effort experienced by the athlete, from rest to maximal exertion. In team sport environments, it is common practice to quantify internal training load using a global RPE value reported post training multiplied by the session duration (session-RPE) (Clarke, Farthing, Norris, Arnold, & Lanovaz, 2013; Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004; Ritchie, Hopkins, Buchheit, Cordy, & Bartlett, 2015). Session-RPE training load data is useful in monitoring athlete injury risk (Gabbett, 2010; Gabbett & Jenkins, 2011; Rogalski, Dawson, Heasman, & Gabbett, 2013), perceived fatigue and performance (Saw, Main, & Gastin, 2016). In light of these multiple applications, it can be desirable for physical preparation staff to have a level of control over the amount of RPE-based load that athletes experience.

As RPE data is collected from athletes post-training, it is difficult to confidently integrate into future planning protocols. A predictive model may enable RPE-based training load planning to be based on more controllable external training load parameters such as duration, distance, and speed. With the growing adoption of athlete monitoring technology and live data capture within professional team sport (Cummins, Orr, O'Connor, & West, 2013) live estimates of RPE may be possible, enabling training sessions to be extended, restricted or modified in order to elicit a desired RPE response. For example, if training load limits are prescribed using session-RPE, the data stream from athlete monitors will enable a live on-going RPE forecast as the session progresses, thus reducing the chances of exceeding thresholds and placing the athletes at higher risk of injury (Gabbett, 2010; Rogalski et al., 2013). Similarly, if coaching staff are attempting to structure training at a specific exertion level, a live estimate of internal training loads could provide immediate feedback on how close the session is tracking to target. An accurate predictive model may also serve a more pragmatic purpose by allowing missing data values to be imputed on the rare occasions when circumstances prevent the collection of RPE.

Moderate to strong relationships between athlete RPE and heart rate have been reported in previous studies (Borresen & Lambert, 2008; Clarke et al., 2013; Impellizzeri et al., 2004; Kelly, Strudwick, Atkinson, Drust, & Gregson, 2016; Lovell, Sirotic, Impellizzeri, & Coutts, 2013; Nicolò, Marcora, & Sacchetti, 2015). Respiratory frequency (Nicolò et al., 2015), running distance and speed (Bartlett, O'Connor, Pitchford, Torres-Ronda, & Robertson, 2016; T. Gallo, Cormack, Gabbett, Williams, & Lorenzen, 2015; Gaudino et al., 2015; Lovell et al., 2013), accelerations and collisions (T. Gallo et al., 2015; Gaudino et al., 2015; Lovell et al., 2013), wellness ratings (T. F. Gallo, Cormack, Gabbett, & Lorenzen, 2016), playing position, and experience (T. Gallo et al., 2015) have also shown associations with RPE. Accounting for different individual responses to external training stimulus has been shown to improve the accuracy of RPE predictions (Bartlett et al., 2016). These results suggest that a predictive modelling approach incorporating multiple training variables and a consideration of individualised responses may enable accurate RPE predictions.

The purpose of this study was to investigate the accuracy of predictive models for RPE in Australian football players using data typically collected during training sessions. It extended previous research by Bartlett et al. (Bartlett et al., 2016) by considering a larger set of predictor variables, alternate modelling approaches and different ways of accounting for individualised responses to training stimulus. Out of sample error estimates were used to evaluate predictive models to prevent overfitting and optimistic error estimates from resubstitution (Hawkins, 2004). Thus providing a robust assessment of the ability of these techniques to generalise to a live prediction environment.

Methods

RPE and training load data were collected in all field-based training sessions from a team of professional Australian football players over a single season. These sessions represented occasions when live data capture was used. Multiple predictor variables and modelling approaches were considered and evaluated on their ability to predict RPE data.

Subjects

Data were collected from 45 male Australian football players (mean ± SD: 23.8 ± 4.3 yr, 188.1 ± 6.6 cm, 85.7 ± 8.2 kg) comprising the entire senior list at a professional club. Consent was received from the club for the analysis of de-identified training data. The La Trobe University Faculty of Health Sciences Human Ethics Committee (FHEC14/233) approved the project.

Data Collection

RPE were collected from the cohort over a period of one competitive season (2015) using the Borg CR10 scale modified by Foster et al. (Foster et al., 2001). This scale has previously been employed in studies examining training loads and injury risk in team sport athletes (Gabbett, 2010; Rogalski et al., 2013). All players were experienced in using the scale and ratings were recorded within 30 minutes of the completion of training. Each player reported a single exertion rating after each field training session. Field training sessions included skill, conditioning, and match simulation sessions. No data from competitive matches or resistance training were included in the analyses.

Player physical movements and physiological responses were recorded from commercially available 10 Hz GPS devices that incorporated 100 Hz tri-axial accelerometers (Catapult® Optimeye S5) and heart rate monitors (Polar® T31) throughout each training session. Each player wore the same device throughout the season and the club performance analyst collected all data. The technology used had been validated as an athlete monitoring tool in Australian football (Boyd, Ball, & Aughey, 2011; Rampinini et al., 2015; Varley, Fairweather, & Aughey1, 2012). Additionally, players reported wellness ratings using a customised questionnaire in the morning prior to each training session. The questions asked players about their levels of fatigue, motivation and soreness. These values were included in the analyses as there is evidence suggesting that athlete wellness levels can influence subsequent RPE data (T. F. Gallo et al., 2016). A description of the variables collected is presented in Table 1.

Modelling Approach

In this study the task of predicting athlete RPE was treated as a supervised machine learning problem (James, Witten, Hastie, & Tibshirani, 2013). For each unique player training session (i) a set of predictor variables (x_i) was observed (Table 1) and an outcome label (y_i) was recorded, the athlete RPE. A supervised machine learning approach seeks to find a relationship between the predictor variables and outcome labels, enabling prediction of unknown outcomes given new data. In this context, new data may be coming in the form of live sensor data from players during training sessions. Two predictive modelling approaches were considered, regression and classification.

Table 1. Predictor variables

Category	Variable	Description
Running	Duration	Session time (min)
	Distance	Total distance (m) above 3 km·h^{-1}
	Vel. zones 1-7	Distance covered (m) in velocity zones: 3-7, 7-12, 12-18, 18-24, 24-27, 27-29 & 29-40 km·h^{-1}
Heart rate	HR zones 1-7	Time (min) spent in heart rate zones: 50-60, 60-70, 70-80, 80-85, 85-90, 90-95 & 95-105% of max heart rate
Acceleration	Accelerations (High/Med/Low)	Number of accelerations in zones: 1.5-3, 3-4 & 4-8 m·s^{-2}
	Explosive efforts	Sum of high intensity accelerations, decelerations and changes of direction
	Effort zones 1-3	Number of times entering into velocity zones 5-7
Player load	Player load	Magnitude of rate of change of acceleration (Boyd et al., 2011)
Wellness	Fatigue	1-10 rating
	Stress	1-10 rating
	Motivation	1-10 rating
	General soreness	Mean rating of body part soreness (hamstrings, quadriceps, groins, calves, lower back)
Derived metrics	Mean speed	Distance / duration (m·min^{-1})
	Vel. zone 4%	Vel. zone 4 / distance
	Vel. zone 5-6%	Vel. zone 5-6 / distance
	Player load per minute	Player load / duration
	Vel. zones 1-7 per minute	Distance in each velocity zone / duration
	Explosive efforts per minute	Explosive efforts / duration
	Explosive efforts per metre	Explosive efforts / distance
	Distance-load	Distance × mean speed
	TRIMP per metre	Edwards TRIMP (Edwards, 1993) / distance
	Player load per TRIMP	Player load / TRIMP
	Total accelerations	Sum of all accelerations, decelerations and changes of direction

Regression models

The regression approach treated the RPE response (y_i) as a continuous real-valued number. This approach reflected that players were not restricted to integer responses when reporting their RPE. Models were built using R (R Core Team, 2014) and the CARET package (Kuhn, 2008), the regression models considered were:

- Linear regression
- Multivariate Adaptive Regression Splines (MARS) (Milborrow, 2012)
- Random forests (Liaw & Wiener, 2002)
- Support vector regression (SVM) with Gaussian kernel (Karatzoglou, Smola, Hornik, & Zeileis, 2004)
- Neural networks (single hidden layer feedforward with sigmoid activation function) (Venables & Ripley, 2002)

Linear regression provided a baseline test for predictive accuracy and has been employed by other studies on RPE and training data (Lovell et al., 2013). MARS, random forest, SVM and neural network models were chosen to compare with a linear model as they are able to account for non-linear relationships (Kuhn & Johnson, 2013). Neural networks were trained using backpropagation and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm to optimise weights (Venables & Ripley, 2002). Support vector regression with linear and polynomial kernels was also considered but not included in final model comparisons. The linear kernel method gave accuracy similar to ordinary linear regression and a polynomial kernel improved accuracy but was outperformed by a Gaussian kernel.

For each model three different data pre-processing protocols (R1, R2, R3) were considered.

- R1: Scale each predictor variable by subtracting the mean and dividing the standard deviation (calculated from pooled player data).
- R2: Scale each predictor variable *for each player* using means and standard deviations calculated from each player's individual data. This approach prevented the use of wellness features as some players exhibited zero variance in these variables.
- R3: Scale RPE outcomes as well as predictors for each player. Predictions were then transformed back to the original scale before evaluating results. Similar to protocol R2 this approach prevented the use of wellness variables as features.

For all scaling protocols, means and standard deviations were calculated from the training data set and applied to the testing data before calculating error metrics. Scaling the data by each player's specific mean and standard deviation (protocol R2 and R3) was performed in order to try and account for the individual effects of age, experience, and fitness on RPE values (Bartlett et al., 2016; T. Gallo et al., 2015).

Classification models

The classification approach treated the RPE response as a discrete categorical variable. Although players were not restricted in what they could report, an examination of the data showed that the majority of outcome labels given were integer or half-integer values. The classification models considered were;

- Random forests (Liaw & Wiener, 2002)
- Support vector machines (Gaussian kernel) (Karatzoglou et al., 2004)
- Naive Bayes (Weihs, Ligges, Luebke, & Raabe, 2005)
- C5.0 decision rules (Kuhn, Weston, Coulter, Culp, & Quinlan, 2014)
- Neural networks (single hidden layer feedforward with sigmoid activation function) (Venables & Ripley, 2002)
- Ordered logistic regression (Venables & Ripley, 2002)

For each model three different data preparation protocols (C1, C2, C3) were considered.

- C1: Scale predictor variables by substracting the mean and dividing by the standard deviation calculated from each player's individual data and restrict RPE to {1, 2, …, 10} (10 classes). This restriction caused a loss of training data when the outcome label was non-integer, however due to the relative rarity of these events model performance was not significantly negatively impacted.
- C2: Scale predictor variables using the pooled mean and standard deviation and allow RPE in {1, …, 10} or {4.5, 5.5, 6.5, 7.5, 8.5} (15 classes) to incorporate the most commonly reported non-integer values.
- C3: Scale predictor variables using the pooled mean and standard deviation and allow RPE in {1, 2, …, 10} (10 classes). Non-integer predictions were then generated by examining the model probabilities for each of the 10 classes and employing the rule; if the largest predicted class probability ≤ 0.5 then return the mean of the two most probable classes (e.g. if a training session was predicted to have an RPE of 6 with probability 0.45 and RPE of 7 with probability 0.4 then return an RPE of 6.5), otherwise return the most probable class.

Feature sets

To investigate which training variables best predicted RPE values, seven combinations of predictor variables were tested for each modelling and data pre-processing approach (Table 2). The selected predictors were chosen to reflect findings from previous studies that heart rate, running distances and speeds, accelerations and wellness ratings impact athlete RPE (Bartlett et al., 2016; Borresen & Lambert, 2008; Clarke et al., 2013; T. Gallo et al., 2015; T. F. Gallo et al., 2016; Gaudino et al., 2015; Impellizzeri et al., 2004; Lovell et al., 2013; Nicolò et al., 2015). The combinations were chosen to investigate the relative predictive ability of different variable categories when used alone and together.

Table 2. Feature sets for predictive models

Feature set	Categories
1	Running + Player Load
2	Accelerations
3	Derived metrics
4	Heart rate
5	Running + Derived metrics + Player Load
6	Running + Derived metrics + Heart rate + Player Load
7	All variables

Model evaluation

Nested cross validation was used to evaluate the accuracy of each predictive model (10-fold outer cross validation) and to tune model parameters (5-fold inner cross validation) (Varma & Simon, 2006). The sampling for the inner and outer folds was not stratified by player identity. This approach was taken to ensure that models were being evaluated on out-of-sample predictions, giving a realistic estimation how well they will generalise to new data (Hawkins, 2004; Varma & Simon, 2006). Predictive accuracy of each model was assessed using the root mean square error (Equation 1).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \qquad (1)$$

Where $\hat{y}_i$ is the predicted RPE, y_i is the observed RPE, and n is the number of observations. RMSE measures the mean difference between predicted values and actual values, giving an indication of how reliable the model will be when deployed. Smaller RMSE values indicate better predictive accuracy.

Model parameters were tuned during the inner cross validation loop using a grid search implemented by the CARET package in R (Kuhn, 2008). The values considered for each model were;

- Neural networks: number hidden nodes = {1, 3, 5, 7, 9, 11, 13, 15} and weight decay = {0, 0.0001, 0.1}.
- SVM: regularisation parameter = {0.25, 0.5, 1.0} and inverse kernel width automically chosen using the kernlab R package (Karatzoglou et al., 2004).
- Random forests: number of trees = 500 and number of randomly selected variables at each node = {2, 6, 10}.

- MARS: maximum number of model terms = {2, 8, 10} and maximum degree of interaction = 1.
- C5.0 rules: number of boosting iterations = {1, 10, 20}.

Results

There were 3398 observations of athlete RPE which were recorded from 45 players during the season considered from on-field football training sessions. The median number of records per player was 76 (range 28-100). The variation in player record numbers reflected the different levels of training interruption caused by player injuries. The median RPE reported was 6 (range 0.5-10) suggesting that training plans incorporated a range of intensity levels throughout the season.

Regression models

Figure 1 shows the mean and standard deviation of RMSE for each tested regression model. The best performing regression model (RMSE ± SD = 0.96 ± 0.08 au) was a random forest using player normalised running, heart rate and derived metrics as predictors (set 6) and player normalised RPE as the outcome label (protocol R3).

Data pre-processing protocols R1 and R3 gave similar performance outcomes, and both showed consistently better predictions than those using protocol R2. This suggests that if predictive features are to be scaled by each individual player identity, it is important to also scale the RPE outcomes. This makes intuitive sense since RPE is a subjective value that is likely to have some dependence on player identity.

Models trained using only acceleration data (feature set 2) or heart rate data (set 4) gave significantly poorer predictions than other methods. Improved accuracy was observed with the inclusion of more information to the models (feature sets 5-7). This result indicates that running distances and speeds are the strongest predictors of athlete RPE in Australian football players. It also highlights that metrics derived from distances and speeds cannot fully explain the variance in RPE and that predictions can be improved by including heart rate and wellness variables.

For each pre-processing protocol and feature set pair, some common trends were seen in the performance of each machine learning algorithm. Random forests consistently gave the best RMSE values, followed by support vector machines (SVM) and neural networks in most cases, whilst linear regression was generally the worst performing method. This result suggests that there is complexity within the relationship between objective training measurements and athlete RPE that is better captured by more powerful machine learning models than ordinary linear regression.

Figure 2 shows the relative importance of each predictor variable in the best performing model. The three variables identified as most important in predicting RPE were; (i) distance covered in velocity zone 4 (18-24 $km \cdot h^{-1}$), (ii) total distance above 3 $km \cdot h^{-1}$ and (iii) distance-load (a derived metric calculated as the product of total session distance and mean speed). High speed velocity zones 5-7 were afforded little importance in the random forest model. This unexpected result may indicate that intermittent bouts of high intensity running influence RPE less than sustained moderate intensity running in Australian football players.

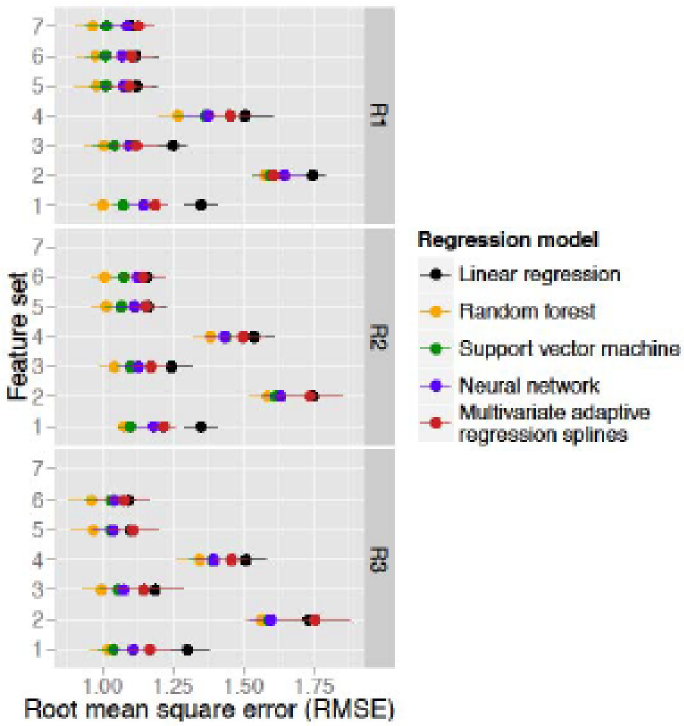

Figure 1. Mean and standard deviation of RPE prediction error for regression models under data pre-processing protocols R1 (scaled predictors), R2 (individualised scaled predictors) and R3 (individualised scaled predictors and outcomes) and feature sets 1 (Running & Player Load), 2 (Accelerations), 3 (Derived metrics), 4 (Heart rate), 5 (Running, derived metrics & Player Load), 6 (Running, derived metrics, heart rate & Player Load) and 7 (All variables). Smaller RMSE values indicate better performance. Feature set 7 was excluded from protocols R2 and R3 due to players exhibiting zero variance in wellness variables.

Given the small number of predictors identified as highly important, another random forest prediction model was built and tested using only 3 predictor variables and protocol R1. Protocol R1 was chosen as it is a simpler, and possibly more practical, data pre-processing protocol than R3. The model performed with RMSE ± SD = 1.09 ± 0.05 au which is only a minor decline in accuracy from the best performing regression model. This reduction in performance may be worthwhile given the significant reduction in model complexity by reducing the number of features from 33 to 3. A predictive model using only 3 sessional distance and speed variables may be possible to practically integrate with training plans.

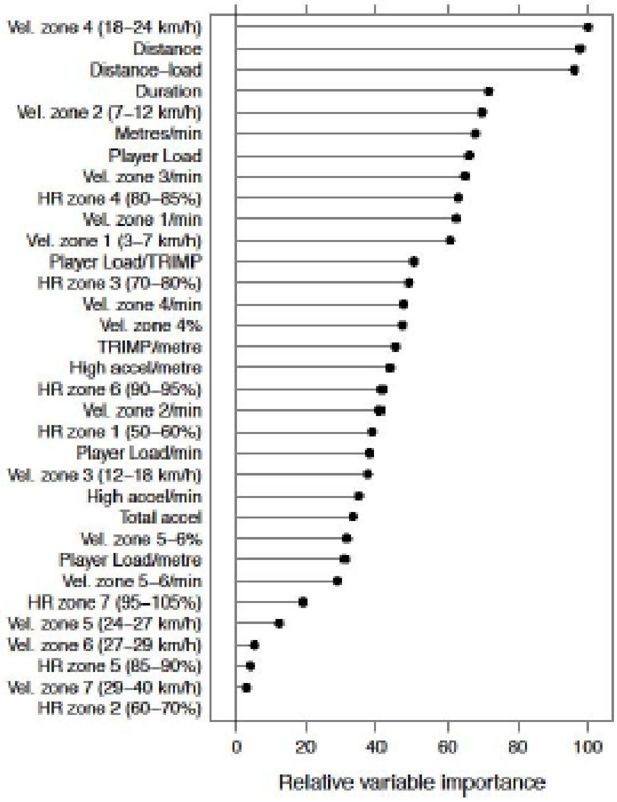

Figure 2. Relative importance of each predictor variable in the best performing random forest regression model.

Classification models

Figure 3 shows the RPE prediction results using classification models. The best performing model (RMSE ± SD = 1.04 ± 0.09 au) was a random forest using normalised running and derived variables (set 6) with 10 allowed classes and predictions based off class probabilities (protocol C3).

Data processing protocol C1, which modelled RPE as a discrete 10-category variable displayed poorest performance, suggesting this restriction prevented models from reflecting the true nature of athlete reported RPE. Protocol C2 allowed the responses to take a selected set of common half-integer values and lead to improved predictions. The best performance was observed in C3 by allowing for non-integer values based off predicted class probabilities.

Similar to the results observed with regression models, feature sets containing running variables provided the most accurate predictions. The inclusion of heart rate and derived metrics provided only marginal improvements in model predictive ability.

Random forest classification models gave the most accurate RPE predictions in nearly all cases. Similar performance was observed for neural networks, C5.0 decision trees, support vector machines, and ordered logistic regression models. A naive Bayes approach general gave the least accurate predictions. Similar to the results from regression modelling, the more powerful machine learning techniques were able to better capture the relationships between training variables and athlete reported RPE.

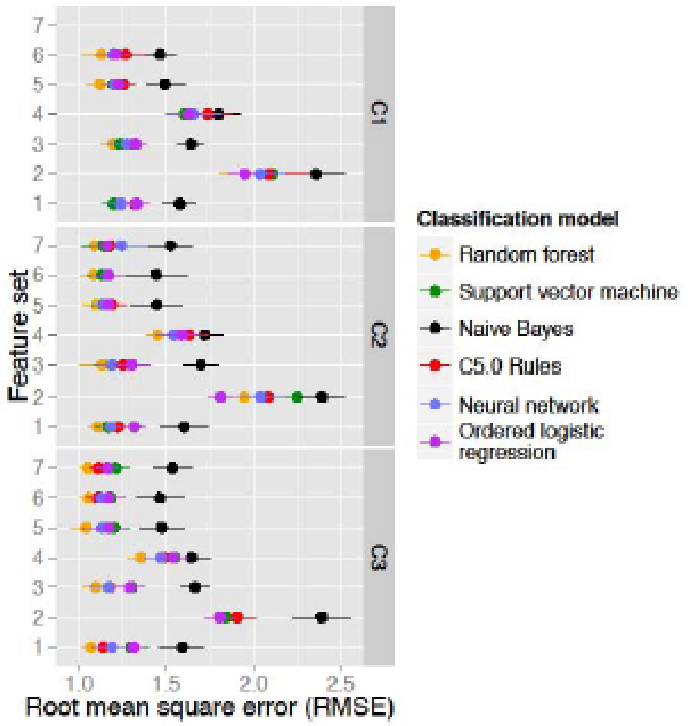

Figure 3. Mean and standard deviation of RPE prediction error for classification models under data pre-processing protocols C1 (10 classes), C2 (15 classes) and C3 (10 classes with mixing based on class probabilities) and feature sets 1 (Running & Player Load), 2 (Accelerations), 3 (Derived metrics), 4 (Heart rate), 5 (Running, derived metrics & Player Load), 6 (Running, derived metrics, heart rate & Player Load) and 7 (All variables). Smaller RMSE values indicate better performance. Feature set 7 was excluded from protocol C1 due to players exhibiting zero variance in wellness variables.

Discussion

This study aimed to develop and assess the accuracy of predictive models in predicting RPE in Australian football players from data typically collected during training sessions. Collectively, the results demonstrated that RPE could be predicted from a non-linear regression model using total distance above 3 $km \cdot h^{-1}$, distance covered between 18-24 $km \cdot h^{-1}$ and the product of distance and mean speed as predictor variables. Including additional predictors such as wellness ratings, heart rate and accelerations lead to only marginal improvements in predictive accuracy.

Modelling approaches

Training data was modelled to identify which interaction between measures could best predict RPE data. Both the regression and classification approaches provided similar predictive ability for RPE, with the two methods achieving a best case RMSE of approximately 1. The models that could account for non-linearity in the relationship between training variables and RPE showed a clear tendency to give better predictions, similar to previous studies (Bartlett et al., 2016). Suggesting that linear approaches were less able to capture the complexity of interactions between training variables and exertion ratings.

The accuracy of classification models was dependent on the number of allowed classes. Protocol C3 displayed the best performance by allowing for non-integer predictions. This potentially replicates the thought process of an athlete who cannot decide whether to give a session a 5 or 6 RPE so chooses 5.5. Regression models gave marginally better predictions and were simpler to implement as they naturally allowed non-integer RPE predictions. Collectively, this demonstrated that a regression approach may be more appropriate for practical implementation in the prediction of RPE values using training monitoring data.

The different methods of data pre-processing showed only slight influence on model performance. Normalising predictor variables and RPE responses by player identity improved the accuracy of the models when compared to predictor scaling without consideration of player identity (Figure 1). However the improvements were only marginal and this pre-processing procedure may be potentially compromised by the introduction of new players to a team, or at the start of a new competitive season when it is not possible to scale predictors from past data. For these reasons, a normalisation procedure that is not player identity dependent could be more readily implemented in a practical setting with minimal impact on prediction accuracy. As such, a global prediction model could assist in training planning using RPE data without the need to consider individual athlete characteristics.

Predictor variables

The training variables identified as most important when predicting athlete RPE were related to external training load measures; distance covered at speeds between 18-24 $km{\cdot}h^{-1}$, total distance above 3 $km{\cdot}h^{-1}$, and the product of total distance and mean speed. Such measures encompassed information related to both training session volume and intensity, identifying both aspects as important contributors to perceived exertion in team sport training, in agreement with previous studies (Bartlett et al., 2016; T. Gallo et al., 2015; Gaudino et al., 2015; Lovell et al., 2013).

The most accurate RPE predictions were from models that incorporated multiple running and heart rate variables (RMSE ± SD = 0.96 ± 0.08 au), supporting the suggestion that RPE is related to the imposed external demands and resultant physiological responses (Lovell et al., 2013; Scott, Lockie, Knight, Clark, & Janse de Jonge, 2013). However, a considerably simpler model using only three variables gave comparable prediction accuracy (RMSE ± SD = 1.09 ± 0.05 au) and compared favourably to previous modelling studies using multiple neural networks (RMSE = 1.24 ± 0.41 au)(Bartlett et al., 2016). It should be highlighted that the choice of predictor variables in a practical setting may largely depend on the required task. Using a smaller subset of variables may be more appropriate for planning purposes when manual manipulation is required. When high accuracy is the most important objective, results suggest that using a larger combination of variables from multiple sources may lead to better performance.

Limitations and extensions

The study was limited to a single season worth of data due to changes in data collection processes between competitive seasons. The accuracy of predictive models for previously unseen players was not evaluated. As such, the ability of models to generalise to a new player joining the team was not investigated. A larger data set would enable a better assessment of the accuracy of the modelling approach taken.

The data used is from a cohort of professional Australian football players. It is likely that their training history and physiological characteristics have been shaped by the demands of their sport and the models produced would not likely generalise well to other athletes. However, it is proposed that a similar approach would provide accurate results for other sports that use similar training monitoring and planning practices.

The limitations of GPS devices for accurately recording movement patterns in team sports have been previously highlighted (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Rampinini et al., 2015). However results suggested that the current level of accuracy was sufficient to predict athlete RPE in Australian football. Improvements in player tracking technology may lead to improvements in the accuracy of predictive models.

Applications

Predictive models using live sensor data from GPS and heart rate devices allows for live RPE forecasting during training sessions. Decision making regarding training drill intensity and duration to elicit desired exertion levels in athletes may be performed with increased accuracy and confidence. It may also allow physical preparation staff to better match actual training outcomes with plans. An RPE estimation method also enables RPE-based planning of athlete training loads. This has potential benefits for training practitioners given the level of evidence regarding injury risk and RPE-based training load measures (Gabbett, 2010; Gabbett & Jenkins, 2011; Rogalski et al., 2013).

A comparison between predicted RPE values and actual observations may prove useful for player monitoring and retrospective analysis. Athletes reporting exertion ratings considerably different to those predicted may indicate an altered physical state, and may provide a useful trigger for intervention.

Conclusion

Athlete RPE can be predicted in professional Australian football players using a machine learning approach. Objective data recorded using GPS devices, accelerometers and heart rate monitors can accurately predict RPE from field-based training sessions. Regression modelling using non-linear machine learning algorithms outperformed classification approaches and linear approaches. The results could potentially enable athlete training practitioners to monitor an estimated RPE live during training sessions and to plan future training to obtain desired session-RPE levels.

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OPEN ACCESS

Training loads and injury risk in Australian football—differing acute: chronic workload ratios influence match injury risk

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ABSTRACT

Aims (1) To investigate whether a daily acute:chronic workload ratio informs injury risk in Australian football players; (2) to identify which combination of workload variable, acute and chronic time window best explains injury likelihood.

Methods Workload and injury data were collected from 53 athletes over 2 seasons in a professional Australian football club. Acute:chronic workload ratios were calculated daily for each athlete, and modelled against non-contact injury likelihood using a quadratic relationship. 6 workload variables, 8 acute time windows (2–9 days) and 7 chronic time windows (14–35 days) were considered (336 combinations). Each parameter combination was compared for injury likelihood fit (using R^2).

Results The ratio of moderate speed running workload (18–24 km/h) in the previous 3 days (acute time window) compared with the previous 21 days (chronic time window) best explained the injury likelihood in matches (R^2=0.79) and in the immediate 2 or 5 days following matches (R^2=0.76–0.82). The 3:21 acute: chronic workload ratio discriminated between high-risk and low-risk athletes (relative risk=1.98–2.43). Using the previous 6 days to calculate the acute workload time window yielded similar results. The choice of acute time window significantly influenced model performance and appeared to reflect the competition and training schedule.

Conclusions Daily workload ratios can inform injury risk in Australian football. Clinicians and conditioning coaches should consider the sport-specific schedule of competition and training when choosing acute and chronic time windows. For Australian football, the ratio of moderate speed running in a 3-day or 6-day acute time window and a 21-day chronic time window best explained injury risk.

INTRODUCTION

Training loads can influence performance[1–3] and injury risk[4–9] in team sport athletes. The acute: chronic workload ratio is defined as the ratio of an athlete's short-term (acute) training load to the mean of their long-term (chronic) training load.[10–12] The acute:chronic workload ratio appears to be a valid tool to assess an athlete's level of readiness to train or compete and their risk of injury.[10–15] Blanch and Gabbett[10] reported a quadratic relationship (R^2=0.53) between the 1-week (acute) to 4-week (chronic) workload ratio and injury risk in a pooled set of athletes from cricket, rugby union and Australian football. Improvements in injury risk models may be possible by varying the way the acute:chronic workload ratio is calculated.

The acute:chronic workload ratio has previously been quantified using different internal and external workload variables.[12 13 15] Hulin *et al*[13 15] used balls bowled and session duration×rating of perceived exertion (session-RPE)[16] in cricket;[13] studies of rugby league used total distance run.[12 15] The relationships between different acute:chronic workload ratios and injury risk are yet to be explored in Australian football. It is possible that different internal or external workload variables may have greater influence on injury likelihood than others.

Acute workloads were defined as the total amount of training load in the previous calendar week, and chronic loads as the mean weekly load in the preceding 3–4 weeks.[12 13 15] However, the rationale for these time windows are based on studies of swimmers tapering for performance[1 2] and it is not known if varying these time periods will increase or decrease the accuracy of injury risk models. Furthermore, previous studies have modelled workload ratios against injury likelihood in the current and subsequent weeks.[12 13] It is not known if workload ratios calculated on a *daily* basis can explain injury likelihood in individual training sessions and matches.

This study aimed to: (1) investigate whether daily acute:chronic workload ratios can inform non-contact injury risk in training sessions and matches, as well as the subsequent 2 and 5 days in Australian football, and (2) identify which combination of workload variable (athlete training loads monitored using Global Positioning System (GPS) devices, accelerometers and session-RPE), acute and chronic time window (varying between 2–9 days and 2–5 weeks) best explained the variation in injury likelihood.

METHODS

Participants

All participants involved in the study were from one professional Australian football club competing in the Australian Football League (AFL). The club fielded 45 athletes in the 2014 season and 45 in the 2015 season, giving a total of 90 player-seasons from 53 unique athletes (mean±SD 22.9±4.0 years, 188.2±6.7 cm, 85.7±8.1 kg). Informed consent was received from the club for collection and analysis of de-identified training and injury data. The project was approved by the La Trobe University Faculty of Health Sciences Human Ethics Committee (FHEC14/233).

Data collection

All players wore commercially available 10 Hz GPS devices and 100 Hz triaxial accelerometers (Catapult Optimeye S5) during all outdoor training sessions and matches. The technology used has been previously validated for use as an athlete monitoring tool in Australian football.[17–19] Session-RPE data were recorded in all sessions that GPS devices were used.[16] While session-RPE is able to monitor loads in other training modalities (eg, resistance training and cross-training), these data were not available.

Seasons were structured with a precompetition phase (15 weeks), followed by a competitive phase (27 weeks) with regularly scheduled matches usually between 6 and 8 days apart. The weekly training schedule during the competitive phase varied depending on the number of days turnaround between matches. In general, the 2 days postmatch were dedicated to recovery and the main training session was held 2 or 3 days prior to the next match, the main training session was never held within the recovery period. When the schedule permitted, an additional accessory training session was included in between the recovery period and the main training day. The competitive phase of the season was defined to begin once the team started playing matches against competing clubs. Thus interclub practice matches were treated the same as regular season matches in all injury risk analyses and precompetition training sessions were included in chronic load calculations.

Injury definition

Injuries were recorded and classified by club medical staff using the Orchard Sports Injury Classification System (OSICS).[20] All injuries were classified according to the mechanism by which they occurred (contact or non-contact) as well as severity (transient or time loss). Time-loss injuries were defined as those causing a player to be unavailable for training or competition.[21] In this study, we focused on time-loss non-contact injuries. Transient injuries and traumatic injuries caused by collisions and other contact events were excluded from injury risk models.

Injury lag periods

To account for possible delay effects in injury occurrence and reporting, we considered three different injury lag periods (figure 1). On each training or match day, we observed whether an injury occurred: (1) that day (no lag time), (2) that day or the following 2 days, or (3) that day or the following 5 days. These periods were chosen to represent risk in: (1) a single session, (2) a short period postsession not including the next main session and (3) a longer period incorporating the next main session but not overlapping with more than one competitive match.

Daily acute:chronic workload ratio

We propose a method of *daily* acute:chronic workload calculation using moving averages of daily loads. Defining the workload of an athlete on day i as w_i, the acute:chronic workload for that day (r_i) is calculated:

$$r_i = \sum_{j=i-a}^{i-1} \frac{w_j}{a} \Big/ \sum_{j=i-c}^{i-1} \frac{w_j}{c} \qquad (1)$$

where a and c represent the time windows (in days) over which the acute and chronic workloads are calculated. This formula calculates the workload ratio each day by taking the average daily workload in the previous a days (ie, not including what was done on that day) and dividing it by the average daily load in the previous c days.

In defining the above acute:chronic workload ratio, there is freedom of choice in the parameters a and c as well as the workload variable w. In this study, we investigated the effect of varying the acute and chronic time windows on the ability of the acute:chronic workload ratio to inform injury risk. We allowed parameters to vary such that: $a \in \{2, 3, 4, 5, 6, 7, 8, 9\}$ and $c \in \{14, 18, 21, 24, 28, 32, 35\}$ and considered each of the 56 possible combinations.

The set of workload variables considered in this study is presented in table 1. For each of the 6 workload variable choices, we examined 56 combinations of acute and chronic time windows, giving a total of 336 unique parameter combinations. The discrete velocity bands used in this study (18–24 and 24+ km/h) were chosen to represent the speeds at which Australian football players reached their anaerobic threshold and sprinting threshold, respectively (unpublished data). Individualised velocity bands can offer a different interpretation of running demands;[22–24] however, these data were not available in the studied cohort.

Data analysis

For each combination of acute time window, chronic time window and load variable {a, c, w}, we calculated the acute: chronic workload ratio (r) for each player, each day. Workload ratios were binned into quantile groups and injury likelihood in each bin calculated as the proportion of match or training sessions resulting in injury.[10] To account for possible effects introduced by choosing the number of quantile bins, models were generated for 7, 9 and 11 bins and results averaged to give a more robust assessment of the strength of relationship between workload ratio and injury risk. All figures were produced using 11 quantile bins for clarity of presentation.

Workload ratios were modelled against injury risk using a quadratic regression similar to Blanch and Gabbett.[10] The independent variable was taken to be the mean of workload ratio within each bin and the dependent variable the associated injury likelihood. The ability of each workload ratio to explain injury likelihood was assessed using the R^2 statistic. All models were created using the R statistical programming language (R Core

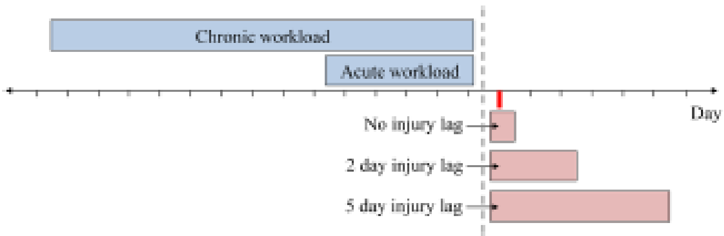

Figure 1 The definition of acute and chronic workloads and injury lag periods on a given day during the season (highlighted in red). Note the separation between workload and injury outcome periods.

Team. R: a language and environment for statistical computing. Vienna, Austria, 2014).

Injured players were included in risk analyses as soon as they began rehabilitation at the club. Their workloads in rehabilitation training were recorded and their ratio calculations did not differ from other players. To avoid extreme spikes in workload ratio for players with abnormally low chronic loads (ie, players returning from injury or after a scheduled break), a data preprocessing step was applied to remove observations when the chronic workload was <2 SDs below the mean.[12] This did not interfere significantly with match observations due to a selection process that restricted players from participating in matches if they did not have a sufficient fitness base.

RESULTS

Injuries

Over the two seasons, monitored players experienced a total of 178 time-loss non-contact injuries. A breakdown of the injuries by injury site and activity performed on the date the injury was recorded is shown in online supplementary table S1. The majority of injuries were recorded in matches (n=59) and main training sessions (n=68). The distribution of match turnaround times and injury rates is shown in table 2. Similar rates of injury (~3%) were observed for 6, 7, 8 and 9+day gaps between matches. Table 2 also shows that players were very rarely required to play consecutive matches without at least a 6-day break. It is likely that this distribution of turnaround times is representative of other professional Australian football teams since the sport's governing body gives consideration to match turnaround times when creating the competition schedule.

Acute:chronic workload ratio and injury risk

The ratio of 6:14 days distance load best explained the variation in injury likelihood in matches and training sessions combined (mean R^2=0.91; figure 2A). However, when the relationship was decomposed by session type (figure 2B), we observed considerably different injury risk profiles. Matches were associated with higher injury likelihood than training sessions, irrespective of the athlete workload ratio (relative risk (RR)=4.04, 95% CI 2.86 to 5.70). Thus, while it is appropriate to group matches and training sessions together for load calculations, it may not be so when analysing injury likelihood. Since results suggested that most injury risk is contained within competitive matches, we have focused our injury risk analyses on matches. The following sections exclude injuries sustained during the precompetition phase (n=65) and injuries by players completing rehabilitation of previous injuries (n=16).

Table 1 Workload variables considered in workload ratio modelling

Variable	Definition
Distance (m)	Distance above 3 km/h
Session-RPE (arbitrary units)	Athlete rating of perceived exertion×session duration
Player load (arbitrary units)	Custom metric measuring the magnitude of rate of change of acceleration[17]
Distance-load (m^2 min^{-1})	Distance×mean speed
HSR (m)	Distance above 24 km/h
MSR (m)	Distance between 18 and 24 km/h

HSR, high speed running; MSR, moderate speed running.

Table 2 Distribution of times between player matches and injury rates

Time between matches (days)	Count (player matches)	Time-loss non-contact injury rate (%)
5	8	0.0
6	321	3.4
7	557	3.8
8	345	3.5
9+	454	3.3

Best predictors of match injury risk

Figure 3 shows the best performing (highest mean R^2) risk models for each injury lag period in matches only. The ratio of 3:21 days moderate speed running load (highlighted cells) was observed to consistently explain injury likelihood for each time period considered (mean R^2=0.76–0.82). This compared favourably with the 7:28 distance ratio (mean R^2=0.04–0.41), and with previous studies using workload ratios calculated weekly (R^2=0.53).[10]

The best performing injury risk models displayed similar shapes to those seen in previous studies.[10 11 13] Irrespective of the acute time window, chronic time window or workload variable, the risk profiles suggested that athletes minimised their likelihood of non-contact injury when they approached matches with workload ratios around 0.8–1.0. Injury likelihood was greater for athletes with lower or higher ratios.

To investigate the different levels of risk, a RR analysis was performed on injury likelihood for workload ratios in the range 0.8–1.2 versus all observations outside of this range. The significant RR values for matches (95% CIs excluding 1) are shown in table 3. RR values including a 2-day or 5-day injury lag period are included in online supplementary tables S2–S3. These data quantify the level of risk associated with being outside of the 'safe' range (0.8–1.2) for different acute:chronic workload parameter combinations.

Similar to figure 3, the RR analysis identified moderate speed running with a 3-day acute time window as able to discriminate between high-risk and low-risk athletes in matches and the subsequent 2–5 days (RR=2.29–2.59). High speed running workload ratios were also highlighted by the RR analysis in table 3; however, the magnitude of risk was not significantly higher (RR=2.74 vs 2.59) than for moderate speed running and R^2 values were lower (R^2=0.24 vs 0.65). This suggested that while high speed running workload ratios appear to influence injury risk, moderate speed running may be a better choice to track in Australian football.

Effects of varying acute and chronic time window

Figure 4 shows the effects of varying the acute and chronic time windows on the ability of moderate speed running workload ratio to explain non-contact injury risk in Australian football matches (figure 4A) and the subsequent 2 (figure 4B) or 5 days (figure 4C). Moderate speed running was chosen for the workload variable due to it appearing as a top 3 workload parameter more than any other choice (figure 3).

Peaks in model R^2 for acute windows of 3 days and chronic windows of 21 days are clear for each injury lag period, and corresponded to the highlighted workload ratios in figure 3. The model performance contours suggested that acute time windows of 3 and 6 days generated better performing injury risk models,

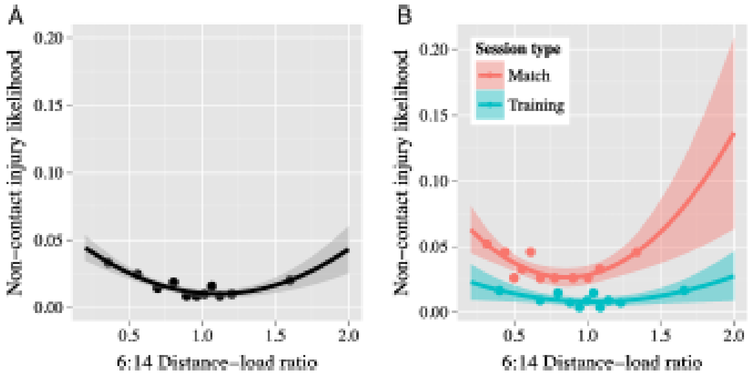

Figure 2 Relationship (with 95% CI) between 6:14 distance-load ratio and non-contact injury likelihood for: (A) matches and training sessions combined (mean R^2=0.91) and (B) matches (mean R^2=0.54) and training sessions (mean R^2=0.53) separately.

Injury lag	Rank	Workload ratio	Mean R^2
A			
Non-contact injury (n=59)	1	3:21 MSR	0.79
	2	6:24 Distance	0.73
	3	3:18 MSR	0.71
B			
Non-contact injury (+2 days) (n=69)	1	9:32 Player load	0.79
	2	6:14 Distance	0.78
	3	3:21 MSR	0.76
C			
Non-contact injury (+5 days) (n=85)	1	3:21 MSR	0.82
	2	6:32 HSR	0.75
	3	6:21 MSR	0.75

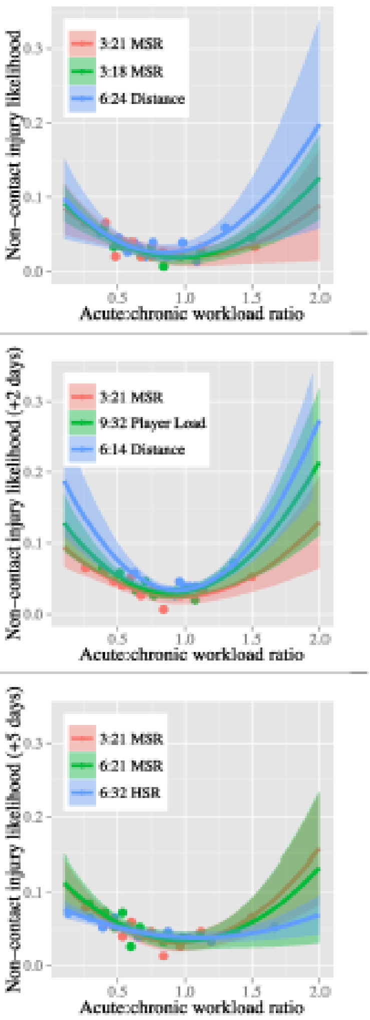

Figure 3 Injury likelihood profiles (with 95% CIs) of the top 3 performing parameter combinations for explaining: (A) match injuries, (B) match injuries and following 2 days, and (C) match injuries and the following 5 days. HSR, high speed running (>24 km/h); MSR=moderate speed running (18–24 km/h).

Table 3 Relative risk of non-contact time-loss injury in matches

Acute window (days)	Chronic window (days)	Variable	Relative risk (95% CI)	Mean R^2
5	14	High speed running	2.74 (1.19 to 6.33)	0.24
3	28	Moderate speed running	2.59 (1.18 to 5.66)	0.65
5	24	High speed running	2.49 (1.08 to 5.76)	0.11
3	21	Moderate speed running	2.43 (1.11 to 5.32)	0.79
3	32	Moderate speed running	2.24 (1.03 to 4.90)	0.66
5	14	Moderate speed running	2.18 (1.05 to 5.47)	0.26
9	18	Session-RPE	1.97 (1.17 to 3.31)	0.46
9	28	Session-RPE	1.69 (1.02 to 2.81)	0.08

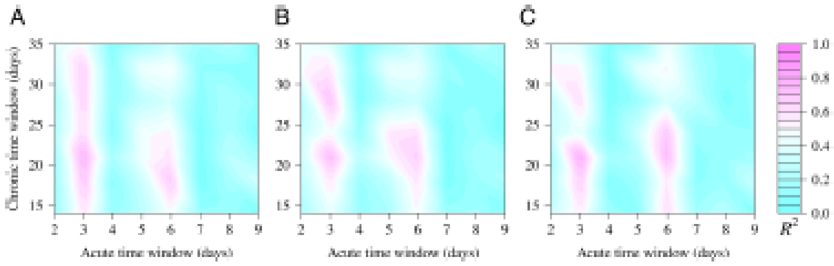

Figure 4 Effects of varying acute and chronic time window on model R^2 performance for: (A) match injuries, (B) match injuries and following 2 days, and (C) match injuries and the following 5 days. Moderate speed running used as the workload variable.

and that performance was highly sensitive to the choice of an acute time window. The optimal choice of a chronic time window was less clear, but 21 or 28 days (3 or 4 weeks) appeared to be a valid choice.

Effects of including injury lag periods

The similarity in model performance across each injury lag period (best R^2=0.76–0.82, mean R^2=0.26–0.28 and peak RR=2.29–2.74) suggested that the daily acute:chronic workload ratio can inform injury risk in Australian football matches and that including a forward looking injury lag period does not significantly improve the ability to explain variations in match injury rates.

DISCUSSION

Daily acute:chronic workload ratio and injury risk

Acute:chronic workload ratios using moderate speed running, a 3-day or 6-day acute time window and a 21-day or 28-day chronic time window were best able to explain non-contact injury risk in the following three time periods: (1) matches, (2) matches and the next 2 days, and (3) matches and the next 5 days. The performance of injury risk models suggests that it is valid to track Australian football player workload ratios on a daily basis. This extends previous studies that found workload ratios, calculated on a weekly basis, and explained injury risk in cricketers[13] and rugby players.[12 15]

Non-contact injury risk was significantly higher in competitive matches compared with training sessions (RR=4.04, 95% CI 2.86 to 5.70), suggesting that injury risk models can be strengthened by modelling match injuries separately to training injuries. Previous studies[10 12] using weekly workload ratios avoided this issue by considering time spans that covered multiple training sessions and potentially multiple matches.

Injury likelihood profiles in figure 3 have consistent shape to previous study findings,[10 11 13] suggesting that athletes are at minimum injury risk when their workload ratios are in the range 0.8–1.0. Risk increases as players have ratios on either side of this region. Using the ratio of 3:21 days moderate speed running, the model predicted that match injury risk doubled (from 1.8% to 3.6%) if the workload ratio deviated from 1 to 1.4 or 0.5. This result, using a daily workload ratio, extends conclusions from previous studies[11] that rapid changes in training loads are associated with increased injury likelihood. The rate of increase in injury risk may differ for different parameter combinations, evidenced by the divergence of the curves in figure 3. However, a lack of data for athletes with very high workload ratios leading into matches prevented the identification of particular workload ratios as more 'risky' than others (due to a large overlap of CIs).

Choice of acute and chronic time window

Figure 4 shows that the choice of an acute window significantly influences the ability of workload ratios to explain injury likelihood in matches and the days following. Moderate speed running ratios captured with acute time windows of 3 or 6 days and chronic time windows of 3 or 4 weeks were best able to explain injury likelihood. Injury models using previously reported parameters of 7-day acute and 28-day chronic distance loads[12] explained less of the variance (mean R^2=0.04–0.41) in this study population. We suggest that teams model their own data so that over a period of years they will find which ratio is most useful for them.

The structure of a professional Australian football season means that 3-day acute periods include the main training sessions prior to matches but never the previous match. Results highlighting 3-day acute time windows may reflect this specific structure. Similarly, 6-day acute windows will include the previous match when teams are scheduled for a short turnaround between matches but will not for longer breaks.

These observations suggest that it may be best practice to choose an acute time window that reflects the schedule of an athlete's competition and training when monitoring injury risk (ie, different windows may be optimal in sports with different schedules such as basketball, soccer or cricket).

Choice of workload variable

Moderate speed running was the workload variable that explained a quadratic variation in injury likelihood (R^2=0.76–0.82) and discriminated between high-risk and low-risk athletes (RR=2.3–2.6). While parameter combinations using other workload variables were able to generate models with high R^2 and RR, none appeared as consistently as moderate speed running. Thus, in professional Australian football, distance covered at a velocity of between 18 and 24 km/h is an appropriate choice of workload variable when using the acute:chronic workload ratio to monitor injury risk. This is potentially a consequence of the specific demands of the sport and physiological characteristics of competing athletes and alternative workload variables may be more suited to other sports.

Choice of injury lag period

Figures 3 and 4 show the differences between injury models for the likelihood of injury in: (1) matches, (2) matches and the following 2 days, and (3) matches and the following 5 days. Models showed similar ability to explain variation in injury likelihood (figure 3) and similar changes in performance when varying acute and chronic time windows (figure 4). This suggests that managing one choice of athlete workload ratio (using an appropriate acute and chronic time window) may be effective in reducing injury risk in matches *and* the days immediately following.

Limitations and extensions

The study considered injuries classified as non-contact and causing the athlete to be unavailable for training or competition. Injury data also contained more detailed subclassifications by type of pathology (muscle, tendon, bone, ligament or joint injury); however, an examination of injury risk within each subclass was beyond the scope of this study. A larger sample of injuries may enable future studies to examine the relationships between acute and chronic time windows, workload variables and different injury pathologies.

Australian football was the only sport considered in this study. The reported results may not generalise to other sports due to the differences in physical demands. Investigations into different choices of acute:chronic workload ratio parameters may lead to improved athlete monitoring tools in other sports.

Previous studies of training loads and injuries have reported that risk factors are impacted by chronic loads[12] as well as variables such as player age and experience.[5] Different modelling techniques able to incorporate multiple risk factors were considered to be beyond the scope of this study. Future modelling attempts incorporating these factors may be able to improve on the predictive power of the injury models used in this study.

The analyses in this study compared the injury risk for athletes with acute:chronic workload ratios between 0.8 and 1.2 to those outside of this range. An extension considered beyond the scope of this study would be to compare the RR of approaching matches with a low workload ratio (underloading) versus a high workload ratio (overloading).

CONCLUSION

Daily acute:chronic workload ratios were able to explain the variation in non-contact injury likelihood in Australian football players. The 3:21 days moderate speed running ratio was the combination that performed best—it provided a better model fit than the commonly used 7:28 days ratio. The results suggested that the best choices of acute and chronic time windows may need to be identified sport by sport or team by team and it may depend on the specific structure of an athlete's competition and training schedule.

What are the findings?

- The acute:chronic workload ratio, calculated on a daily basis, can explain variations in non-contact injury risk in Australian football players.
- The ratio of moderate speed running loads in a 3-day or 6-day acute time window and a 21-day or 28-day chronic time window best explained injury risk in matches and the following 2–5 days. Including a forward looking injury lag period did not significantly improve the ability to explain variations in injury rates.
- The size of an acute time window showed strong influence over the ability of the workload ratio to inform injury risk.

How might it impact on clinical practice in the future?

- Daily monitoring of the acute:chronic workload ratio is a valid tool for injury risk management in Australian football.
- The schedule of training and competition should be considered when choosing the size of acute and chronic monitoring periods.

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Competing interests None declared.

Ethics approval La Trobe University Faculty of Health Sciences Human Ethics Committee (FHEC14/233).

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Predictive Modelling of Training Loads and Injury in Australian Football

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Abstract

To investigate whether training load monitoring data could be used to predict injuries in elite Australian football players, data were collected from athletes over 3 seasons at an Australian football club. Loads were quantified using GPS devices, accelerometers and player perceived exertion ratings. Absolute and relative training load metrics were calculated for each player each day. Injury prediction models (regularised logistic regression, generalised estimating equations, random forests and support vector machines) were built for non-contact, non-contact time-loss and hamstring specific injuries using the first two seasons of data. Injury predictions were then generated for the third season and evaluated using the area under the receiver operator characteristic (AUC). Predictive performance was only marginally better than chance for models of non-contact and non-contact time-loss injuries (AUC<0.65). The best performing model was a multivariate logistic regression for hamstring injuries (best AUC=0.76). Injury prediction models built using training load data from a single club showed poor ability to predict injuries when tested on previously unseen data, suggesting limited application as a daily decision tool for practitioners. Focusing the modelling approach on specific injury types and increasing the amount of training observations may improve predictive models for injury prevention.

KEYWORDS: INJURY, MACHINE LEARNING, TRAINING LOAD

Introduction

Training loads are known to be associated with injuries in team sport athletes (Carey et al., 2016; Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2015; Malone et al., 2016; Murray, Gabbett, Townshend, & Blanch, 2016; Rogalski, Dawson, Heasman, & Gabbett, 2013; Thornton, Delaney, Duthie, & Dascombe, 2016). Monitoring and adjusting loads to reduce injury risk is considered to be an important aspect of athlete management (Soligard et al., 2016), especially since injuries can have a detrimental effect on team sport performance (Hägglund et al., 2013). Existing studies have found associations between injuries and both absolute and relative training loads (Drew & Finch, 2016). Therefore monitoring these metrics has been recommended in recent reviews (Bourdon et al., 2017; Drew & Finch, 2016; Soligard et al., 2016). Relative training loads are typically quantified using the acute:chronic workload ratio (Blanch & Gabbett, 2016; Gabbett, 2016; Hulin et al., 2015; Murray et al., 2016; Williams, West, Cross, & Stokes, 2016b). This is calculated by dividing the short term (acute) training load for an athlete, typically around 7 days, by their load over a longer (chronic) period, typically 3 weeks or longer. Absolute training loads are usually reported using cumulative totals or absolute weekly loads (Colby et al., 2014; Rogalski et al., 2013). Other methods of training load calculation that take into account daily variations, such as monotony and strain, are also useful for athlete monitoring (Foster et al., 2001).

Multiple metrics exist for quantifying load in team sport athletes (Bourdon et al., 2017; Soligard et al., 2016). External loads refer to objective measures of training activity such as training duration, running distance, or accelerations (Bourdon et al., 2017; Soligard et al., 2016). They can be measured using sensor technologies such as global positioning systems (GPS) and accelerometers (Bourdon et al., 2017; Soligard et al., 2016). Internal training load is defined as the physiological and psychological response to external loads. Internal load is typically assessed using metrics derived from heart rate, blood lactate and athlete ratings of perceived exertion (RPE) (Bourdon et al., 2017; Soligard et al., 2016).

It has been suggested that machine learning approaches may provide a way to progress the field of training load monitoring and injury prediction by allowing for non-linear pattern recognition and interactions between variables (Bittencourt et al., 2016; Bourdon et al., 2017). Despite existing studies reporting associations between training load and injury (Carey et al., 2016; Colby et al., 2014; Rogalski et al., 2013), the ability of load monitoring to predict future injury in Australian football is not well established. Studies in rugby league populations have examined the performance of training load models to predict injuries in new data (Gabbett, 2010; Thornton et al., 2016). Currently no specific modelling methodology has established superiority for accurate injury predictions. The ability of models to predict particular injury types is unknown. Yet to be explored are techniques to deal with the large imbalance between injured and non-injured observations, and how the volume of data used to build predictive models affects the quality of predictions.

This study investigates the ability of training loads to predict future injuries in elite Australian football players using statistical learning approaches. The proposed aetiology of sports injury is complex and multifactorial (Windt & Gabbett, 2017). Recent evidence suggests that training loads are a major risk factor (Soligard et al., 2016). Insights into the ability of training load models to predict injury may assist decision making by coaches and athletes, and narrow the focus of future research.

Relative and absolute training loads were included as predictor variables in this investigation to align with previous studies (Drew & Finch, 2016). Age was included as a proxy for playing experience, which has been identified as a potential moderator of the relationship between training loads and injuries (Rogalski et al., 2013). A binary indicator variable for whether a player was scheduled to play a match was also included because injury rates in Australian football are higher in matches than training sessions (Carey et al., 2016). The modelling approaches considered were informed by comparable studies in rugby league that used random forests, generalized estimating equations and logistic regression (Gabbett, 2010; Thornton et al., 2016). In particular, generalised estimating equations have been proposed as an appropriate way to model repeated observations in injury risk factor studies (Williamson, Bangdiwala, Marshall, & Waller, 1996). Support vector machines were also used to fit potentially non-linear relationships (Vapnik & Vapnik, 1998). Different data processing protocols to deal with collinear predictors and unbalanced classes were compared, and learning curves were constructed to explore how the amount of available data influenced the quality of future predictions.

Sampling strategies to combat class imbalance have not been considered in previous modelling studies. Problems with mulitcollinearity were examined by using PCA for dimensionality reduction, as has been suggested for multivariate training load analysis (Weaving, Jones, Till, Abt, & Beggs, 2017; Williams, Trewartha, Cross, Kemp, & Stokes, 2016a). Univariate and multivariate predictive models were trained on two years of player monitoring data and evaluated on one year of unseen future data in order to get a realistic estimation of predictive ability. Models were compared using the area under the receiver operator characteristic (AUC). Particular emphasis was given to the method of evaluating predictive performance given recent commentary on the misuse of the term prediction in sports science studies measuring association between risk factors and injury (McCall, Fanchini, & Coutts, 2017).

Methods

Participants

The participants involved in the study were from one professional Australian football club. The club fielded 45, 45 and 43 players in the 2014, 2015 and 2016 seasons respectively, giving 133 player seasons from 75 unique athletes. Informed consent was received from the club for collection and analysis of de-identified training and injury data. The project was approved by the La Trobe University Faculty of Health Sciences Human Ethics Committee (FHEC14/233).

In the 2016 season the club participating in this study fielded a comparatively high number of new players due to multiple season long suspensions. The impact of this on the predictive models was explored by comparing the results for new versus returning players. This enabled evaluation of the impact of introducing new players on the performance of injury models.

Data Collection

Player tracking data were collected using commercially available 10 Hz global positioning system (GPS) devices and 100 Hz triaxial accelerometers (Catapult Optimeye S5). All players were monitored during all outdoor training sessions and matches. The devices used in the study are valid for use in this athletic population (Boyd, Ball, & Aughey, 2011; Rampinini et al., 2015). Additionally, players gave a rating of perceived exertion (RPE) after each session (Foster et al., 2001). Missing data were imputed using predictive mean matching (Buuren & Groothuis-Oudshoorn, 2011).

Club medical staff recorded all injuries. Injuries were classified using the Orchard Sports Injury Classification System (OSICS) (Rae & Orchard, 2007) and were categorised as contact or non-contact. Injury severity was classified as either transient (not causing unavailability for training or matches) or time-loss (causing the player to be unavailable for regular training or match activity). Hamstring injuries were defined to include all injures when the OSICS 'specific' category was 'Hamstring strain' or 'Hamstring tendon injury'.

Training load quantification

Training loads were quantified using 5 different training load variables (Table 1). For each workload variable (w) a number of metrics were derived on each day and used as the predictor variables for injury models. The training load metrics were chosen from the existing literature associating them with injury risk.

Table 1. Workload variables and descriptions.

Training load variable	Definition
(i) Distance (m)	Distance above 3 km/h
(ii) Moderate speed running (MSR) (m)	Distance between 18-24 km/h
(iiii) High speed running (HSR) (m)	Distance above 24 km/h
(iv) Session-RPE (arbitrary units) (Foster et al., 2001)	Rating of perceived exertion multiplied by session duration
(v) Player load (arbitrary units) (Boyd et al., 2011)	Proprietary metric measuring the magnitude of rate of change of acceleration

(i) Total distance covered has been used a load metric in previous injury risk studies in Australian football (Carey et al., 2016; Colby et al., 2014; Hulin et al., 2015; Murray et al., 2016) and provides a measure of global running load.

(ii) Moderate speed running (MSR; 18-24 km/h) was included because it had previously been identified as a risk factor in Australian football (Carey et al., 2016).

(iii) High speed running (HSR; 24+ km/h) has been identified as a specific risk factor for hamstring injury as well as general non-contact injury (Colby et al., 2014; Duhig et al., 2016) and is potentially a better measure of training intensity than total distance.

(iv) Session-RPE was included as internal load metric. RPE is a subjective metric that can take into account influences such as heat stress, residual fatigue and other contextual factors that the other objective measures cannot. Additionally it has been identified as an injury risk factor in previous studies (Gabbett, 2010; Rogalski et al., 2013).

(v) Player load is a workload metric based on accelerometer data, that has the potential to capture information about activities such as tacking, jumping and collisions that the running based metrics cannot (Gabbett, 2015).

Rolling averages (C) were calculated on each day of the season (i) using a 3, 6 and 21 day accumulation window. These time periods have been identified as appropriate for quantifying cumulative load in Australian football (Carey et al., 2016; Colby et al., 2014).

$$C_i = \sum_{j=i-c}^{i-1} \frac{w_j}{c} \text{ for } c \in \{3, 6, 21\}$$

Exponentially weighted moving averages ($EWMA$) were calculated daily with 3, 6 and 21 day decay parameters (N). An exponentially weighted moving average weights the influence of training loads less the longer ago they happened. The method used was adapted from Williams et al. (Williams et al., 2016b) so that the value calculated each on day 'i' had no dependence on the training load that day (w_i). This is necessary to avoid information recorded on the day of an injury being used to try and predict that injury.

$$EWMA_i = \lambda \cdot w_{i-1} + (1-\lambda) \cdot EWMA_{i-1}$$
$$\lambda = \frac{2}{N+1} \text{ for } N \in \{3, 6, 21\}$$

Training monotony was calculated each day as the average training load in the previous 7 days divided by the standard deviation of daily loads over the same time (Foster et al., 2001). Monotony represents the variation in training done by an athlete, with higher values indicating more monotonous training. Training strain was calculated as the sum of load in the previous 7 days multiplied by the training monotony. Strain is an extension of cumulative training volume that incorporates a weighting factor based on the amount of daily variation (Foster et al., 2001). Monotony and strain were not calculated for HSR due to players frequently accumulating zero HSR load in the previous 7 days.

Daily acute:chronic workload ratios (*r*) were derived for each workload variable. The acute:chronic workload ratio represents the relative amount of short term (acute) training load compared to the long term (chronic) load. 3 and 6 day acute time windows were used with a 21 day chronic window. These choices have been identified as appropriate for discriminating between high and low risk athletes in the study cohort (Carey et al., 2016). When players had no chronic workload (and by definition zero acute load) they were assigned an acute:chronic workload ratio of zero.

$$r_i = \sum_{j=i-a}^{i-1} \frac{w_j}{a} \bigg/ \sum_{j=i-c}^{i-1} \frac{w_j}{c}$$

Exponentially weighted acute:chronic workload ratios were included as a modification of the acute:chronic workload ratio where the rolling averages were replaced by exponentially weighted moving averages (Murray et al., 2016; Williams et al., 2016b). Murray et al. suggested that the exponentially weighted acute:chronic workload ratio gave a better indicator of injury risk than the rolling average method (Murray et al., 2016).

In total, for each of the 5 training load metrics (Table 1), 12 features were derived; 3, 6 and 21-day rolling and exponentially weighted average load. ACWR and exponentially weighted ACWR (using 3:21 and 6:21 day windows), as well as monotony and strain (excluding HSR), resulting in 58 workload features. The inclusion of a large number of features reflected the multiple injury risk factor findings from previous studies (Carey et al., 2016; Colby et al., 2014; Duhig et al., 2016; Hulin et al., 2015; Malone et al., 2016; Murray et al., 2016; Rogalski et al., 2013). There was no a-priori justification to exclude any. The size of the feature space and the possible correlations between predictor variables was given particular consideration when choosing the modelling and data processing approaches.

Injury classification

Three different types of injury were considered; any non-contact (NC), non-contact causing time-loss (NCTL) and any hamstring (HS). Separate models were built for each injury outcome to investigate whether predictive models performed better for specific injury types. Hamstring injuries were chosen as they were the most frequently occurring specific injury in this cohort and are a common injury in Australian football (Orchard, Seward, & Orchard, 2013). A possible lag period between spikes in training load and increased injury risk has been reported in previous studies (Hulin et al., 2015). Models were also built for the likelihood of a player sustaining an injury in the next five days to investigate whether including a lag period could improve predictive performance.

Modelling approach

Predictive models were built on two years of load and injury data (model training data) and tested on one season of unseen future data (testing data) (Figure 1). Evaluating models on a season of unseen data is required to get an estimate of the ability to predict injuries. Multivariate statistical models can have many degrees of freedom and can be tuned to fit a particular data set very well. To test whether a model will generalise and be useful in practice, the predictions must be evaluated on a new data set (Kuhn & Johnson, 2013).

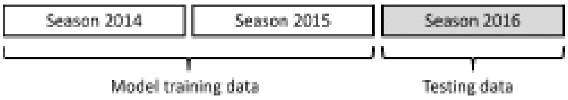

Figure 1. Data split for model training and testing.

Models were built to try and predict whether an athlete would be injured, given knowledge of their training loads. Each day that a player completed training or a match, or reported an injury, was included as an observation in the model training data. Predictions were then generated for each training or match day in the testing data set and evaluated against actual injury incidence.

Prediction algorithms

Multiple algorithms were tested to compare their ability to predict injury in team sport athletes. Multivariate models were constructed using all 58 training load variables as well as two additional features; player age (years) and a binary indicator variable for whether or not the player was scheduled to play a in a competitive match that day. The approaches considered were:

- Logistic regression (LR) is commonly used to model injury outcomes (Colby et al., 2014; Gabbett, 2010; Murray et al., 2016). Elastic net regularisation was introduced due to the large number of predictor variables used (Zou & Hastie, 2005).
- Random forest (RF) models were chosen for their ability to fit non-linear patterns in data and deal with collinear predictors (Breiman, 2001). Random forests have been used in injury prediction studies in rugby league (Thornton et al., 2016).
- Generalised estimating equations (GEE) are an extension of generalised linear models that account for correlations between repeated observations taken from the same subjects (Liang & Zeger, 1986). A binomial link function and auto-regressive correlation structure was used (Williamson et al., 1996).
- Support vector machines (SVM) with a radial basis function were used to model the potentially non-linear pattern between load and injury in high dimensional data (Vapnik & Vapnik, 1998).

In addition, univariate LR models were constructed for each training load variable (Colby et al., 2014; Gabbett, 2010; Murray et al., 2016) to provide a comparison for the more complex multivariate and non-linear models used.

Models hyperparameters (elastic net mixing parameter and regularisation strength for LR, number of trees and variables sampled at each node for RF and regularisation penalty for SVM) were tuned using 10-fold cross validation on the model training data and a grid search method (see supplementary table 1 for details). The choice of hyperparameter that gave the best performance (area under ROC curve) during cross validation was then used to construct a model on the full training data set (2014-15). This model was then tested on the hold-out season (2016). All analyses were performed using the R statistical programming language.

Data pre-processing

To allow for players to accumulate sufficient training loads to calculate workload ratios and exponentially weighted moving averages, the first 14 days of each season were removed from the model training and testing data. This loss of data could potentially be avoided in future studies if monitoring of chronic workloads extended into the off-season period. Players in rehabilitation training were excluded from modelling until they returned to full training.

Many of the training load variables collected were likely to be correlated (Weaving et al., 2017). Thus our prediction problem may suffer from multi-collinearity, potentially leading to instability and errors in the model building process (Kuhn & Johnson, 2013). Principal component analysis (PCA) is a dimensionality reduction process that reduces a large number of predictor variables to a smaller number of uncorrelated variables (called principal components) to combat the problems associated with multi-collinearity (Kuhn & Johnson, 2013). PCA has been advocated as a way of dealing with collinearity in multivariate training load modelling (Weaving et al., 2017). It has been employed in previous studies of training load monitoring (Weaving, Marshall, Earle, Nevill, & Abt, 2014; Williams et al., 2016a). To explore the effects of PCA pre-processing, each multivariate model was trained with unprocessed data and data pre-processed with PCA and the results were compared. Principal components were calculated using the singular value decomposition method (Jolliffe, 1986). A 95% cumulative variance threshold was used to extract m principal components, where m was the smallest number of components that explained at least 95% of the total variation in the data (Jolliffe, 1986; Kuhn & Johnson, 2013).

Class imbalance refers to prediction problems when one class is far more common than the other (Kuhn & Johnson, 2013). Injury prediction suffers from large class imbalance since injuries are far less common than days when a player doesn't get injured. Severe class imbalance can cause prediction algorithms to have trouble correctly predicting the rare class (Kuhn & Johnson, 2013). Two sampling techniques were implemented to combat class imbalance. Under-sampling randomly removes non-injury days from the model building data until there is an equal number of injury and non-injury days. Synthetic minority over-sampling (SMOTE) synthetically creates new injury samples in the model training data and under-samples a fraction of the non-injury days to even up the classes (Chawla, Bowyer, Hall, & Kegelmeyer, 2002). Each model was built using unprocessed data, under-sampled data and SMOTE sampled data.

Model evaluation

To evaluate the performance of each modelling approach, predicted injury probabilities were generated for each training or match day in the full testing data set. A receiver operator characteristic curve was constructed and the AUC calculated. Importantly, each model was evaluated on exactly the same data set (i.e. no under-sampling or SMOTE applied to testing data) to allow for fair comparisons. A perfect model would have AUC=1.0 and random guessing would be expected to produce AUC=0.5. This gives a performance metric preferable to error rate for problems with unbalanced data; where low error can be achieved by simply predicting the more common class every time (Kuhn & Johnson, 2013; Thornton et al., 2016) (e.g. if the injury rate is 1%, a model always predicting no-injury is 99% accurate).

To estimate the variability introduced into the modelling procedure by randomly sampling the data during the pre-processing and model tuning stages, 50 repetitions of the entire process were run, generating a set of performance estimates for each model. Under-sampling and SMOTE sampling introduce variability into the modelling pipeline because they select a random subset of the training data before the model building stage. A different selection may result in a different model. Variability is also introduced during the model tuning stage. During cross validation the training data set is randomly partitioned into 10 folds, model hyperparameters are then chosen based on the performance across these folds. It is possible that when the process is repeated the composition of the folds will change. In this circumstance a different hyperparameter will be chosen and a different model created.

Results

The number of reported injuries (and frequency relative to the number of sessions) is shown in Table 2. Hamstring injury rates were similar across seasons (0.004 vs. 0.003 injuries per session), however non-contact (0.035 vs. 0.014 injuries per session) and non-contact time-loss (0.017 vs. 0.009 injuries per session) injury rates were lower.

Table 2: Injury counts and rates (relative to total number of sessions) in the model training and testing data. (NC = non-contact, NCTL = non-contact time-loss, HS = hamstring, 'lag' suffix indicates outcome is injury within 5 days).

Injury outcome	Model training data (2014 & 2015)	Testing data (2016)
NC	321 (0.035)	67 (0.014)
NCTL	156 (0.017)	42 (0.009)
HS	36 (0.004)	13 (0.003)
NC-lag	1601 (0.174)	479 (0.103)
NCTL-lag	784 (0.085)	295 (0.063)
HS-lag	183 (0.020)	88 (0.019)
Total records (match & training)	9203	4664

Predictive ability of different modelling approaches

Predictive performance was limited for multivariate models when using un-processed data (Figure 2). Using regularised LR to model hamstring injuries performed best (mean AUC=0.72), all other multivariate models had a mean AUC of less than 0.65 on the testing data. Univariate models performed worse than multivariate models for each injury outcome (best AUC<0.6 for NC and NCTL, and best AUC<0.7 for HS).

Attempting to account for a possible lag time between training load spikes and injury occurrence (NC lag, NCTL lag and HS lag in Figure 2) did not improve predictive performance (mean AUC=0.50-0.57). In general, models provided predictions only marginally better than chance.

The performance of HS injury models (particularly LR and RF) was more variable than non-specific injury models (Figure 2). The increased variability is likely due to the smaller number of HS injuries in the model training data (n=36). The random inclusion or exclusion of one or more of these injuries during the model building stage has a greater impact on the final model.

No particular prediction algorithm showed a strong tendency to outperform others across different injury outcomes. The more complex models (RF and SVM) did not tend to outperform generalised linear models (LR). Accounting for individual clustering effects (GEE) did not lead to better results.

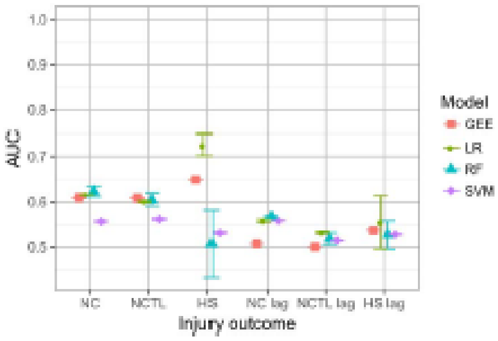

Figure 2: Area under ROC curve evaluated on the testing data set (mean and standard deviation of 50 repetitions) for different prediction algorithms and injury outcomes (no data pre-processing). (NC = non-contact, NCTL = non-contact time-loss, HS = hamstring, 'lag' suffix indicates outcome is injury within 5 days. GEE = Generalised estimating equation, LR = regularized logistic regression, RF = random forest, SVM = support vector machine).

Hamstring injury prediction

Regularised LR for hamstring injuries showed better performance (mean AUC=0.72) than other models (Figure 2). The model gives a predicted injury probability each day, how this translates into practice (i.e. modifying player training and preventing injuries) is dependent on the preferences of the decision maker. Specifically, how they weight the consequences (cost) of a false negative (missed injury) relative to a false positive prediction (unnecessarily cancelling or modifying a session by decreasing volume or intensity). To illustrate this we considered three arbitrary relative costs: 1 missed injury (i.e. one we didn't predict) costs as much as 50 unnecessarily modified sessions (aggressive risk), as much as 100 sessions (moderate risk), or as much as 1000 sessions (conservative risk). The estimated optimal performance metrics for the three choices are shown in Table 3. There is a trade-off between correctly predicting more injuries and incorrectly flagging non-injury sessions. In general, the AUC values for other models in the study were similar or below the HS model, suggesting they would not perform significantly better than the results in Table 3.

Table 3: Estimated optimal performance of HS injury models for different relative cost ratios (values reported as median of 50 repetitions).

Cost of false negative relative to false positive	True positive rate	False positive rate	Positive likelihood ratio	Negative likelihood ratio	Probability injury given positive prediction	Probability injury given negative prediction
50 (aggressive risk)	0.08	0.004	17.9	0.93	0.05	0.003
100 (moderate risk)	0.54	0.11	5.0	0.52	0.01	0.001
1000 (conservative risk)	0.92	0.53	1.7	0.16	0.005	0.0004

Effect of data pre-processing

The effects of different data pre-processing protocols are shown in Figure 3. Model performance varied under different protocols, yet the differences in predictive ability were generally small. Reducing the number of predictors to a smaller, uncorrelated set by applying PCA pre-processing caused minor performance improvements in the models considered (Figure 3). This suggested that multicollinearity was a potential cause of poor performance when using un-processed data. Additionally, the variability in performance tended to decrease (especially for RF models).

Under-sampling non-injury days led to performance decreases for all models except the SVM (Figure 3). This is possibly due to the information lost from the model training data when a large number of the non-injury days are removed. Under-sampling may not be appropriate for the injury prediction problem. SMOTE sampling did not lead to any major performance improvements (Figure 3). In the SMOTE procedure new injury observations were synthetically created using the common characteristics observed in actual injuries. This may not help the generalisability of models if new injuries show little resemblance to past ones. SVM models were the exception, and benefited from both sampling methods used, suggesting their performance was more negatively affected by imbalance between injury and non-injury observations. Combining SMOTE sampling and PCA pre-processing was similarly unsuccessful in improving predictive performance.

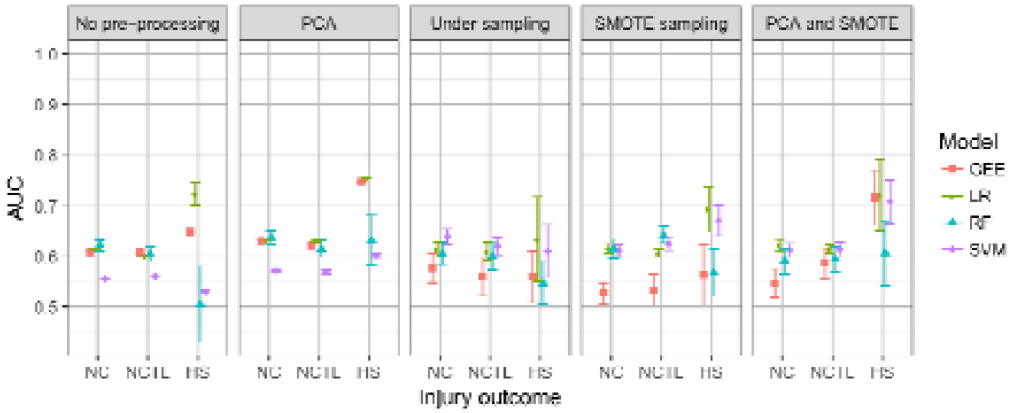

Figure 3: Effects of data pre-processing protocols and sampling methods on model performance (mean and standard deviation of 50 repetitions) for each injury outcome (NC = non-contact, NCTL = non-contact time-loss, HS = hamstring. GEE = Generalised estimating equation, LR = regularized logistic regression, RF = random forest, SVM = support vector machine).

Applying sampling methods to the data to try and reduce the amount of imbalance between the number of injured and non-injured observations led to increased variability in the results (Figure 3). This is a consequence of randomly removing different subsets of the data before building models in each simulation. ROC curves for the best performing models (highest mean AUC) for each injury type are shown in Figure 4. ROC curves for the modelling procedures that included under-sampling and SMOTE sampling of the training data showed much more variability between the 50 repetitions (Figure 4(a-b)). The best performing hamstring model (Figure 4(c)), which didn't use any sampling methods, showed only very small variability between repetitions (nearly perfect overlap for each repetition).

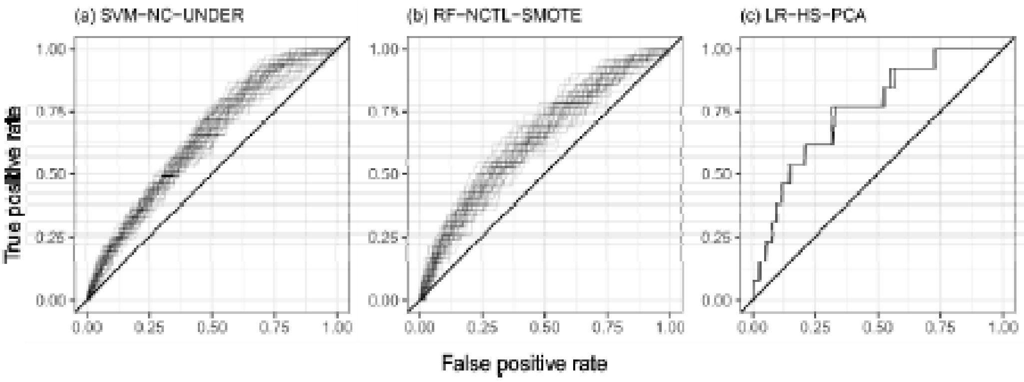

Figure 4: ROC curves for 50 repetitions of the best performing (highest mean AUC) modelling process for each injury type: (a) SVM with under-sampling for NC, (b) RF with SMOTE sampling for NCTL and (c) LR with PCA for HS injuries (NC = non-contact, NCTL = non-contact time-loss, HS = hamstring. LR = regularized logistic regression, RF = random forest, SVM = support vector machine).

Principal component analysis

PCA pre-processing applied to the full training data set (i.e. before any sampling strategies were applied) required 14 principal components to explain 95% of the variance in the data (Figure 5(a)). The first two components accounted for close to 60% of the variance. This implied that much of the information contained in the multiple training load metrics could be captured in a lower dimension. The correlation between the predictor variables and the first two principal components is shown in Figure 5(b). A clear grouping effect between variables of the same types was observed. The relative training load variables (ACWR and exponentially weighted ACWR) were related to the principal components in similar ways. The grouping could also be observed for 21-day cumulative loads and 3-day cumulative loads. Separation between monotony, strain (calculated over 7 days) and 6-day cumulative load variables was less clear. This was potentially due to their similar timescales. The two non-training related variables, age and match indicator, were not strongly correlated with either of the first two principal components.

Model performance for new versus returning players

Predictive accuracy of NC and NCTL injury models did not significantly change when new players and returning players were considered separately (Figure 6). Hamstring models appeared to perform better on returning players, suggesting they may have started to identify patterns leading to hamstring injury in the existing playing group. However, of the 13 total hamstring injuries in the testing data; 10 were to new players and only 3 to returning players. The inflated results for the returning players may be a consequence of the small sample size and not truly representative of expected future performance.

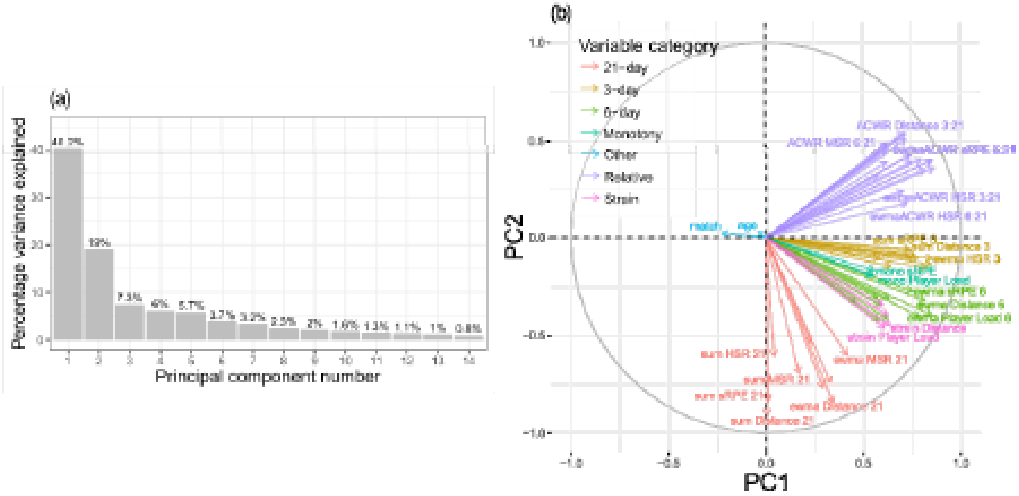

Figure 5: Results of principal component analysis applied to full training data set. (a) Scree plot showing the percentage variance explained by the first 14 principal components (the number required to pass 95% cumulative variance explained). (b) Variable factor map showing how correlated each predictor variable is with the first two principal components (a representative subset of variable labels were chosen for figure clarity).

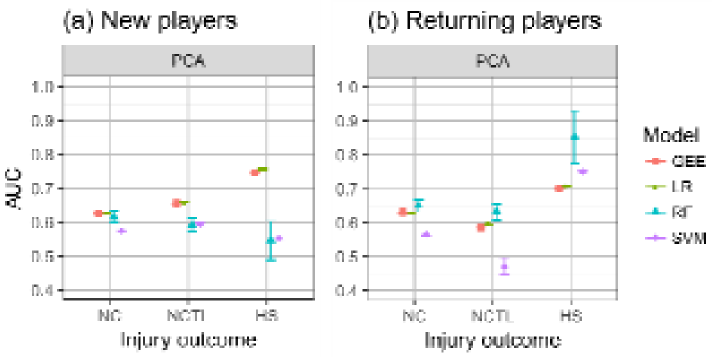

Figure 6: Model performance (mean and standard deviation of 50 repetitions) for (a) new players and (b) returning players (PCA pre-processing).

Effect of increasing the number of model training samples

The performance of predictive models can be influenced by the amount of data available to build models (Kuhn & Johnson, 2013). A learning curve shows the performance of a model on the training and testing data sets as the size of the training data set is increased. This indicates whether performance is improving or plateauing as more data is used. Learning curves were constructed for two injury models (Figure 7) to investigate whether the poor performance could be attributed to insufficient amounts of data.

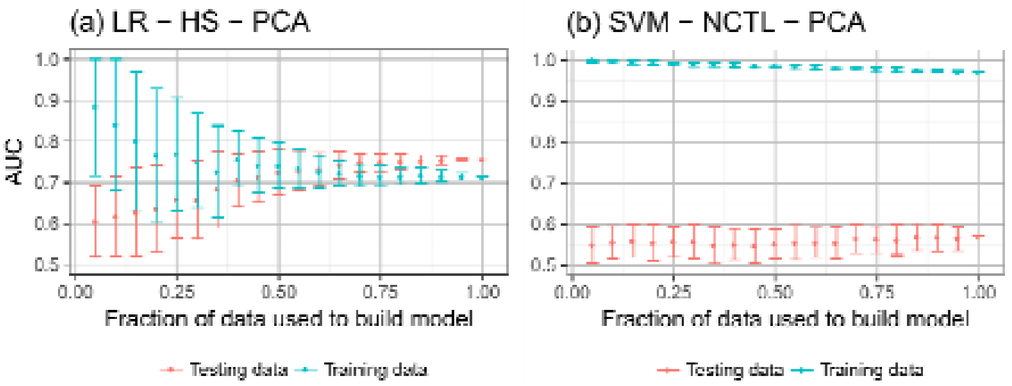

Figure 7: Learning curves showing mean and standard deviation of performance for; (a) LR model of HS injuries (b) SVM model of NCTL injuries (both with PCA pre-processing). (NCTL = non-contact time-loss, HS = hamstring. LR = regularized logistic regression, SVM = support vector machine)

The performance of LR to predict hamstring injury (with PCA) is shown in Figure 7(a). Test set performance increased as the amount of data used the build the model increased, suggesting the model was learning to recognise hamstrings injuries better. The performance on the training and testing sets appeared to converge to a similar level (mean AUC=0.7-0.8) once the full data set was used. However this represented a limited ability to predict injuries (Table 3); meaning the model was unable to fully explain the relationship between the predictor and outcome variables, or had underfit the problem. Underfitting suggested the model was unable to capture enough complexity in the data or that the predictor variables did not contain enough information to predict injuries (Kuhn & Johnson, 2013).

Figure 7(b) shows the learning curve for an SVM model for NCTL injuries (with PCA). The performance on the model training data was near perfect but test set performance was well below desired levels. The learning curve suggests the model may be suffering from overfitting; it has perfectly fit the injuries in the model training data but does not generalise well to new data. Potential strategies for addressing this are collecting more data (especially more positive injury samples) or penalising the model for increasing complexity (regularisation) (Kuhn & Johnson, 2013). The increase in performance observed when the size of the training data set was increased from 460 to 9203 samples was approximately 5%. Estimating further improvements is difficult given the potentially non-linear relationship, however it appears at least an order of magnitude (tenfold) more data may be needed.

Discussion

Models of the relationships between training loads and injuries in elite Australian footballers showed limited ability to predict future injuries. Multivariate models of non-contact and non-contact time-loss injuries performed better than univariate models, yet only marginally better than would be expected by random chance (mean AUC<0.7). The levels of performance were comparable to similar modelling in rugby league (AUC=0.64-0.74) (Thornton et al., 2016).

Considering hamstring injuries on their own led to improvements in model performance (best AUC=0.76) (Figure 2-4). Implementing such a model in practice would require practitioners to consider how much modification of player training they are willing to accept in an attempt to prevent injuries. Results suggested that predicting half of the hamstring injuries would incur a false positive rate above 10% (or more than 1 in 10 player sessions unnecessarily modified) (Table 3). The multivariate models used in this study provided improved predictive ability compared to findings by Ruddy et. al. (Ruddy et al., 2016) in a larger cohort of hamstring injuries in Australian football (AUC=0.5-0.63).

Pre-processing data to account for multicollinearity of predictors (with PCA) and sampling to reduce the level of class imbalance resulted in minor improvements to predictive performance (Figure 3). Particularly in the more complex models (SVM) that tended to over-fit the model training data. Consideration of these issues may improve predictive performance in future modelling studies.

Results from the PCA analysis showed the different training load variables to strongly correlated (Figure 5(b)). A large proportion of the total variance in the 60 variable data set could be captured by only a few principal components (Figure 5(a)). The metrics used in this study were originally chosen in an attempt to represent different physiological demands imposed on players. The results suggested that in Australian football the different metrics contain largely overlapping information. This finding highlights issues with performing multivariate training load modelling without initially treating the data to extract orthogonal components (Weaving et al., 2017). The amount of redundancy in the predictor variables may also partially explain the inability to predict injuries with high accuracy. The inclusion of multiple GPS and accelerometer derived metrics provided little additional information and future studies may benefit from including different sources of information in modelling approaches (e.g. anthropomorphic measurements, injury histories or psychological profiles). The internal training load variable (sRPE) did not appear to provide different information to external loads (Figure 5). The strong correlations between different training load metrics may be a consequence of the particular demands of training and matches in Australian football, and it is not known if this finding generalizes to other athletic cohorts.

Possibilities for improving injury prediction models

The learning curves for different modelling approaches are shown in Figure 7. These provide some indicators for ways to potentially improve the performance of future injury prediction models. Underfitting models (Figure 7(a)) can be improved by increasing the model complexity or by increasing the number and variety of predictors (Kuhn & Johnson, 2013). This suggests that linear models such as logistic regression may not be well suited to modelling complex injury relationships, supporting the contention of Bittencourt et. al. (Bittencourt et al., 2016). The more complex models (RF and SVM) tended to over-fit the small number of injuries in the data (Figure 7(b)) and did not generalise well to future injury observations. Collecting more player monitoring and injury data (>10 team-seasons) may provide a way to construct practically useful prediction models.

Given the low injury per session rate (0.4% for hamstring to 3% for all non-contact) and the large number of possible risk factors, a probabilistic approach to load and injury risk models that allows for clinical judgement given context and other sources of information may improve outcomes. Future studies may see progress by taking this approach and not considering injury prediction as a binary classification problem.

Utility of training load monitoring for injury risk reduction

Results of this study suggested that training loads models were limited in their ability predict future injuries for an athlete on a given day. However this not does not rule out training load monitoring as a valid practice. There is strong evidence (Blanch & Gabbett, 2016; Carey et al., 2016; Hulin et al., 2015; Malone et al., 2016; Murray et al., 2016; Soligard et al., 2016) that rapid increases in load and spikes in acute:chronic workload ratio are associated with increases in team injury rates. For this reason, measuring absolute and relative training loads in team sports to monitor load progression and allow for informed modification of plans is still considered best practice (Drew & Finch, 2016; Soligard et al., 2016). Using individual training loads as a daily decision tool for athlete injury prediction has limited utility in this study.

Limitations

The professional sporting team participating in this study had comparatively high player turnover. This may have impacted on the accuracy of injury prediction models (Figure 6) and restricted the ability to build player specific models. The small injury sample size was a consequence of conducting this study within a single club. There were an insufficient number of injury records of a particular type (other than hamstrings) to create different injury specific models.

This study included a number of the commonly used training load measures (GPS and session-RPE) and derived metrics (cumulative load, acute:chronic workload ratio, monotony and strain). Running demands in relative speed zones, subjective wellness and fatigue markers and biomechanical screening data were not available. These variables may contain relevant information to improve predictive models.

In both the model training and testing seasons physical preparation staff were aware of the emerging body of research on training loads and injury risk (Colby et al., 2014; Gabbett, 2010, 2016; Hulin et al., 2015; Rogalski et al., 2013) and gave consideration to this when planning training. This may have influenced the distribution of training load variables recorded.

Practical applications

The results of this study highlighted the limitations of using training load based predictive models as a daily decision tool for practitioners in Australian football. We outlined how a practitioner's judgement on the "cost" of an injury relative to a modified training session can influence how a predictive model is implemented in practice (Table 3). Improved predictive performance for hamstring specific models suggests that modelling specific injury outcomes instead of general non-contact injuries may be more informative for assessing injury risk in practice. The findings relating to insufficient data set size and poor model performance address an issue likely encountered by practitioners operating in a team-sport environment.

CONCLUSION

Models of training load, age and session type showed limited ability to predict future injury in Australian footballers. Hamstring specific injury models showed better predictive performance than general non-contact models. Future studies may benefit by considering specific injury types as outcomes variables. Predictive performance also improved with increasing quantity of data. This highlighted the limitations of predictive modelling attempts conducted within a single team and the need for collaboration or larger cohorts. Training load may be an important injury risk factor to monitor, yet considering it in isolation as a daily decision tool has limited ability to predict injury.

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Human Kinetics
ORIGINAL INVESTIGATION

Optimizing Preseason Training Loads in Australian Football

David L. Carey, Justin Crow, Kok-Leong Ong, Peter Blanch, Meg E. Morris, Ben J. Dascombe, and Kay M. Crossley

Purpose: To investigate whether preseason training plans for Australian football can be computer generated using current training-load guidelines to optimize injury-risk reduction and performance improvement. ***Methods:*** A constrained optimization problem was defined for daily total and sprint distance, using the preseason schedule of an elite Australian football team as a template. Maximizing total training volume and maximizing Banister-model-projected performance were both considered optimization objectives. Cumulative workload and acute:chronic workload-ratio constraints were placed on training programs to reflect current guidelines on relative and absolute training loads for injury-risk reduction. Optimization software was then used to generate preseason training plans. ***Results:*** The optimization framework was able to generate training plans that satisfied relative and absolute workload constraints. Increasing the off-season chronic training loads enabled the optimization algorithm to prescribe higher amounts of "safe" training and attain higher projected performance levels. Simulations showed that using a Banister-model objective led to plans that included a taper in training load prior to competition to minimize fatigue and maximize projected performance. In contrast, when the objective was to maximize total training volume, more frequent training was prescribed to accumulate as much load as possible. ***Conclusions:*** Feasible training plans that maximize projected performance and satisfy injury-risk constraints can be automatically generated by an optimization problem for Australian football. The optimization methods allow for individualized training-plan design and the ability to adapt to changing training objectives and different training-load metrics.

Keywords: AFL, injury, performance, workload ratio

Training-load prescription in team-sport athletes is a balance between performance improvement[1,2] and injury-risk reduction.[3–6] The manipulation of training intensity, duration, and frequency to induce improvements in athletic performance is a fundamental objective of training-plan prescription.[7] To inform this process, mathematical models of the relationship between training loads and performance have been proposed for multiple athletic populations.[1,7,8] Banister et al[1] modeled the response to a training dose using 2 time-decaying functions representing fitness and fatigue. This allowed performance to be projected at a later time by taking the difference between the modeled fitness and fatigue functions. While the accuracy of these models in predicting performance has been limited,[7,9] they provide a generalized basis for training prescription. Studies modeling team-sport performance are fewer, possibly due to difficulties in quantifying individual performance in a team environment and mixed training methods.

Training load has been identified as a risk factor for injury in recent reviews, with both absolute and relative loads needing to be considered when assessing injury risk.[4,6] The acute:chronic workload ratio quantifies an athlete's relative amount of short-term (acute) to long-term (chronic) training and is an injury-risk factor in a number of team sports.[4–6,10] In addition, there is evidence that cumulative absolute workloads can influence injury risk in Australian football.[3]

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Currently, physical-preparation staff are tasked with balancing the training guidelines associated with injury-risk reduction and performance improvement when prescribing training loads. Mathematical optimization is a method that may help in this process, particularly as more data on training-load monitoring become available.[5,6,10–12] Optimization is the task of finding a set of values (decision variables) that maximize an objective function (goal) and satisfy a set of constraints. Optimizing training loads has been explored in studies of tapering[8] and to generate training plans for performance improvement.[13] No study has explored optimization models that incorporate training guidelines for injury prevention based on cumulative loads and workload ratios in team-sport athletes.

This study aimed to determine the extent to which current training-load guidelines (for relative and absolute training loads) can be used to generate optimized preseason training plans in Australian football and to investigate the effects of varying optimization targets and load constraints on the computer-generated plans.

Methods

The task of planning preseason training loads was posed as an optimization problem. The decision variables were the amount of training prescribed each day, and constraints were defined based on recommended acute:chronic workload ratio and cumulative load limits for injury-risk reduction.

The fixture for an elite Australian football club was used as a template. Players were scheduled to play 3 practice matches 98, 104, and 112 days from the start of preseason and their first competitive match on day 125. Outside of these matches, training loads were able to be freely prescribed on each day.

Decision Variables

The goal of the optimization procedure was to generate a full preseason training plan by specifying the workload value (w) each day:

$$w_i = \text{training load on day } i; \quad i \in \{1, 2, \ldots, 125\}$$

In this study, total distance and sprint distance (SD) were explored since most of the research to date has examined the relationship between these variables and injury risk in team sport.[3,5,10] However, in general, the workload variable could be substituted for any method of training-load quantification.

For clarity, the following sections describe the complete optimization formulation for total session distance and then present the simple modifications needed to adapt the method to SD. This illustrates how the methodology can be generalized to different training-load representations.

Constraints

The optimization model required training plans to satisfy 5 constraints:

- Daily training loads were constrained to be 0 to 50,000 m (a generous upper bound based on unpublished data from previous seasons).

$$0 \le w_i \le 50{,}000$$

- The acute:chronic workload ratio (r) was calculated on a daily basis, using a 6-day acute and 24-day chronic time window, found to be appropriate for this cohort.[10]

$$r_i = \sum_{j=i-6}^{i-1} \frac{w_j}{6} \Big/ \sum_{j=i-24}^{i-1} \frac{w_j}{24}$$

  Training plans were constrained to keep daily workload ratios in the previously described "safe zone" for injury-risk reduction ($0.6 < r_i < 1.3$).[5,10]

- Three-weekly cumulative distance loads of 73,721 to 86,662 m were reported to increase preseason injury risk in Australian footballers (odds ratio 5.49).[3] To account for this, a rolling 21-day cumulative load (C_i) was calculated and constrained to not exceed 73,721 m.

$$C_i = \sum_{j=i-21}^{i-1} w_j$$

$$C_i < 73{,}721$$

- Rest days ($w_i = 0$) need to be considered when planning training in professional team sport due to contractual entitlements. Rest days were included by replicating the proposed rest schedule at the football club. While it can be argued that the timing of rest may be a component of designing an optimal plan, considerations around public holidays, weekends, and player requests were considered beyond the scope of mathematical constraints.
- Match demands were taken from the 2015 AFL GPS Report[14] and incorporated by constraining the total match distance to be 13,200 m ($w_{125} = 13{,}200$). This is an average value and may not reflect the largest loads seen in matches or the differences between playing positions. By increasing the match-demand constraint the method can be adapted to prepare for higher match loads.

Preseason matches in the AFL are subject to altered rules that generally involve more interchange players and shorter match durations. Unpublished data collected in the participating club suggested that total distances covered were approximately 15% lower in preseason matches than in in-season matches ($w_{98,104,112} = 11{,}220$).

Calculating cumulative workloads and acute:chronic workload ratios at the beginning of preseason requires knowledge of off-season chronic loads. At the participating club, players are generally given, and expected to follow, an off-season training program but are not monitored with GPS devices due to league restrictions. As such there is an inherent assumption that players are completing their off-season training. Two levels of off-season chronic load were considered (representing typically prescribed loads): 14 km/wk and 21 km/wk.

Objective

Two objective functions (f_A, f_B) were considered. Objective A was to maximize the total amount of training distance in the preseason, representing the simple goal of allowing players to complete as much training as possible without violating injury-risk constraints (assumed desirable for team sports).

$$f_A(\mathbf{w}) = \sum_{i=1}^{125} w_i$$

Objective B was to maximize the Banister-model[1]-projected performance on match day. This objective was chosen as it included a consideration of the fatiguing effects of training, as well as a realistic goal of trying to maximize players' preparation before their first match. Banister-model parameters were adapted from a study of middle-distance runners,[15] as no such research has been undertaken in Australian football.

$$p_i = p_0 + k_1 \sum_{j=1}^{i-1} w_j e^{\frac{-(i-j)}{t_1}} - k_2 \sum_{j=1}^{i-1} w_j e^{\frac{-(i-j)}{t_2}}$$

$$k_1 = 1, \quad k_2 = 2, \quad t_1 = 45, \quad t_2 = 11$$

$$f_B(\mathbf{w}) = p_{125}$$

Modifications for Sprint Distance

Adapting the optimization problem outlined herein to SD (defined as the distance covered above 75% of an athlete's recorded top speed[3]) requires only a few parameter changes:

- The three-weekly cumulative load constraint was changed to $C_i < 1{,}453$ to reflect findings on increased injury risk by Colby et al.[3]
- Regular and preseason match demands were changed to 268 m and 200 m of SD, respectively.[3]
- Off-season chronic loads were considered at 150 m/wk and 225 m/wk of SD to reflect levels typically prescribed by the participating club.

These example values are taken from a study of 1 team and may not represent the demands of other athletes. It is recommended that constraints be tailored to suit team-specific demands when adapting this methodology.

Simulations

Training plans were initialized by random sampling from a normal distribution: mean (standard deviation) = 3 km (1 km) and 30 m (10 m) for distance and SD, respectively. Starting from the random training plan, the optimization software sought to find a solution that satisfied all the constraints and maximized the objective function (see supplemental movie available online with this article).

Optimization was performed using the MATLAB software package (MATLAB 8.1, The MathWorks Inc, 2013, Natick, MA), the nonlinear programming solver and the sequential quadratic programming algorithm. Default step and function convergence tolerances were used (10^{-6}). Twenty simulations were run for distance and SD under each combination of objective and off-season chronic load.

Results

The optimization approach produced solutions that were able to satisfy both the acute:chronic workload ratio and cumulative workload constraints. Each simulated preseason training program converged to an optimal objective value within a similar number of iterations (Figure 1), suggesting that the optimization-problem formulation and the algorithms used were appropriate. Increasing the off-season chronic-load parameter resulted in higher total preseason training loads under optimization objective A (Figure 1[a] and 1[c]) and higher projected performance under objective B (Figure 1[b] and 1[d]).

The distribution of prescribed session distances and session SD loads for each objective is shown in Figure 2. Each simulation had slightly different distributions (ie, the lines in Figure 2 do not perfectly overlap), meaning it was possible for the optimization software to achieve the same objective value using slightly different training plans. Changing the objective of the optimization problem resulted in different load distributions in the generated training plans. In general, plans constructed with the objective of maximizing Banister-projected performance (objective B) prescribed more short sessions (distance <5000 m and SD <100 m), as well as more long sessions (distance ~7000–11,000 m and SD >100 m).

Sample preseason training plans (for distance and SD) generated by the optimization procedure are shown in Figure 3. Plans for total session distance (Figure 3[a] and 3[b]) were generally similar under the different objective functions. The longest prescribed sessions were ~15 km and scheduled approximately 30 days into preseason. A notable difference was observed near the end of the preseason before the first regular-season match. Plans aiming to maximize total distance (Figure 3[a]) prescribed frequent training up to and around matches, whereas those generated using the Banister model refrained from prescribing any training in the 2 to 3 days preceding the first competitive match (Figure 3[b]). This difference can likely by attributed to the fatigue component of the Banister-objective function used. Refraining from training before the first regular-season match allows for the fatigue component to decay toward zero and the projected performance level to be maximized.[1]

SD plans (Figure 3[c] and 3[d]) showed a different load progression than that of distance plans. A gradual increase in SD load was prescribed by the optimization software, with maximal loads not reached until around 90 days into preseason. Similar to distance plans, using the Banister model to guide training led to a reduction in SD load leading into the first match (Figure 3[d]).

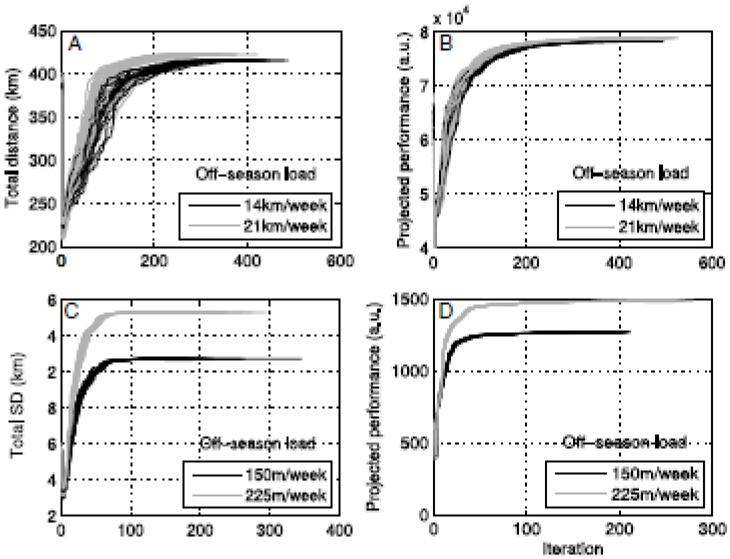

Figure 1 — Convergence of 20 simulated preseason training plans for (a) distance under objective A, (b) distance under objective B, (c) sprint distance (SD) under objective A, and (d) SD under objective B. Objective A is to maximize total preseason load; objective B is to maximize Banister-projected performance at round 1.

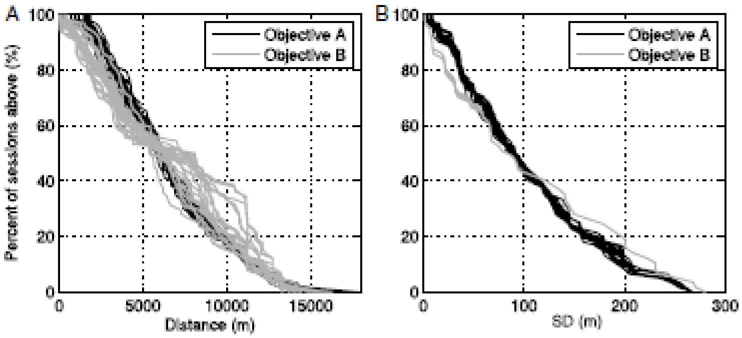

Figure 2 — Distribution of session loads in optimal preseason plans for (a) distance and (b) sprint distance (SD). Objective A is to maximize total preseason load; objective B is to maximize Banister-projected performance at round 1 (off-season chronic loads: 14 km/wk distance and 150 m/wk SD).

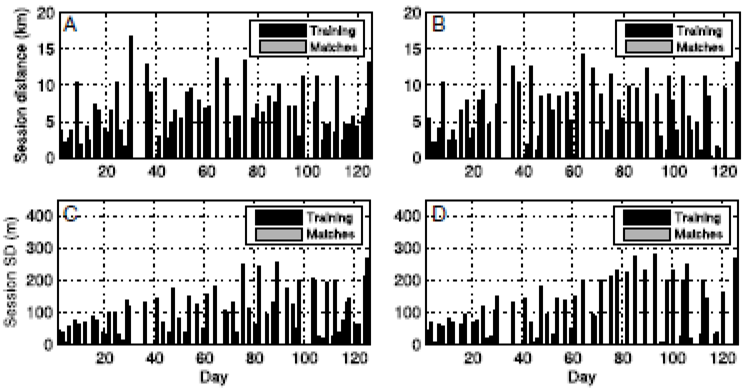

Figure 3 — Computer-generated optimal preseason training plans for (a) distance under objective A, (b) distance under objective B, (c) sprint distance (SD) under objective A, and (d) SD under objective B. Objective A is to maximize total preseason load; Objective B is to maximize Banister-projected performance at round 1 (off-season chronic loads: 14 km/wk distance and 150 m/wk SD).

Discussion

This study aimed to determine whether training-load guidelines could be used to generate optimized preseason training plans in Australian football and how varying optimization targets and load constraints influenced the computer-generated plans. The results demonstrated that the total and SD distances across preseason training programs could be generated using an optimization approach. Cumulative load and acute:chronic workload-ratio guidelines for injury-risk reduction[3–5,10] were able to be satisfied on each day of the preseason plan when they were defined as mathematical constraints. The theoretical approach taken, based on match demands and workload constraints, generated preseason plans (Figures 1 and 3) comparable to those previously reported in professional Australian football teams (mean total distance = 314–411 km, mean total SD = 2.7–8.9 km).[3] This research extends the approach of Schaefer et al[13] by including constraints based on injury-risk factors and putting the approach in a sport-specific context.

Choice of Optimization Objective

The choice of optimization objective influenced the distribution of training sessions prescribed by the model (Figure 2). The generated plans were generally similar in how they progressed loads until the latter stages of the preseason, prior to the first competitive match (Figure 3; days 112–125). Maximization of projected performance with a Banister model (objective B) was achieved by reducing training frequency leading into competitive matches. This reduction allows for the fatigue component of the Banister model to decay toward zero,[1] maximizing the projected fitness level. This aligns with previous theoretical results from Fitz-Clarke et al,[8] where a taper before competition maximized projected performance. Maximizing total preseason volume (objective A) was accomplished by prescribing more frequent moderately sized sessions. More frequent training is a way to accumulate more load (the goal of objective A) without breaking acute:chronic workload constraints. No taper is included since objective A does not include consideration for fatigue accumulation, suggesting that a Banister-model objective may be more appropriate.

Effect of Off-Season Chronic Load

Modifying the off-season chronic-load parameter changed the amounts of prescribed training and projected performance in the generated plans (Figure 1). A higher off-season chronic load (21 km/wk for distance or 225 m/wk for SD) enabled the optimizer to prescribe larger "safe" training volumes (Figure 1[a] and 1[c]) and achieve higher projected performance (Figure 1[b] and 1[d]). These findings highlight the potential benefit of prescribing and adhering to training plans during off-season periods to promote follow-on positive effects. The importance of high chronic workloads aligns with the findings of Malone et al[11] that they may be protective against injury in Gaelic football.

Ability to Customize Plans

The methodological framework outlined in this study allows for customization and individualization of training plans depending on the preferences of the practitioner and needs of the athlete and team. For example, more aggressive or conservative training plans could be generated by simply modifying the workload-ratio constraint, lowering it to 1.1 for a safer plan or raising it to 1.5 if the user is willing to accept higher injury risk.[5] Individualized planning could be incorporated by changing the off-season chronic-load parameter or cumulative-load constraint. For example, first-year players or athletes returning from injury could be assigned a lower off-season chronic load or a lower acceptable cumulative load—and have their plans represent this lower load capacity.

The framework also allows for customization to suit different team objectives. For example, a team may want to employ a game style that requires a higher amount of SD. This could be incorporated into plans by increasing the match-demand constraint for SD from 268 to 350 m (or whatever the desired level may be). The time frames used in this study (125-d preseason with practice matches on days 98, 104, and 112) can be modified for teams or sports with different schedules. This could be accomplished by moving the timing of the match-demand constraints (eg, for a 30-d-shorter preseason: $w_{95} = 13{,}200$ and $w_{68,74,82} = 11{,}220$).

The optimization objective can also be adapted to suit different goals. Instead of maximizing projected performance (peaking) at round 1, the user may prefer to have athletes peaking for each preseason practice match, as well, or a match later in the season. A plan with this goal could be generated by changing the objective function to be the sum of Banister-projected performance on each practice-match day or on a day later in the season.

In general, the optimization approach described can be used to generate training plans that consider a number of combinations of the modifications described herein, allowing for rapid troubleshooting of different training strategies.

Limitations

This study presented a method for optimized training-plan generation in the context of a standard Australian football preseason. As such, the parameters considered were specific to the cohort of interest. A full evaluation of the effects of varying model parameters to reflect different possible training philosophies and timelines was considered beyond the scope of this study. The intent of the study was to determine if training plans could be generated using an optimization approach. As such, there were no data available on the implementation of a generated plan to allow for comparison between planned and actual loads. Future studies are needed to evaluate the effects of an optimization approach on injury occurrence and performance.

A Banister impulse-response model was used to model athlete responses to training loads.[1] A discussion of the merits of using a Banister model for team-sport athletes was considered beyond the scope of this study, and it is possible that other models may be more appropriate.

Practical Applications

The methodology outlined in this report provides an adaptable framework for physical-preparation staff to quickly create athletic-training plans that objectively optimize training goals while satisfying injury-risk and life-balance constraints (ie, days off) without exposing their plans to subjective bias. Practical applications include individualized training-plan design and adaptability to changing training objectives. The framework described also provides theoretical scope for testing different training strategies and assumptions (eg, how much more total training volume could athletes attain if acute:chronic workload-ratio limits are increased to 1.5, or are athletes able to reach match fitness levels if their off-season chronic loads are reduced by 50%?).

Conclusion

Feasible preseason training plans for Australian football can be automatically generated using an optimization approach that maximizes performance while being constrained by injury-risk guidelines. Training plans generated for athletes who enter preseason with higher off-season chronic loads prescribed larger total training volumes. This allowed larger projected performance improvements while theoretically avoiding exposure to high-risk training patterns. The methodology described allows for individualized training-plan design and the ability to adapt to changing training objectives.

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Modeling Training Loads and Injuries: The Dangers of Discretization

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[1]La Trobe Sport and Exercise Medicine Research Centre, College of Science, Health and Engineering, La Trobe University, Melbourne, AUSTRALIA; [2]Essendon Football Club, Melbourne, AUSTRALIA; [3]Rehabilitation Department, Aspetar Orthopedic and Sports Medicine Hospital, Doha, QATAR; [4]Research Centre for Data Analytics and Cognition, La Trobe University, Melbourne, AUSTRALIA; and [5]Healthscope, Northpark Private Hospital, Melbourne, AUSTRALIA

ABSTRACT

CAREY, D. L., K. M. CROSSLEY, R. WHITELEY, A. MOSLER, K.-L. ONG, J. CROW, and M. E. MORRIS. Modeling Training Loads and Injuries: The Dangers of Discretization. *Med. Sci. Sports Exerc.*, Vol. 50, No. 11, pp. 2267–2276, 2018. **Purpose:** To evaluate common modeling strategies in training load and injury risk research when modeling continuous variables and interpreting continuous risk estimates; and present improved modeling strategies. **Method:** Workload data were pooled from Australian football (n = 2550) and soccer (n = 23,742) populations to create a representative sample of acute:chronic workload ratio observations for team sports. Injuries were simulated in the data using three predefined risk profiles (U-shaped, flat and S-shaped). One-hundred data sets were simulated with sample sizes of 1000 and 5000 observations. Discrete modeling methods were compared with continuous methods (spline regression and fractional polynomials) for their ability to fit the defined risk profiles. Models were evaluated using measures of discrimination (area under receiver operator characteristic [ROC] curve) and calibration (Brier score, logarithmic scoring). **Results:** Discrete models were inferior to continuous methods for fitting the true injury risk profiles in the data. Discrete methods had higher false discovery rates (16%–21%) than continuous methods (3%–7%). Evaluating models using the area under the ROC curve incorrectly identified discrete models as superior in over 30% of simulations. Brier and logarithmic scoring was more suited to assessing model performance with less than 6% discrete model selection rate. **Conclusions:** Many studies on the relationship between training loads and injury that have used regression modeling have significant limitations due to improper discretization of continuous variables and risk estimates. Continuous methods are more suited to modeling the relationship between training load and injury. Comparing injury risk models using ROC curves can lead to inferior model selection. Measures of calibration are more informative judging the utility of injury risk models. **Key Words:** ACUTE:CHRONIC WORKLOAD RATIO, INJURY RISK, ROC CURVES, CALIBRATION

One of the challenges for coaches, physical preparation practitioners, clinicians, and researchers in sports science and sports medicine is estimating the risk of injury during sporting competitions and training (1,2). Relationships between training loads and injuries have been studied extensively in recent publications (2–14). Training load has been reported as a key injury risk factor in recent consensus statements (1,15). Studies of training loads and injuries often model the relationships between continuous risk factors (e.g., cumulative load or acute:chronic workload ratio [ACWR]) and binary outcomes (injury or no-injury) (4–14).

Discretization is the practice of transforming continuous data into discrete categories and is a prevalent methodology in studies of training load and injury risk (4–10). Discretization methods in sports medicine research include median splits (5,7), percentiles (5,6,13), z-score categories (4,7), and arbitrary bins (8–10). These methodologies have not been critically examined in the context of modeling training loads and injuries. Discretization of continuous covariates in risk models has been criticized in other fields (16–19). Discretization of a continuous risk factor into categories assumes that each individual within that category has equal risk. For example, if cumulative training load is split into low, medium, and high categories using percentiles, then it is assumed that each athlete in the high category has identical risk, irrespective of how broad the category is (i.e., an athlete at the 67th percentile is considered to be at the same risk as one at the 99th percentile). This practice causes a loss of information because within-category variation is ignored (17). The loss of information lowers the statistical power of the study and may reduce the ability to detect relationships between variables, increasing the

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likelihood of a false-negative result (17,18,20). Discretization can also lead to inflated false discovery rates (17,18). It is common for studies using discretization to analyze results by choosing a reference category and making multiple comparisons to each other category, increasing the chance of finding a significant result (17). It has also been shown by Wainer et al. (21) that categorization of continuous variables can make trends appear in otherwise unrelated data if there is freedom to choose the boundaries of the categories. Modeling methods that allow risk factors to vary continuously, such as cubic regression splines and fractional polynomials have therefore been advocated as appropriate alternatives to discretization for modeling nonlinear risk profiles in epidemiology (16,20).

The increase in studies investigating training load as a risk factor for injury has been accompanied by an increase in studies exploring injury prediction (5,11,12,14,22,23). Injury prediction models have been evaluated and compared using metrics, such as sensitivity, specificity or area under the receiver operator characteristic curve (AUC) (5,11,12,14,22,23). These scoring metrics are designed to evaluate binary predictions (i.e., injury or no-injury) and look at how often the model predictions match the actual outcomes (24). In a practical setting, where there is a clinician or coach to synthesize other sources of information to make a contextualized judgment, a model would not be expected to make a yes/no decision. In this scenario, it could be more informative to evaluate injury risk models using measures of calibration (19,25). Calibration refers to how well a model is able to estimate the probability of an event (24).

In this study, we critically evaluated the modeling and evaluation methodologies found in the existing literature on the relationships between training load and injury. Training load data collected from Australian football (6) and soccer (26) were used to generate a set of hypothetical data sets with known injury risk profiles (27). Discrete risk models using *z* score, percentile, and arbitrary binning methods (4–10) were compared with continuous methods, regression splines, and fractional polynomials (16,20). Models were evaluated using measures of discrimination (AUC) and calibration (Brier score) to assess which metrics were the most informative for assessing the utility of risk models (24).

METHODS

Training Load Data

The ACWR is a relative training load variable calculated by dividing an athlete's acute workload (typically 1 wk) by their chronic workload (typically 4 wk) (2,27). It is a bounded continuous variable that has been studied extensively as an injury risk factor (2–14). The ACWR data were pooled from two studies on separate male populations; a two season study at a single Australian Football club (6) (n = 2550), and a two-season study of 17 soccer teams in the Qatar Stars League (26) (n = 23,742). One-week acute and 4-wk chronic periods (overlapping) were used for both data sets. Total distance was used as the load variable in the Australian football data set and training/match duration in the soccer data set (the only available load metric). Combined, these data had a mean and standard deviation of 1.05 and 0.42; similar to values reported in previous studies (5,7,8) (see Figure, Supplemental Digital Content 1, histogram of ACWR values, http://links.lww.com/MSS/B302). The pooling of data from independent sources was done to ensure the distribution of values used in the simulations was as representative as possible (i.e., it is a good approximation of what a researcher could expect to collect in a hypothetical future study). Alternate ACWR calculation methods that use exponentially weighted averages (28) or decouple the acute and chronic time windows (29) have been proposed. These modifications likely change the distribution of ACWR values (e.g., decoupling causes the ACWR to become unbounded). Despite this, each method still produces a continuous variable and the investigation into the effects of discretization in this study remains relevant irrespective of the ACWR calculation method. Ethical approval for this study was obtained from the Shafallah Medical Genetics Centre, Approval number: 2012-017 and the La Trobe University Faculty of Health Sciences Human Ethics Committee (FHEC14/233). Informed consent was obtained from the participating teams for the analysis of deidentified data.

Injury Risk Profiles

Traditional research designs collect data and build models in an attempt to estimate the true relationship between variables of interest (e.g., ACWR and injury). To evaluate different modeling approaches we have used a different strategy. Artificial injuries were inserted into existing training load data based on predefined risk profiles. This enabled us to compare different models based on how well they were able to recover the true relationship in the data. Three predefined theoretical risk profiles were considered (Fig. 1).

- U-shaped: To align with the hypothesized relationship between ACWR and injury (2,27), with minimum risk corresponding to ACWR = 1.

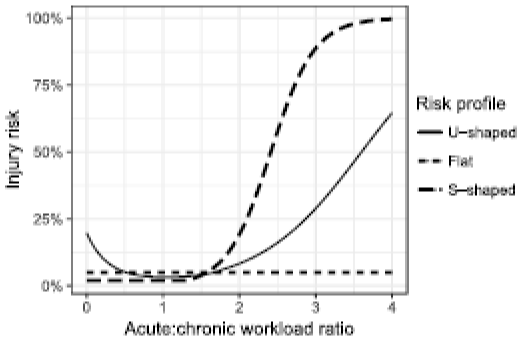

FIGURE 1—Theoretical risk profiles used to simulate injuries.

- Flat: To represent the null hypothesis that ACWR does not influence injury risk (every observation poses a uniform 5% injury risk).
- S-shaped: An alternative risk profile that has injury risk as constant (2%) for ACWR < 1 then rises sharply to very high injury risk.

Details on the mathematical form of risk curves can be found in the supplementary text (see text, Supplemental Digital Content 2, equations of risk profiles, http://links.lww.com/MSS/B303).

Simulating Study Data

To examine the outcomes of different modeling approaches, we simulated hypothetical new studies using the data collected from Australian football and soccer (6,26). The simulation procedure was:

- Choose a sample size (N_s) and randomly choose N_s observations of ACWR from the pooled data distribution (see Figure, Supplemental Digital Content 1, histogram of ACWR values, http://links.lww.com/MSS/B302).
- Assign an injury probability (p_i) to each observation using one of the predefined theoretical risk profiles (Fig. 1).
- Randomly generate injuries by treating each observation as a Bernoulli trial with probability of injury p_i. Simply, this means for an observation with injury risk of 20%, we randomly assigned it an injury or no-injury label with probability 0.2 and 0.8, respectively.

We considered study sizes of 1000 and 5000 observations (representing a single-season or multiseason study in team sport) and three different risk profiles (U-shaped, flat, and S-shaped). For each of these six combinations, we simulated 100 studies to estimate the variability in any results. Simulations were performed using the R statistical computing language (30). An implementation of the simulation procedure is included in the supplementary code (see text, Supplemental Digital Content 3, simulation code, http://links.lww.com/MSS/B304).

Training Load—Injury Models

Two types of modeling approach were considered, discrete and continuous. Discrete models were defined as those that applied a discretization strategy to the ACWR values *before* modeling them against injury incidence. We considered three different discretization methods to reflect those found in the existing literature (4,5,7–10,13).

- D1: Normalize ACWR values (z-score) then split into seven categories using cutpoints: $\{-\infty, -2, -1, 0, 1, 2, 3, \infty\}$ (4,7).
- D2: Split into five quantiles (5,6,13).
- D3: Split the ACWR into five categories using the cut-points: $\{0, 1, 1.35, 1.5, 2, \infty\}$ (10).

After discretization, ACWR was modeled against injury incidence using binary logistic regression, with the central group used as the reference level. This method of analysis replicates that commonly used in previous studies (8–10,13).

To contrast the discrete models, two continuous modeling methodologies (C1 and C2) were considered. The continuous methods apply a transformation to the independent variable (ACWR) within the logistic regression. This allows for nonlinear relationships that vary continuously to be modeled.

- C1: Restricted cubic splines model relationships by subdividing the range of values of the covariate (at locations called knots), and fitting a cubic polynomial between each pair of knots. The polynomials are constrained to join smoothly at each knot and to be linear in the two outermost regions (19). Restricted cubic splines are a common method of analysis in epidemiological studies of nonlinear dose–response relationships (16,19,20). Spline models were fitted in R using the *splines* package (30). Spline regression models were constructed with three internal knots placed at equally spaced percentiles (19,20). The number of knots was chosen *a priori* in this study but in general can be chosen by comparing multiple options using an objective criterion (e.g., Akaike information criterion (AIC)) (19).
- C2: Fractional polynomials are a flexible method of modeling nonlinear, continuous relationships. Fractional polynomials consider a combination of candidate functions and select a final model after a series of tests for nonlinearity and complexity (31). A potential benefit of fractional polynomials over cubic splines is that they are more interpretable. The final model can be described by a closed form equation and offers potential insight into the underlying relationship. Their drawback is that they are a global model (i.e., they fit the entire range of data with a single function) and, therefore, cannot fit local features as well as splines. Fractional polynomial models were fitted in R using the *mfp* package (30,32).

Presently, few studies of the relationship between ACWR and injury have used modeling methods that allow for nonlinear trends and avoid discretization of the ACWR. An implementation of each modeling method considered is included in the supplementary code (see text, Supplemental Digital Content 3, simulation code, http://links.lww.com/MSS/B304).

Each of the models (discrete and continuous) was used to produce estimates of injury risk for each ACWR observation in the simulated data sets. This replicates a study design from a team sport environment where workload risk factor and injury outcomes are recorded daily.

Evaluating Injury Models

Comparison between true and modeled risk curves. A direct comparison can be made between the modeled risk profile and the true risk profile in this study because the function used to simulate the injuries was predefined (i.e., it is exactly known, as shown in Fig. 1). Root mean square error (RMSE) (24) was calculated for the difference between the true risk and predicted risk for each observation in each simulated study. This provides a measure of how well the modeling procedure was able to recover the true risk profile used to generate the data.

False discovery and false rejection rates. The flat injury risk profile was used to estimate the false discovery rate for each modeling approach (Fig. 1). Data simulated under the flat profile contained no association between ACWR and injury risk. Therefore, any simulated study finding a significant relationship in the data could be considered a false discovery (Type I error). Significance testing for discrete models (D1, D2, D3) was performed by comparing the reference ACWR level to all other levels in the discretized ACWR (4,5,7–10,13). A simulation was deemed to have a significant finding if any of the 95% confidence intervals for the odds ratios did not contain 1. Significance testing for spline regression (C1) and fractional polynomials (C2) was performed by comparing to a null model using the likelihood ratio test with $\alpha = 0.05$ (32).

False rejection rates (type II error) were estimated for each model by counting the number of times no significant result was found when the data were simulated with a U-shaped or S-shaped risk profile. Discretizing continuous variables causes a decrease in statistical power (17,18), potentially causing the false rejection rates of discrete models to increase.

Receiver operator characteristic. The AUC has been used to evaluate predictive models of training load and injury in previous studies (5,11,12,14). The AUC measures the ability of the model to discriminate between the two outcome classes (injury and no-injury). It has been used as a way to select the best performing injury prediction model in studies comparing multiple methods (11,12,14,23). Cross-validation (10-fold) was used to obtain estimates of AUC for each simulated study. Without some kind of resampling or out-of-sample testing, the results can be positively biased (i.e., they will be better than could be expected in practice) (24).

Calibration. Calibration is a measure of how well a model is able to estimate the probability of an event. It can be assessed visually by constructing calibration curves (19,33). Calibration curves show how closely the predicted probabilities match the observed event rates (i.e., for observations estimated to have injury risk of 20%—was the actual injury incidence rate on those days around 20%?). Calibration can also be assessed quantitatively by computing the Brier score or logarithmic scoring rule (19). In the case of a binary outcome variable, the Brier score is calculated as the square of the probability assigned to the incorrect class (e.g., if the model predicts injury with probability 0.2, and there was no injury, the Brier score would be $0.2^2 = 0.04$, but if there *was* an injury, then the score would be $0.8^2 = 0.16$). A lower Brier score indicates a better model. The logarithmic scoring rule is evaluated by taking the natural logarithm of the probability assigned to the correct class (e.g., a predicted injury probability of 0.2 and no injury would score $\log(0.8) = -0.22$, and if there was, an injury would score $\log(0.2) = -1.61$). A higher score indicates better probability estimates. Logarithmic scoring may be more appropriate than the Brier score in the case of rare event estimation (34). Brier and logarithmic scores were estimated for each model and simulated study using 10-fold cross-validation (24).

Longitudinal Models of Training Loads and Injury

For clarity of message in the previous sections, we have simulated ACWR and injury data with no correlation structure and used logistic regression assuming independence of observations to illustrate the effects of discretization. However, training load monitoring data collected from sporting teams often consists of repeated measurements taken from the same athletes. It is therefore possible that the observations from the same athletes will be correlated. To investigate the effects of this correlation on injury risk modeling, we simulated longitudinal training load data sets using the *SimCorMultRes* package (35) (see text, Supplemental Digital Content 3, simulation code, http://links.lww.com/MSS/B304). Injuries were simulated in the data by defining a marginal risk profile and specifying a within-subject correlation strength (35). Four longitudinal data sets were simulated (100 times each) to investigate the effects of different sample sizes, within-subject correlations and marginal risk profiles. The first simulated 50 observations from 20 participants with a U-shaped marginal risk (Fig. 1) and a within-subject correlation of 0.1. The second increased the correlation strength to 0.7. The third considered a larger sample size of 100 observations from 50 participants. The fourth considered the effect of reducing the strength of the marginal risk by reducing the injury risk by a factor of 0.5 for each ACWR value.

Each longitudinal data set was analyzed using naïve logistic regression (i.e., assuming independence of observations) and generalized estimating equations (GEE) (36). The GEE models have been used in previous studies of training load and injury (5,12,14). The GEE models were fitted using the R package *geepack* (37) using a binomial link and exchangeable working correlation structure. Both analysis methods allowed for the relationship between ACWR and injury risk to vary continuously using restricted cubic splines (as previously described). Modeling approaches were compared for their ability to recover the predefined marginal effect of ACWR on injury risk using RMSE. Additionally, significance testing was performed for each simulated study result by comparing to a null model using a likelihood ratio test (see text, Supplemental Digital Content 3, simulation code, http://links.lww.com/MSS/B304).

RESULTS

Simulated Studies

Details of the simulated studies (injury summary statistics) are found in supplementary Table 1 (see Table, Supplemental Digital Content 4, simulated injury statistics, http://links.lww.com/MSS/B305).

Comparison between True and Modeled Risk Profiles

A visual inspection of how well each modeling procedure was able to recover the true risk profile used to generate the data is shown in Figure 2. It is clear that models that discretized the ACWR (Fig. 2(D1-3)) are unable to fully capture the U-shaped relationship. Continuous modeling methods C1 (spline regression) and C2 (fractional polynomials) fared much better at fitting the true risk profile (see Figures, Supplemental Digital Content 5, S-shaped risk, http://links.lww.com/MSS/B306 and Supplemental Digital Content 6, flat risk, http://links.lww.com/MSS/B307).

The RMSE performance of each modeling strategy under the different simulation parameters is shown in Figure 3. Continuous modeling methods (C1, C2) had noticeably lower RMSE for data generated using a U or S-shaped injury risk profile (particularly in larger simulated studies with $N_s = 5000$). The difference between discrete and continuous methods was less pronounced for the flat injury risk profile. In general, the total error and variance in error for each model tended to decrease when the simulated sample size increased from 1000 to 5000 observations.

False Discovery Rates

Discrete modeling methods had higher false discovery rates than continuous methods (Fig. 4). For 100 simulated studies with flat injury risk profile (i.e., no relationship in the data) and 5000 observations, discrete models (D1, D2, D3) had false discoveries 21, 16, and 16 times, respectively. The continuous methods had false discovery rates of 7/100 and 3/100 for C1 and C2, respectively. Alarmingly, in the 100 simulated studies, we found that at least one of the three discrete methods had a false discovery 42 times.

Choice of reference level. Discretizing the ACWR then running a logistic regression introduces another choice into the modeling procedure when the reference level is chosen by the researcher. There has been little consistency in existing studies, with the lowest (10,13), highest (8), and central ACWR interval (5) being used. This freedom of choice is an issue because it can change the reported findings. For example, using discrete model D1 and a flat risk profile; 11 of 100 simulations had a false discovery if the highest interval was used as the reference, but if the central interval was used, this increased to 21 of 100 false discoveries. Avoiding discretization and modeling a continuous relationship removes this choice.

False Rejection Rates

Discrete methods (D2, D3) had higher false rejection rates when data were simulated with U-shaped or S-shaped risk profiles (see Table, Supplemental Digital Content 7, false rejection rates, http://links.lww.com/MSS/B308). For data sets with 1000 observations and a U-shaped risk relationship, 59 and 57 of 100 simulated studies did not find a significant result when analyzed using discrete methods D2 and D3 respectively. The false rejection rate was much lower when using methods D1 (5/100), C1 (12/100) or C2 (19/100). As expected, increasing the sample size from 1000 to 5000 observations reduced the false rejection rates for each modeling approach

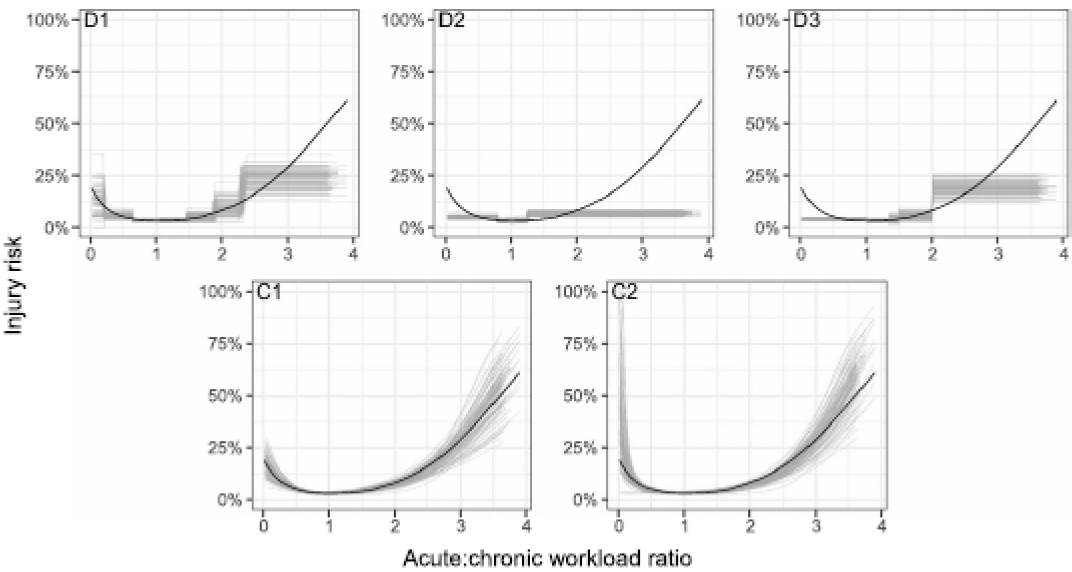

FIGURE 2—Comparison of 100 simulated study results ($N_s = 5000$ and U-shaped risk) analyzed using discrete models (D1, D2, D3) and continuous models (C1, C2). *Solid line* represents the true risk profile used to generate the data and each grey line represents one simulated study result.

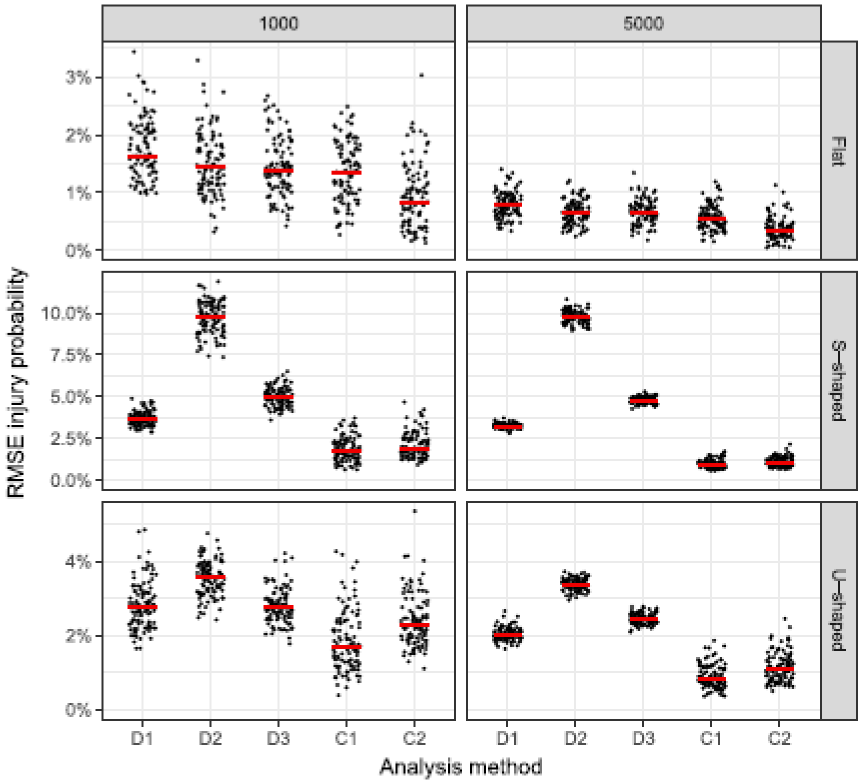

FIGURE 3—RMSE of model probability estimates for 100 trials of each theoretical risk profile and sample size (*red bar*, median).

(see Table, Supplemental Digital Content 7, false rejection rates, http://links.lww.com/MSS/B308).

Receiver Operator Characteristics

Area under the receiver operator characteristic (ROC) curve was estimated for each of the 100 simulated studies using 10-fold cross-validation (24). The continuous analysis methods had higher median AUC values but did not clearly outperform discrete methods under this evaluation metric. If AUC was used to select the best performing model in each simulation, we found that one of the discrete models was chosen on 38 of 100 occasions and 31 of 100 occasions for U-shaped and S-shaped risks, respectively (Table 1).

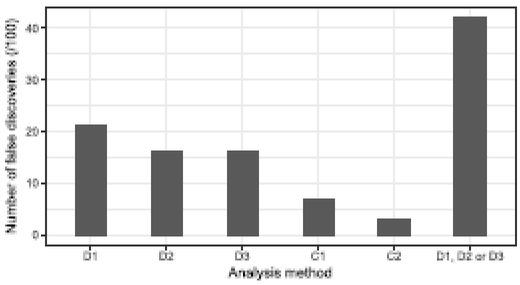

FIGURE 4—False discovery rates (of 100 simulated studies with N_s = 5000 and flat risk profile).

Calibration

To compare with ROC curves, Brier and logarithmic scores were estimated for each model using 10-fold cross-validation (19,24). When the Brier score was used to select the best performing model in each simulation, discrete models were chosen on only 6 of 100 occasions and 0 of 100 occasions for U-shaped and S-shaped risks, respectively (Table 1). When logarithmic scoring was used the rates were 3 of 100 and 1 of 100. Brier and logarithmic scoring favored the continuous methods far more than evaluation with ROC curves.

Calibration curves offer a way to visually evaluate injury risk models (Fig. 5). A calibration curve shows the relationship between the predicted probabilities and actual event occurrence rate (perfect calibration is represented by the diagonal line). An exemplar set of calibration curves is shown in Figure 5 (one simulated study with U-shaped risk and N_s = 5000). Ideally, a

TABLE 1. Comparison of model selection rates using AUC, Brier score, and logarithmic scoring as the evaluation metric (N_s = 5000).

	No. Times Selected as Best Model (/100 Simulated Studies)					
	U-Shaped Risk			S-Shaped Risk		
Method ID	AUC	Brier	Logarithmic	AUC	Brier	Logarithmic
D1	28	6	3	15	0	1
D2	2	0	0	0	0	0
D3	8	0	0	16	0	0
C1	35	80	70	26	73	75
C2	27	14	27	43	27	24

well-calibrated risk model will have a curve that is close to the diagonal line and covers a large range of probabilities (i.e., has confidence in identifying both high- and low-risk scenarios). Discrete model D2 provided little information other than the baseline injury rate. Model D3 did not appear to be well calibrated. Models D1, C1, and C2 were well calibrated (close to diagonal line); however, the continuous methods covered a much larger range of probabilities.

Longitudinal Data Models

The GEE and naive logistic regression models had similar ability to recover the marginal effect in each simulated longitudinal data set (Table 2). Median RMSE values were near identical for each approach. Increasing the sample size (100 observations from 50 participants) lowered the median RMSE values whilst increasing the within-participant correlation strength increased the median RMSE (Table 2).

The naïve logistic regression approach (assuming independence of observations) had higher false rejection rates (i.e., lower statistical power) than the GEE approach (Table 2). The difference in false rejection rates became more pronounced when the strength of relationship between ACWR and injury risk was decreased (47/100 for logistic vs 18/100 for GEE). Using a larger sample size caused the false rejection rate to drop to zero for both methods. Increasing the strength of within-participant correlation did not have a strong effect on false rejection rates.

DISCUSSION

Discrete versus Continuous Modeling Strategies

Discrete models showed limited ability to capture the risk profiles used to generate the simulation data (Figs. 2–3). Discretization forced the models to fit an unrealistic and discontinuous step profile to the data (Fig. 2 and Supplemental Digital Content 5, S-shaped risk, http://links.lww.com/MSS/B306). This illustrates how discretization of continuous risk factors can lead to inaccurate estimation of effects (17,20). Figure 2 shows how using percentile splits (method D2) groups a large range of ACWR values together and provides an inaccurate estimated effect that is far lower than the true risk for ACWR values greater than 2. Similarly, the ACWR categories used in method D3 assume homogeneity

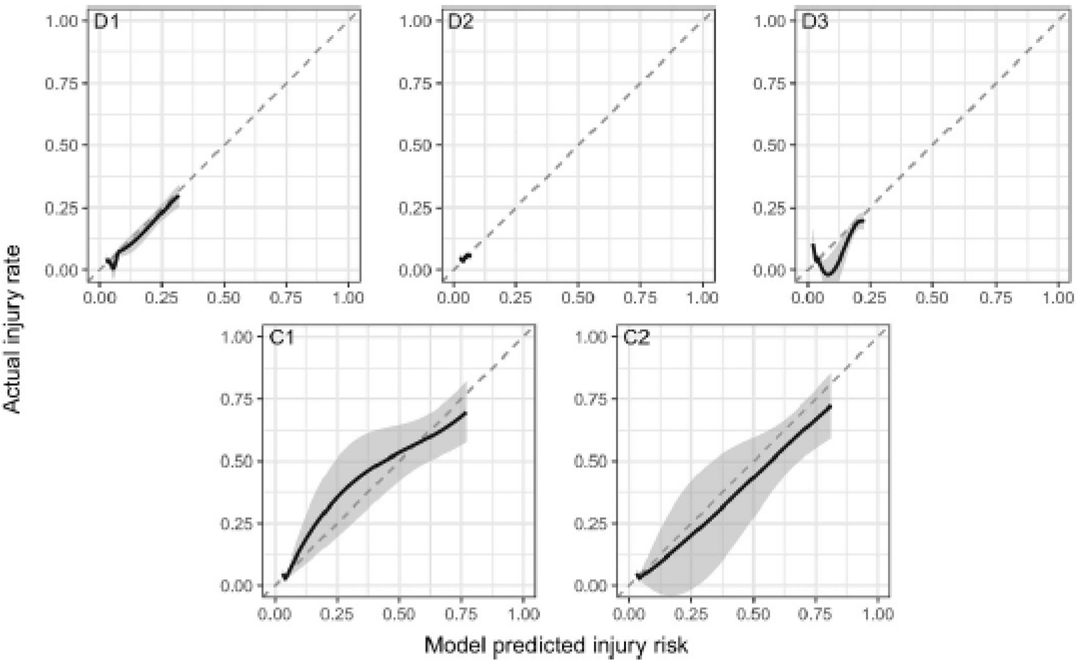

FIGURE 5—Comparison of cross-validated calibration curves from a single simulated study (N_s = 5000 and U-shaped risk) analyzed using discrete (D1, D2, D3) and continuous models (C1, C2). *Diagonal line* represents perfect calibration and shaded area represents 95% CI. 95% CI, 95% confidence interval.

TABLE 2. Comparison of logistic regression and GEE modeling for longitudinal data.

Marginal Risk Profile	Study Size (Observations × Participants)	Correlation Strength	Significant Results (/100)		Median RMSE (IQR)	
			Logistic	GEE	Logistic	GEE
U-shaped	50 × 20	0.1	84	95	0.020 (0.013–0.025)	0.021 (0.014–0.025)
U-shaped	50 × 20	0.7	86	97	0.030 (0.024–0.037)	0.028 (0.021–0.035)
U-shaped	100 × 50	0.1	100	100	0.009 (0.007–0.012)	0.009 (0.007–0.011)
U-shaped (diluted ½)	50 × 20	0.1	53	82	0.013 (0.011–0.017)	0.014 (0.011–0.017)

of risk over the range 0 to 1, leading to an estimated effect that cannot capture the rise in risk seen for small ACWR values. Our simulations suggest that the discrete methods found in the current literature (4–8,10,13) are unsuited to modeling the continuous U-shaped risk profile between ACWR and injury proposed in the literature (2,27).

Continuous modeling methods (spline regression and fractional polynomials) were better suited to fitting the nonlinear risk profiles (U-shaped and S-shaped) and provided more accurate estimated effects. This was demonstrated by lower RMSE scores (Fig. 3) and also confirmed visually by the 100 simulations shown in Figure 2. These findings align with recommendations from other fields that continuous modeling methods are preferable to discretization (17,20). Future studies may benefit from using continuous modeling methods instead of discretizing continuous training load variables when analyzing their relationship to injury.

False Discovery Rates

Data generated under the assumption that ACWR had no relationship to injury risk (Fig. 1, flat risk profile) was used to estimate the false discovery rate for each modeling approach. False discovery rates were inflated by using discrete models (16%–21%) (Fig. 4). Splitting the ACWR into multiple categories before modeling leads to multiple comparisons between groups and may explain the higher false discovery rates (17,18). Discrete method D1 used the most categories (7 groups) and had the highest false discovery rate (21%). A secondary issue was the choice of reference level when categorical predictors are used in generalized linear models (e.g., logistic or Poisson regression). Discrete model D1 had 21/100 false discoveries when the central ACWR category was used as the reference but only 11/110 if the highest was used.

There is currently no consensus in the literature regarding the discretization strategy or choice of reference level when modeling ACWR and injury risk (5,8,10,13). The apparent freedom of choice of discretization and reference level may have caused highly inflated false discovery rates in previous studies (38). When a choice of only three methods was considered in our simulations false discovery rates were as high as 42% (Fig. 4). Continuous modeling methods do not require choosing a reference level and do not suffer from multiple comparisons between predictor categories. Spline regression and fractional polynomials had substantially lower false discovery rates (7% and 3%).

False Rejection Rates

Models that transformed the continuous ACWR into discrete categories showed higher false rejection rates in the simulated studies (see Table, Supplemental Digital Content 7, false rejection rates, http://links.lww.com/MSS/B308). This aligns with findings from other studies that discretization lowers statistical power (17,18,20). Simulations using a larger sample size ($N_s = 5000$) were not as prone to false rejections, highlighting the benefits of larger sample sizes. The negative consequences of discretization on statistical power are particularly relevant for research in elite sport cohorts where sample sizes are often constrained.

Evaluating Injury Risk Models

ROC curves. Comparing models using the area under the ROC curve did not always identify that continuous methods were better fits to the risk profiles (Table 1). RMSE scores showed that continuous methods were clearly superior when modeling U-shaped or S-shaped risk profiles when a sample size of 5000 observations was used (Fig. 3). Despite this, AUC incorrectly identified discrete methods as superior in 38 and 31/100 simulations for U and S-shaped risk (Table 1). This suggests that using AUC as the sole evaluation metric when selecting injury prediction models (11,12,14) runs the risk of selecting an inferior model.

A ROC curve is constructed by sampling through the possible decision thresholds that could be applied (i.e., cut points where the models makes an injury or no-injury prediction). This may not realistically represent the purpose of the model if it to be used for risk estimation. If the output of the model is used along with context and clinical judgment, and not required to make a binary decision, then AUC may not be an appropriate evaluation metric (25). The ROC curves also assume that false positive errors and false negative errors are of equal consequence (39). This is likely not the case when a false negative means an injured athlete and a false positive may be a modified or missed training session. We suggest that ROC curves in isolation are insufficient to evaluate the performance of injury prediction models.

Probabilistic scoring and calibration curves. Evaluating the modeling strategies with Brier scores and logarithmic scoring strongly favored the continuous models (Table 1). Discrete models were selected in only 6/100 and 0/100 simulations using the Brier score and 3/100 and 1/100 when using logarithmic scoring. These provide a much closer reflection of the RMSE scores (ground truth) than evaluating models with AUC. The Brier and logarithmic scores are probabilistic scoring rules designed to evaluate probability estimates (19) and are therefore better suited to assessing injury risk models. We suggest that Brier scores, logarithmic scoring, or another comparable probabilistic scoring rule (34) be included in future studies to compare injury risk models.

Calibration curves (Fig. 5) provided an informative visualization of the performance of injury risk models (33). They showed how closely the risk estimates of each model matched the observed injury rates and how well each model discriminated between high and low risk instances. Figure 5 clearly shows that continuous models gave more informative probability estimates (closer to the observed event rates and over a larger range of values) than the discrete models. Calibration curves show absolute risks and thus may be a more important result for clinicians and decision makers (40).

Longitudinal Models

Extending the simulation study to include correlated within-individual observations showed the negative effects of incorrectly assuming independence between repeated measurements. The naïve logistic regression approach had higher false rejection rates than a GEE approach (Table 2). Assuming independence can cause the standard errors for time varying covariates to be overestimated (41) and may have been the cause of the inflated false rejection rates. When the strength of the "signal" in the data was decreased the difference between logistic and GEE approaches became more pronounced, and the naïve logistic approach had very high false rejection rate (47/100). This highlights the importance of accounting for correlated observations when modeling longitudinal training load data, particularly if the expected strength of signal in the data is small.

Both longitudinal modeling approaches showed similar ability to recover the true marginal risk profile. This is likely because the parameter estimates from logistic regression and GEE models are generally very similar (41). In all simulations, larger sample sizes improved the accuracy of model estimated effects, suggesting the potential benefits of collaborative studies with large sample sizes.

Limitations and Extensions

Restricted cubic spline regression and fractional polynomials were considered as the alternative modeling methods in this study. Although they are common approaches for modeling nonlinear relationships (16,20) they are not the only possible approaches. A number of other nonparametric and semi-parametric methods may have been suitable (e.g., locally weighted regression, generalized additive models, and smoothing splines) (19).

We did not consider multivariable modeling and used only a single covariate (ACWR) in our simulations. This was done for clarity of the message. The issues caused by discretization are equally problematic in multivariable modeling. Spline and fractional polynomial techniques can still be used when there is more than one covariate to allow for proper modeling of continuous variables (19,32). For example, recent studies have investigated the effect of ACWR on injury risk moderated by absolute chronic workload dichotomized using a median split (4,5,7). This dichotomization removes a significant amount of variation in the data, leading to decreased statistical power and inaccurate estimation of effects (17,20). It is possible, and we would suggest more appropriate, to avoid discretization and model both risk factors continuously using a technique such as restricted cubic surfaces (19). This study did not consider time-to-event approaches for modeling training loads and injury (e.g., survival analysis and Cox regression (42)). Discretization of baseline or time-varying covariates can have similar consequences on statistical power and estimated effects in these contexts and continuous approaches are advised (19).

CONCLUSIONS

Modeling methods that discretize continuous risk factors are inappropriate for studying the relationship between training loads and injuries. Discrete models have inflated false discovery and false rejection rates and are unsuited to fitting nonlinear risk profiles. Strong justification is required for research that chooses a discrete approach and we suggest avoiding discretization and modeling relationships with continuous methods, such as spline regression or fractional polynomials. Accounting for correlated observations in longitudinal training data decreases the risk of false rejection. Evaluating injury risk models using ROC curves may not reflect their practical use and may lead to inferior model selection. Probabilistic scoring methods, such as Brier scores, logarithmic scoring, and calibration curves, may be more informative when assessing injury models.

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