# Hamstring strain injury: objective assessment tools and exercise-specific progression criteria during pain-threshold rehabilitation

Submitted by

# **Jack Thomas Hickey**

Master of Clinical Exercise Physiology Bachelor of Applied Science (Human Movement)

> Doctor of Philosophy (Thesis with Published Papers)

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School of Exercise Science, Faculty of Health Sciences



# **Statement of authorship and sources**

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Jack Thomas Hickey

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#### **Publications related to thesis**

- Hickey JT, Timmins RG, Maniar N, Williams MD, Opar DA. Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: A systematic review. *Sports Medicine* 2017; 47(7):1375-87
- Hickey JT, Hickey PF, Maniar N, Timmins RG, Williams MD, Pitcher CA, Opar DA. A novel apparatus measuring knee flexor strength during various hamstring exercises: A reliability and retrospective injury study. *Journal of Orthopedic and Sports Physical Therapy* 2018; 46(2):72-80. Doi: 10.2519/jospt.2018.7634

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- Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Painfree versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial. *Scandinavian Congress of Medicine & Science in Sports –* Copenhagen, February 2018.
- Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Painfree versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial. *Research to Practice, Exercise & Sports Science Australia* – Brisbane, March 2018.

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- Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Why does rehabilitation fail? Challenging current theories. *Sports Medicine Australia, Hamstrung: The Hamstring Injury Journey* – Melbourne, February 2017.
- Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Objective assessment and alternative rehabilitation for hamstring strain injury. *Exercise* and Sports Science Australia, Victoria Symposium – Melbourne, June 2017.
- Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Hamstring strain injury rehabilitation: alternative exercise progression. *Clinical Edge, Sports Injuries Virtual Conference* – December 2017.
- Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Exercise progression and pain during hamstring strain injury rehabilitation. *Sports MAP Network, High Performance Rehabilitation* – Melbourne, February 2018.

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#### Abstract

Hamstring strain injury (HSI) is a persistent cause of time lost in sports that involve high speed running. Clinicians working with sports injuries are therefore often faced with the task of HSI rehabilitation, with the simultaneous aims of minimising time to return to play (RTP) and risk of re-injury. Following rehabilitation and RTP clearance, previously injured hamstrings display elevated risk of re-injury likely, in part, due to persistent deficits in eccentric knee flexor strength and biceps femoris long head (BFlh) fascicle length. Elevated re-injury risk and persistent deficits in hamstring muscle structure and function suggest inadequacies in current rehabilitation practices.

The aim of chapter 3 was to systematically review criteria used to guide HSI rehabilitation progression and determine RTP clearance. The review identified a wide variety of criteria, which were used to progress HSI rehabilitation across the nine included studies. By far the most common guideline was to only perform and progress HSI rehabilitation in the complete absence of pain, despite the fact that such recommendations have never been compared to an alternative approach. Objective criteria were rarely implemented as part of rehabilitation progression and RTP decision making, especially where knee flexor strength was concerned. Three of the nine studies did implement isokinetic dynamometry as an objective measure of knee flexor strength, which is a lab-based methodology rarely available to clinicians dealing with HSI rehabilitation. As such, the need to develop objective measures of knee flexor strength, which could be implemented by clinicians during HSI rehabilitation, was identified.

The primary aim of chapter 4 was to establish the test re-test reliability of a novel apparatus capable of objectively measuring knee flexor strength during a range of hamstring exercises commonly implemented during HSI rehabilitation. Secondary to this, chapter 4 aimed to investigate whether this apparatus could identify between-leg deficits in previously injured hamstrings during these exercises. The apparatus displayed moderate to high test re-test reliability for isometric knee flexor strength (ICC = 0.87 to 0.92), peak rate of force development (RFD) during isometric contraction (ICC = 0.87 to 0.95) and mean force impulse during the eccentric slider exercise (ICC = 0.83 to 0.90). Previously injured hamstrings displayed large deficits (*d* range = -0.88 to -1.09) in mean force impulse during the unilateral eccentric slider,

isometric knee flexor strength and peak RFD. The novel apparatus provides clinicians with an objective tool to monitor knee flexor strength during exercises commonly implemented throughout rehabilitation.

Further to improving objective measures of knee flexor strength, chapter 5 aimed to provide clinicians with exercise-specific guidelines for the progression of a HSI rehabilitation protocol with an emphasis on early eccentric loading. It is commonly recommended that eccentric loading be delayed until the alleviation of pain and/or between-leg deficits in isometric knee flexor strength during HSI rehabilitation. Using exercise-specific progression criteria, eccentric loading was introduced during early HSI rehabilitation and was well tolerated by participants despite concurrent pain and/or between-leg deficits in isometric knee flexor strength. As such, chapter 5 showed that delaying the introduction of eccentric loading until alleviation of pain and/or isometric strength deficits may be unnecessary during HSI rehabilitation.

Chapter 6 investigated RTP clearance time, rates of re-injury and hamstring muscle structure and function following either pain-free or pain-threshold HSI rehabilitation. The median number of days from HSI to RTP clearance was 15 (95% CI = 13 to 17) in the pain-free group and 17 (95% CI = 11 to 24) in the pain-threshold group, which was not significantly different (p = 0.37). Both groups significantly increased BFlh fascicle length from initial clinical assessment to RTP clearance, although these improvements at two-month follow-up, were on average 0.91cm (95% CI = 0.34 to 1.48) greater in the pain-threshold group. The pain-threshold group achieved greater improvements in isometric knee flexor strength at 90/90 degrees of hip/knee flexion compared to the pain-free group at RTP clearance by an average of 15% (95%CI = 1 to 28) and two-month follow-up by an average of 15% (95%CI = 1 to 29). In the six months following RTP clearance, two re-injuries occurred in the both the pain-free (12%) & pain-threshold (10%) group.

This program of research has contributed knew knowledge to the HSI rehabilitation evidence base, specifically by 1) highlighting the large emphasis on subjective criteria for rehabilitation progression and RTP decision making; 2) developing a reliable objective tool used to measure knee flexor strength during various hamstring exercises commonly employed during rehabilitation; 3) describing a HSI rehabilitation protocol with exercise-specific progression criteria, which safely accelerates the introduction of eccentric loading and 4) showing that performing and progressing exercise up to a pain-threshold results in similar RTP clearance time and re-injury rates compared to pain-free rehabilitation, whilst eliciting greater isometric knee flexor strength improvements and greater long-term improvements in BFlh fascicle length. It is anticipated that this new knowledge will improve the clinician's ability to rehabilitate HSI, whilst concurrently minimising RTP times and re-injury risk.

# List of abbreviations and nomenclature

AA	aponeurosis angle
AKE	active knee extension
BFlh	biceps femoris long head
CE	clinical examination
cm	centimetres
d	Cohen's <i>d</i> estimate of effect size
FL	fascicle length
HSI	hamstring strain injury
Hz	hertz
ICC	intraclass correlation coefficient
kg	kilograms
MDC <sub>95</sub>	minimal detectable change at a 95% confidence interval
MRI	magnetic resonance imaging
ms	milliseconds
MT	muscle thickness
Ν	Newtons of force
N.s	Newton seconds of force impulse
N.s/kg	Newton seconds of force impulse relative to kilograms of body mass
NHE	Nordic hamstring exercise

PA	pennation angle
PRISMA	preferred reporting items for systematic reviews and meta-analysis
PSLR	passive straight leg raise
ROM	range of motion
RFD	rate of force development
RTP	return to play
SD	standard deviation
TE	typical error
TSK	Tampa Scale for Kinesiophobia
US	ultrasound
%TE	typical error as a percentage coefficient of variation
90% CI	90% confidence interval
95% CI	95% confidence interval

## **Chapter 1 – Introduction and overview**

Hamstring strain injury (HSI) has long been a leading cause of time lost from competition for many sports that involve high speed running [2, 22, 38, 40, 90, 99, 147]. For example, HSI consistently remained the most common injury over a twenty and thirteen year period in elite Australian football [99] and elite European soccer [39], respectively. These rates show no signs of waning, with HSI prevalence increasing slightly between 2001 and 2014 in soccer [39]. Apart from persistently high prevalence, HSIs display elevated rates of re-injury (16-26%) [37, 99] compared to recurrence of all injuries (12-14%) [38, 99]. Re-injury is of particular concern given recurrent HSI often results in prolonged periods of convalescence compared to the initial injury [22, 37]. It is not only at the elite level where HSI plagues sport. At the community-level, HSI is the most common non-contact injury in Australian football [35, 46, 121] and rugby [108]. As such, clinicians dealing with sports injuries from the community to the elite level are regularly faced with the task of HSI rehabilitation.

The goal of HSI rehabilitation is to return the injured athlete to their previous level of activity with minimal risk of re-injury [52]. Achieving these rehabilitation goals in an expedited manner is often desirable due to financial [36, 54] and performance implications [48] of athlete unavailability. Coaches, athletes and sporting organisations cognisant of such consequences may increase pressure on clinicians to accelerate rehabilitation through their involvement in the shared return to play (RTP) decision [5, 27, 113]. As pressure for expedited RTP is a practical reality of sports injury, particularly at the elite level, clinicians must aim to address the goals of HSI rehabilitation in a timely fashion.

To achieve the aforementioned rehabilitation goals, clinicians need to identify and address not only deficits that occur following HSI, but also modifiable risk factors that may have contributed to the original injury. Deficits in isometric knee flexor strength and range of motion (ROM) exist acutely following HSI [8, 81, 104, 117, 144] and can increase re-injury risk if persistent at RTP [30]. In general, isometric knee flexor strength and ROM deficits typically resolve by RTP clearance [8, 81, 104, 117, 144], however, other deficits in muscle structure and function have been shown in previously injured hamstrings beyond RTP. As evidence of this, previously injured hamstrings display shorter biceps femoris long head (BFlh) fascicles [127, 130] and

deficits in eccentric knee flexor strength [28, 76, 91, 93, 120, 130, 131], even after the completion of rehabilitation.

Persistent deficits in BFlh fascicle length and eccentric knee flexor strength should be alarming to clinicians, as these deficiencies magnify the already elevated risk of HSI associated with previous injury [96, 128]. Regardless of whether deficits in BFlh fascicle length and eccentric strength were a result or cause of initial injury, they suggest short comings in current rehabilitation and RTP practices. Therefore improved strategies to rectify deficits in BFlh fascicle length and eccentric knee flexor strength during HSI rehabilitation are needed prior to RTP clearance.

Eccentrically biased knee flexor and long length hamstring exercises are efficacious interventions for increasing both BFlh fascicle length and eccentric knee flexor strength in uninjured populations [4, 18, 20, 21, 129]. In the context of HSI rehabilitation, long length hamstring exercises with an eccentric bias reduce RTP times compared to conventional exercises with more of a concentric focus [10, 11]. Consequently, recent HSI rehabilitation guidelines advocate the implementation of these interventions [23, 109, 133, 134], although the appropriate timing for the introduction of eccentric loading in particular is less clear.

Conventional guidelines suggest eccentric loading and exercises at long muscle lengths should be avoided while pain is present during early HSI rehabilitation [69, 112]. Pain is believed to induce neuromuscular inhibition as a mechanism to protect injured muscle from excessive load which may cause re-injury [45]. Although pain typically resolves by the time of RTP clearance, previously injured hamstrings display residual neuromuscular inhibition [45], largely confined to maximal eccentric knee flexor contractions at long muscle lengths [93, 94, 120]. It is plausible that the avoidance of eccentrically biased and long length exercises during early HSI rehabilitation may lead to longer term neuromuscular inhibition that contributes to residual BFlh fascicle length and eccentric strength deficits [45].

The aforementioned pressure for accelerated RTP clearance may amplify the consequences of delayed exposure to eccentric loading and long length hamstring exercises during HSI rehabilitation. Under such circumstances, conventional approaches to HSI rehabilitation leave scarce time for exposure to stimulus which can drive positive adaptations to BFlh fascicle length

and eccentric knee flexor strength. Allowing exercises to be performed and progressed up to a pain-threshold has been employed as a safe and effective strategy to increase exposure to rehabilitation stimulus in musculoskeletal conditions of a more chronic nature, such as patellofemoral joint pain and Achilles tendinopathy [114, 115, 118, 124]. However, pain-free rehabilitation is still widely recommended as best clinical practice in the treatment of acute muscle injury [10, 11, 34, 41, 52, 58, 68-71, 75, 78, 112], despite a lack of comparison to alternative approaches.

Aside from the avoidance of pain, it is also typically recommended that acute muscle injury rehabilitation commence with isometric exercises, which are progressed to concentrically biased and finally eccentrically biased exercises [41, 69, 78]. This order of exercise progression has been widely adopted in HSI rehabilitation [52, 58, 75, 79, 83, 84, 105, 112, 133, 134]. However, there is a paucity of evidence beyond clinical experience and expert opinion to support or refute this approach to exercise progression or how and when it is appropriate to progress towards more challenging exercises during HSI rehabilitation.

Cognisant of the aforementioned gaps in the literature, chapter 3 of this thesis provides a systematic review of criteria used to guide HSI rehabilitation progression and the RTP clearance decision. The findings of this systematic review will then further inform experimental studies to follow in chapters 4, 5 and 6 of this thesis. The aims of this thesis are to 1) improve the clinician's ability to objectively monitor knee flexor strength during exercises commonly employed during HSI rehabilitation; 2) outline a HSI rehabilitation protocol implementing exercise-specific progression criteria to emphasise the early introduction of eccentric loading and 3) to determine whether allowing exercise to be performed and progressed up to a pain-threshold is an appropriate alternative to the conventional practice of pain-free rehabilitation following HSI.

#### Chapter 2 – Methodology and design

As per university guidelines, the methods utilised within each study of this thesis are described in their entirety within this second chapter. Subsequently, chapters 3, 4, 5 and 6 contain the specific methods used in studies 1, 2, 3 and 4, respectively, which are presented according to guidelines provided by the journals these manuscripts are either published in or being prepared for submission to.

# **2.1.** Study 1 - Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: A systematic review

## 2.1.1. Study Design

This review is compliant with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [88]. A comprehensive systematic literature search of MEDLINE, CINAHL, SPORTDiscus, Cochrane Library, Web of Science and EMBASE was conducted from inception until July 2015.

## 2.1.2. Search Strategy

The search terms (Table 3.1) aimed to identify muscle group, definition of injury, intervention and outcome. Citation tracking via PubMed was performed to identify any studies published following the original literature search as well as cross checking of reference lists. Studies identified through this search were imported into EndNote software and duplicates were subsequently removed.

## 2.1.3. Study Selection

Titles and abstracts were screened for relevance by the lead author (JH), after which full text assessment was carried out on remaining items by two authors (JH & RT) based on predetermined selection criteria (Table 3.2). Where multiple studies reported on the same data, the study with the greatest number of participants was selected for inclusion. Any disputes were discussed and resolved in consultation with a third author (DO).

# 2.1.4. Study Quality Assessment

Methodological quality was assessed using a modified version of a previously validated checklist (Table 3.3) [33]. Items 5, 8, 14, 15, 20, 21, 23 and 24 were removed due to their lack of applicability across all studies in order to not unfairly favour randomised controlled trials over cohort studies and retrospective investigations. Item 27 relating to sample size calculation and statistical power was altered so one point was awarded if sample size was calculated and a second point if the sample size was subsequently met. An additional two items 28 and 29 were included by the authors to assess method of injury diagnosis and level of control and supervision over rehabilitation.

# 2.1.5. Data extraction

Participant details, each study's method of HSI diagnosis, definition of RTP time, mean RTP time in days and the number of re-injuries following RTP clearance were extracted from each study. Where data were not available or reported as median rather than mean, corresponding authors were contacted for additional information. Both general guidelines and specific criteria for rehabilitation progression and RTP clearance implemented in each study were identified.

Given the wide range of specific RTP criteria, these were subsequently categorised as either clinical assessments, which are typically implemented in regular practice, or performance tests which assess the athlete's ability to complete sports-specific movements and tasks. In addition, isokinetic dynamometry and the Askling H-test were considered in their own separate categories, as they require specialised laboratory based equipment, are not typically implemented in regular clinical practice, or have only been described in the literature recently [9].

# 2.1.6. Statistical analysis

Where individual studies reported mean RTP times and re-injuries within different intervention groups, but implemented identical rehabilitation progression and RTP criteria across interventions, the mean RTP times and overall re-injury rates for these studies were calculated. These means were used in order to investigate subsequent RTP times and re-injury rates, independent of differences between interventions within studies.

Mean RTP times for these studies were calculated using the "weighted.mean" function in R [122]. Weights were chosen as the inverse of the estimated variance in RTP time for each

intervention. Overall rate of re-injury was calculated by dividing the total number of re-injuries by the total number of participants who completed re-injury follow-up in each individual study and expressing this quotient as a percentage. These results along with the categories of RTP criteria implemented by each study were then plotted in a figure created using the "ggplot2" package [145] in R [122].

#### 2.1.7. Primary outcome

The primary outcome of this systematic review was the mean RTP time and overall rate of reinjury for each study, in the context of the criteria implemented to progress through stages of rehabilitation and determine RTP clearance.

# 2.2 Study 2 - A novel apparatus measuring knee flexor strength during various hamstring exercises: A reliability and retrospective injury study

#### 2.2.1. Study design

Reliability and case-control injury study.

#### 2.2.2. Participants

Twenty male participants with no history of HSI were included in the control group and ten male participants with a history of at least one unilateral HSI within the past 18 months were included in the previous HSI group. Participants in both groups were recreationally active, participating in physical activity twice per week as a minimum. Following ethical approval granted by the Australian Catholic University Human Research Committee (2015-253H), all participants provided written informed consent prior to commencing testing. Injury history was obtained during a subjective interview conducted by a health professional (JH) with four year's clinical experience in musculoskeletal injury assessment and rehabilitation. Previous HSI was defined as acute onset posterior thigh pain resulting from a typical mechanism of HSI (i.e. high speed running, acceleration, deceleration, etc.), causing immediate cessation of activity and at least seven days absence from regular activity participation [120]. At the time of testing, all participants with a prior HSI had subsequently returned to their normal level of activity and both groups were free from any current lower limb or lumbo-pelvic pain or injury.

#### **2.2.3. Data collection**

Participants in the control group attended the Australian Catholic University research laboratory on three occasions, whilst the previous HSI group attended on two occasions. Each visit was separated by seven days and lasted approximately 45 to 60 minutes. All visits consisted of isometric knee flexor contractions at three different hip/knee joint angles (0/0, 45/45 and 90/90 degrees), as well as bilateral and unilateral variations of the eccentric slider and hamstring bridge exercises. All of these measures were performed in a novel apparatus consisting of two adjustable ratchet straps hanging in parallel from a power cage, with a wired load cell (MLP-750, Transducer Techniques, Temecula CA, USA) and heel strap attached in series with each (Figure 4.1). All load cell data was sampled at 2000Hz and transferred to a laptop computer via an analogue input data acquisition card (NI9237, National Instruments, Austin TX, USA) and monitored via a custom written software visual interface (LabVIEW 2013 National Instruments, Austin TX, USA). Offline analysis of all data was later performed using custom written code in R [122] version 3.2.4.

#### 2.2.4. Isometric knee flexor contractions

Isometric knee flexor contractions were performed at 0/0, 45/45 and 90/90 degrees of hip/knee flexion while participants were supine on a plinth placed at the end of the apparatus, with an additional strap used to secure participant's pelvis to the plinth (Figure 4.2). In each position participants performed two submaximal repetitions at 50% and then 75% of perceived maximum, followed by three maximal repetitions of three to five seconds duration, with a minimum 30 seconds rest between each. Standardised instructions were given to "push your heel down into the strap, without countermovement, as fast and hard as you can, in three, two, one, go" with strong verbal encouragement provided to ensure maximal effort. Testing position and leg order was randomised for each participant during their first visit, with this order maintained for subsequent sessions and for unilateral variations of the eccentric slider and hamstring bridge

Data for all isometric knee flexor contractions were corrected for leg weight, calculated as the resting force output collected prior to each repetition. Isometric knee flexor strength was defined as the highest recorded force output across the three repetitions for each leg, at each of the three testing positions. In addition to this, peak RFD defined as the greatest increase in force over a

rolling 200ms window, from contraction onset (increase in resting force  $\geq$  4N), until the time point where peak force was achieved. Peak RFD over a 200ms window was selected as this has previously been shown to be more reliable than alternative methodologies [77, 85]. In order to identify contraction onset, the data was low pass filtered (10Hz) using a zero-lag fourth order Butterworth filter. To reduce the chance of countermovement influencing RFD, [77] repetitions with a decrease in resting force  $\geq$  4N in the 200ms prior to contraction onset were removed from analysis. Identification and removal of repetitions with a countermovement was done in a systematic fashion using custom written code in R [122] to reduce risk of subjective bias. Of the remaining repetitions, the single repetition with the greatest peak RFD (N/s) for each leg in each position was used for later analysis.

#### 2.2.5. Eccentric slider and hamstring bridge

Prior to commencing the eccentric slider and hamstring bridge, leg weight was calculated as the resting force output of each leg independently, with participants laying supine on the plinth, arms across their chest and heels resting in the straps of the apparatus, ensuring 0/0 degrees of hip/knee flexion (Figure 4.3a). From the position used to ascertain resting leg weight, participants got into the starting position for the eccentric slider by flexing their knees (Figure 4.3b), then lifting their hips up from the plinth creating a straight line from shoulders to knees (Figure 4.3c).

For the bilateral variation, on the "go" command, participants extended both knees as slowly as possible using their knee flexors to control the movement, keeping hips elevated (Figure 4.3d-f). The unilateral variation was performed in the same way, except on the "go" command, participants lifted the contralateral leg so that active force was only being applied through the heel of the leg being assessed (Figure 4.3g-i). A repetition was deemed complete when full knee extension was reached or when hip extension could not be maintained. Three repetitions of the bilateral and unilateral eccentric slider on each leg were performed by all participants following practice repetitions. The tester (JH) had to be satisfied with technique prior to allowing participants to progress to test repetitions.

The bilateral hamstring bridge was performed from 45/45 degrees of hip/knee flexion, with

participants lifting their hips from the plinth until they achieved a straight line from their shoulders to knees, before returning to the starting position (Figure 4.4a-c). The unilateral variation was performed in the same way except that the leg not being assessed was held out of the strap at approximately 90/90 degrees of hip/knee flexion (Figure 4.4d-f). Speed of each repetition was controlled by a metronome to ensure approximately a three second up (concentric) and three second down (eccentric) phase. Three repetitions of the bilateral and unilateral hamstring bridge on each leg were performed by all participants following practice repetitions. The tester (JH) had to be satisfied with technique prior to allowing participants to progress to test repetitions.

Following correction for resting leg weight, area under the force time curve from the start to end of each eccentric slider and hamstring bridge repetition was defined as force impulse normalised to each participant's body mass (N.s/kg). The start of a bilateral eccentric slider repetition was defined as the first collected data point which coincided with the "go" command, whereas the start of a unilateral eccentric slider repetition was the point at which force of the contralateral leg dropped below resting leg weight. The start of a hamstring bridge repetition was calculated as the point which force exceeded resting leg weight for the bilateral variation or 2 x resting leg weight for the unilateral variation. The end of a repetition for both the eccentric slider and hamstring bridge was calculated as the point which force dropped below resting leg weight for each leg independently for the bilateral variation and 2 x resting leg weight for the unilateral variation. Force impulse was calculated for each repetition with the average of the three repetitions performed for each exercise variation (termed mean force impulse), used for later analysis. It is important to note that the measure of mean force impulse involved the combination of the concentric slider, only the eccentric phases for the hamstring bridge, whereas for the eccentric slider, only

# 2.2.6. Statistical analysis

To determine test re-test reliability, descriptive statistics for all measures from the dominant and non-dominant legs of the control group across three visits were screened for normal distribution, using the Shapiro-Wilk test in SPSS Version 23.0.0.3 (IBM Corporation, Chicago, IL). Intraclass correlation coefficient (ICC), typical error (TE) and typical error as a co-efficient of variation

(%TE) were calculated using a custom spreadsheet, with log-transformed data reported for nonnormally distributed measures [57]. Based on previous studies of similar test re-test reliability data [91, 130], an ICC  $\ge$  0.90 was considered to be high, between 0.80 and 0.89 moderate and  $\le$ 0.79 poor. Minimum detectable change at a 95% confidence interval (MDC<sub>95</sub>) was calculated as TE x 1.96 x  $\sqrt{2}$ .

Within each group, between-leg comparisons were performed using data from the second visit, to account for an anticipated learning effect from visits one to two. The magnitude of between-leg differences were calculated using estimates of effect sizes reported as Cohen's *d* with a  $\pm$  90% confidence interval (CI) using the "effsize" package [132] in R [122]. Cohen's *d* of  $\geq$ 0.8 was considered large;  $\geq$ 0.5 and <0.8 moderate;  $\geq$ 0.2 and <0.5 small, and <0.2 trivial. Where the 90% CI overlapped both the positive ( $\geq$ 0.2) and negative ( $\leq$ -0.2) thresholds of a small effect simultaneously, were defined as unclear [14]. To provide a relative comparison of between-leg differences across all measures, asymmetry was calculated as the non-dominant leg divided by the dominant leg in the control group and the previously injured leg divided by the uninjured leg in the previous HSI group and expressed as a percentage. In the control group, leg dominance was determined by asking participants which leg they prefer to kick a ball with. Due to recently discussed limitations in the selective reporting of p-values [142], these were not calculated as part of primary statistical analysis but can be found in supplementary material.

# 2.3. Studies 3 and 4: Pain-free versus pain-threshold rehabilitation following acute hamstring strain injury: a randomised controlled trial

Studies 3 and 4 were both derived from data collected as part of a randomised controlled trial comparing pain-free and pain-threshold rehabilitation following acute HSI. The overall methodological design and data collection procedures are detailed in full below. Subsequently, chapters 5 and 6 will report the methodology applicable to studies 3 and 4, respectively.

# 2.3.1. Study design

This study was a single-centre, double-blind randomised controlled trial, designed and conducted at the Australian Catholic University in Melbourne, Australia. The Australian Catholic University Human Research Committee (2015-307H) granted ethical approval and the trial was registered with the Australian New Zealand Clinical Trials Registry (ANZCTR12616000307404).

# 2.3.2. Participant recruitment and eligibility

Between February 2016 and May 2017 men and women aged 18 to 40 years were invited to undergo an initial clinical assessment within seven days of suspected acute HSI. Potential participants were recruited via contact made with sporting clubs and sports injury clinics around Melbourne and via social media advertisement. Informed written consent was provided by potential participants prior to undergoing a subjective interview and series of clinical assessments to confirm presence of acute HSI.

Potential participants had to meet all pre-determined eligibility criteria (Table 6.1) [84] to be included in the study. If potential participants presented with signs and symptoms of other causes of posterior thigh pain (hamstring tendinopathy, referred lower back pain etc.) or if the severity of their injury warranted surgical opinion, they were excluded from the study. An independent physiotherapist (ER) with 15 years' experience in sports injury clinical practice and research verified participant eligibility by reviewing relevant subjective interview and clinical assessment data.

# 2.3.3. Randomisation

If eligible, participants were randomly allocated to either a pain-free or pain-threshold rehabilitation group after completion of their initial clinical assessment. A four-block randomisation approach, with stratification for previous HSI and gender was implemented. Four folders marked either 1) male/previous HSI, 2) male/first-time HSI, 3) female/previous HSI or 4) female/first-time HSI, each contained four sealed envelopes, two for both the pain-free and pain-threshold group. The lead investigator (JH) selected an envelope from the relevant folder which indicated either allocation to a pain-free of pain-threshold rehabilitation group. Envelopes were only replaced in their respective folders once all four had been selected.

Participants allocated to the pain-free group were only permitted to perform and progress rehabilitation in the complete absence of pain, rated 0 on a 0-10 numeric rating scale (NRS). In contrast, those in the pain threshold group were permitted to perform and progress rehabilitation in the presence of pain rated  $\leq 4$  on the 0-10 NRS. The 0-10 NRS was explained to all participants in the context of localised pain at the site of injury where 0 represented "absolutely no pain" and 10 was the "worst pain imaginable". Upon allocation, participants were informed only of the pain limits for performance and progression of rehabilitation applicable to their respective group. Participants provided written informed consent prior to commencing their respective rehabilitation protocol.

# 2.3.4. Blinding

All objective outcome measures were collected by members of the research team (DO, NM and RT) who were blinded to group allocation for the duration of the study. In addition, all participants were blinded to the presence of the alternative intervention, to reduce the possibility of cross-group contamination.

#### 2.3.5. Initial subjective interview

Injury details, demographic data and relevant injury history were all ascertained from an initial subjective interview. The subjective interview was conducted by the lead investigator (JH) a health professional with five years' clinical experience in musculoskeletal injury assessment and rehabilitation. Upon completion of the subjective interview, participants were asked to complete the 17 item Tampa Scale for Kinesiphobia (TSK) to assess fear of movement.

#### 2.3.6. Clinical assessments

During each participant's initial visit to confirm presence of acute HSI and prior to each subsequent rehabilitation session, a series of clinical assessments were conducted. These clinical assessments were administered by members of the research team (DO, NM or RT) who were blinded to group allocation. Firstly, ultrasound images were acquired to ascertain biceps femoris long head (BFlh) architecture with participants at rest in a prone position (hips and knees in neutral). The same blinded investigator (RT) with published reliability (ICC = 0.96 to 0.98; %TE = 2.1 to 3.4) and experience [130] collected and later analysed all ultrasound images offline (MicroDicom, Version 0.7.8, Bulgaria). The scanning site was determined as the halfway point

between the ischial tuberosity and knee joint fold, along the line of the BFlh. Images were taken along the longitudinal axis of the BFlh belly on the injured then contralateral uninjured leg utilising a 2-D, B-mode ultrasound (frequency, 12Mhz; depth, 8cm; field of view, 14 x 47mm) (GE Healthcare Vivid-*i*, Wauwatosa, U.S.A).

For each image, six points were digitised as described by Blazevich and colleagues [15], after which muscle thickness (MT) was defined as the distance between the superficial and intermediate aponeurosis of the BFlh. A fascicle of interest, which was the clearest and could be seen across the entire field of view, was then outlined and marked on the image. Pennation angle (PA) was defined as the angle between this fascicle and the intermediate fascicle. Aponeurosis angle (AA) was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal reference line across the captured image. Fascicle length (FL) was determined as the length of the outlined fascicle between the intermediate and superficial aponeurosis and reported in absolute terms (cm). As the entire fascicle was not visible in the field of view, fascicle length was estimated via a validated equation [15].

$$FL = sin (AA + 90^{\circ}) x MT/sin(180^{\circ} - (AA + 180^{\circ} - PA))$$

Participants remained in a prone position where the injured muscle was palpated to determine injury location and pain. The assessor palpated along the length of the injured muscle to identify the location of peak palpation pain. Participants were asked rate their pain on the 0-10 NRS with the peak value was recorded. The distance from the ischial tuberosity to the site of peak palpation pain and the total cranio-caudal length of palpable pain were also measured in centimetres [8, 144].

Hamstring ROM was assessed via the passive straight leg raise (PSLR) [8, 110] and active knee extension (AKE) tests [49, 106]. For both the PSLR and AKE a digital inclinometer was placed on the anterior tibial border just below the tibial tuberosity to objectively measure the angle of hip flexion or knee extension respectively at the point of onset of localised pain or maximal tolerable stretch. Participants were asked to rate their pain on the 0-10 NRS if they experienced localised pain at the site of injury during either the PSLR or AKE tests. Three trials of the PSLR and AKE were performed on the uninjured then injured leg, with the highest ROM value and peak pain score recorded for each test.

Isometric knee flexor strength was assessed with the participant laying supine at 0/0 and 90/90 degrees of hip/knee flexion using a novel apparatus with published reliability, as described in chapter 4 [55]. In each position the uninjured leg was tested prior to the injured leg, with two warm-up repetitions at 50% then 75% of perceived maximal effort followed by three maximal effort isometric knee flexor contractions with a minimum 30 second inter-trial rest. Standardised instructions were given to "push your heel down into the strap, from complete rest without lifting up your heel, as fast and hard as you can, in three, two, one, go" with strong verbal encouragement provided to ensure maximal effort. When performing contractions with the injured leg, the additional instruction of contracting "to an intensity that you feel comfortable with" was given.

Participants were asked to report any pain localised to the site of injury on the 0-10 NRS with the peak pain score recorded in each position. For each day of testing, isometric knee flexor strength at both 0/0 and 90/90 was defined as the highest recorded force output across the three repetitions for each leg, at each position. Isometric knee flexor strength of the injured leg was reported in percentage terms, relative the participant's contralateral uninjured leg at initial clinical assessment.

#### **2.3.7. Rehabilitation protocol**

All participants performed a progressive rehabilitation protocol twice per week, fully supervised by the lead investigator (JH). The rehabilitation protocol included moderate to long length hip dominant exercises with a concentric and eccentric phase and short to moderate length knee dominant exercises which were eccentrically biased. Hip dominant exercises included a hamstring bridge (Figure 5.1) and 45° hip extension (Figure 5.2) and knee dominant exercises included an eccentric slider (Figure 5.3) and Nordic hamstring exercise (NHE) (Figure 5.4).

The bilateral hamstring bridge and 45° hip extension were both progressed to unilateral variations. The bilateral eccentric slider was progressed to both a unilateral variation and the NHE, defined as the introduction of eccentric loading. The NHE was introduced at this time point as the bilateral eccentric slider replicated the knee dominant, eccentric only action of the NHE at a submaximal intensity. Knee flexor force output of the injured and uninjured legs were

objectively measured during performance of both eccentric slider variations and the NHE using custom-built, externally-fixed dynamometry with published reliability [55, 91].

A total of three sets of each type of exercise (hamstring bridge,  $45^{\circ}$  hip extension, eccentric slider and NHE) were permitted to be performed each rehabilitation session. For example, if progression criteria were met for the bilateral hamstring bridge after the first set, a further two sets could be performed unilaterally within that rehabilitation session. Once exercises were progressed to unilateral variations, they were performed by both the injured and uninjured legs.

Rehabilitation commenced immediately following the initial clinical assessment, with all participants attempting bilateral variations of the hamstring bridge,  $45^{\circ}$  hip extension and eccentric slider. Participants were asked to rate any localised pain at the site of injury according to the 0-10 NRS during performance of each exercise, with technique and range of motion closely monitored by the lead investigator. Each exercise was progressed based on three criteria (Figure 5.5), if the participant could perform the exercise 1) through full range of motion, 2) for the prescribed repetition range and 3) within their group's pain limits. Successful completion of each exercise was defined as meeting all three of these criteria.

Pre-determined criteria (Table 6.3) were implemented to provide RTP clearance, which were identical for all participants and based on best available evidence [5, 136]. At the completion of the rehabilitation session where all RTP clearance criteria were met, participants repeated the TSK to assess fear of movement. The lead investigator (JH) provided the same standard recommendation to all participants, that they should complete at least two full on field training sessions prior to returning to competitive sport. However, the final decision to return to competitive sport was left to the participant and where relevant, coach and medical staff at their sporting club. This approach to return to competitive sport was implemented to account for variation in sports, levels of competition and need for shared RTP decision making [5, 27, 113]. All participants were provided with the same general advice to try and continue with one hip dominant and one knee dominant rehabilitation exercise at least once per week, although compliance was not enforced or monitored.

#### 2.3.8. Follow-up

Following RTP clearance, participants were contacted at least once per month, for a six month period to monitor for re-injury. Participants were instructed to contact the lead investigator if they suspected re-injury, with all attempts made to confirm presence of acute HSI via clinical assessment. However, if this was not possible re-injury was confirmed via telephone conversation with the participant and communication with relevant contacts at the participant's sporting club such as a team physiotherapist. All suspected re-injuries were verified by an independent physiotherapist (ER) who was blinded to group allocation and was provided with all available objective and subjective information.

As close to two months following RTP clearance as possible, all participants, except those who had to that point suffered a re-injury, were requested to attend a follow-up assessment. This assessment was conducted entirely by the same blinded assessor (RT, DO or NM) as during rehabilitation, with BFlh muscle architecture, isometric knee flexor strength and the TSK assessed as previously described. In addition, eccentric knee flexor strength was assessed during performance of the unilateral eccentric slider and NHE. For the unilateral eccentric slider, mean force impulse was measured across three repetitions on the uninjured then previously injured leg and normalised to body weight (N.s/kg), as described in chapter 4 using an apparatus with published reliability [55]. For the NHE, the average of peak force (N) was calculated for the left and right legs independently across three maximal effort repetitions using a device with published reliability [91]. Mean force impulse during the unilateral slider and average peak force during the NHE were reported in both absolute terms for the previously injured leg and relative to the contralateral uninjured leg.

Chapter 3 – Literature review and study 1: Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: A systematic review

Publication statement:

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#### **3.1. ABSTRACT**

**Background:** Rehabilitation progression and return to play (RTP) decision making following hamstring strain injury (HSI) can be challenging for clinicians, due to the competing demands of reducing both convalescence and risk of re-injury. Despite increased focus on the RTP process following HSI, little attention has been paid to rehabilitation progression and RTP criteria, and subsequent time taken to RTP and re-injury rates.

**Objective:** The aim of this systematic review is to identify rehabilitation progression and RTP criteria implemented following HSI and examine subsequent time taken to RTP and rates of re-injury.

**Methods:** A systematic literature review of databases MEDLINE, CINAHL, SPORTDiscus, Cochrane Library, Web of Science and EMBASE was conducted to identify studies of participants with acute HSI reporting time taken to RTP and rates of re-injury after a minimum six-month follow-up. General guidelines and specific criteria for rehabilitation progression were identified for each study. In addition RTP criteria were identified and categorised as performance tests, clinical assessments, isokinetic dynamometry or the Askling H-test.

**Results:** Nine articles were included with a total of 601 acute HSI confirmed by clinical examination or magnetic resonance imaging within ten days of initial injury. A feature across all nine studies was that the injured individual's perception of pain was used to guide rehabilitation progression, whilst clinical assessments and performance tests were the most frequently implemented RTP criteria. Mean RTP times were lowest in studies implementing isokinetic dynamometry as part of RTP decision making (12 to 25 days) whilst those implementing the Askling H-test had the lowest rates of re-injury (1.3 to 3.6%).

**Conclusions:** This systematic review highlights the strong emphasis placed on the alleviation of pain to allow HSI rehabilitation progression, and the reliance on highly subjective clinical assessments and performance tests as RTP criteria. These results suggest a need for more objective and clinically practical criteria, allowing a more evidence based approach to rehabilitation progression, and potentially reducing the ambiguity involved in the RTP decision making process.
#### **3.2. INTRODUCTION**

Hamstring strain injury (HSI) is the most prevalent cause of time lost from competition in sports involving high speed running [38, 40, 90, 99, 147]. Individuals with a previous HSI often exhibit deficits in hamstring muscle structure and function, well after completing rehabilitation and being cleared to return to play (RTP) [81, 91, 93, 94, 116, 130]. Regardless of whether these deficits were a result or cause of injury, they suggest current rehabilitation and RTP practices may be inadequate to address these, potentially explaining the elevated risk of re-injury in those with a history of HSI [19, 43, 92]. In elite sport environments, financial [54] and performance [48] consequences of athletes remaining on the sidelines due to injury may modify the decision to progress rehabilitation and ultimately provide clearance to RTP [27, 97, 113]. As a result, clinicians may have reduced authority over such decisions [27, 113], potentially explaining the aforementioned residual deficits in hamstring muscle structure and function [81, 91, 93, 94, 116, 130].

From a clinician's perspective, progression through stages of HSI rehabilitation (eg. from acute to end stage) can be based on pathophysiological time-frames for healing tissue [34, 41, 66-69, 75, 78, 100] or specific criteria [32, 52, 83, 109, 112, 131, 134]. Whilst time-frames for the physiological healing of muscle injury exist, much of this evidence is based on experimental animal models [47, 65, 66, 68, 69] and it remains unknown if these models are relevant to guide rehabilitation progression in humans. More recently, criteria-based rehabilitation progressions have gained popularity [32, 83, 109, 112, 131, 134], as this approach is more individualised than relying on time-frames for healing alone. Despite this recent interest, specific criteria to progress through stages of HSI rehabilitation have not been examined rigorously.

In contrast, criteria to determine RTP clearance following HSI have received much greater attention [5, 9, 26, 31, 42, 83, 97, 98, 134], including a recent systematic review [136] which reported that RTP criteria for HSI have little evidence base. That systematic review [136], however, did not investigate time taken to achieve RTP clearance and rates of re-injury for studies implementing different criteria. It could be argued that implementing different rehabilitation progression and RTP criteria would result in altered RTP times and risk of subsequent re-injury, and investigation of this could help clinicians make evidence based decisions. It is, therefore, the aim of this systematic review to identify and discuss the rationale

for criteria to determine both rehabilitation progression and RTP clearance following HSI and investigate subsequent time taken to RTP and rates of re-injury.

#### **3.3. METHODS**

#### Study design

This review is compliant with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines[88]. A comprehensive systematic literature search of MEDLINE, CINAHL, SPORTDiscus, Cochrane Library, Web of Science and EMBASE was conducted from inception until July 2015.

#### Search strategy

The search terms (Table 3.1) aimed to identify muscle group, definition of injury, intervention and outcome. Citation tracking via PubMed was performed to identify any studies published following the original literature search as well as cross checking of reference lists. Studies identified through this search were imported into EndNote software and duplicates were subsequently removed.

#### **Study selection**

Titles and abstracts were screened for relevance by the lead author (JH), after which full text assessment was carried out on remaining items by two authors (JH & RT) based on predetermined selection criteria (Table 3.2). Where multiple studies reported on the same data, the study with the greatest number of participants was selected for inclusion. Any disputes were discussed and resolved in consultation with a third author (DO).

#### Study quality assessment

Methodological quality was assessed using a modified version of a previously validated checklist (Table 3.3) [33]. Items 5, 8, 14, 15, 20, 21, 23 and 24 were removed due to their lack of applicability across all studies in order to not unfairly favour randomised controlled trials over cohort studies and retrospective investigations. Item 27 relating to sample size calculation and statistical power was altered so one point was awarded if sample size was calculated and a second point if the sample size was subsequently met. An additional two items 28 and 29 were

included by the authors to assess method of injury diagnosis and level of control and supervision over rehabilitation.

Muscle group	Definition of	Intervention	Outcome
	injury		
Hamstring	Strain	Rehab*	Return*
"Posterior thigh"	Injur*	Conserv*	Resum*
"Biceps femoris"	Tear*	Treat*	Time
Semimembranosus	Rupture	Intervention*	Train*
Semitendinosus	Pain*	Therap*	Participat*
	Dysfunction	Manag*	Recurr*
	Trauma*	Clinical*	Re-inj*
		Criteri*	Reinj*
		Progress*	Re-occur*
			Reoccur*
			Outcome*
			Sport*
			Function*
			Convalescen*
			Recover*

**Table 3.1** Summary of keyword grouping employed during database searches.

Boolean term OR was used within categories; AND was used between categories.

\* denotes truncation.

Inclusion criteria	Exclusion criteria
Participants with acute hamstring strain	Participants with complete hamstring
injury diagnosed within 10 days of initial	muscle ruptures (grade 3), avulsion
injury by either clinical examination or	injuries and hamstring tendinopathy
magnetic resonance imaging	
Studies that clearly describe rehabilitation	Studies involving surgical interventions
progression and return to play criteria	
Studies reporting time taken to return to	Individual case studies
play	
Studies reporting rates of re-injury with a	
minimum six-month follow-up period	

 Table 3.2 Criteria for inclusion and exclusion in the systematic review.

Category	Item	Question
Reporting	1	Was the hypothesis/aim/objective of the study clearly described?
	2	Were the main outcomes to be measured clearly described in the introduction or methods section?
	3	Were the characteristics of the patients included in the study clearly described?
	4	Were the interventions of interest clearly described?
	6	Were the main findings of the study clearly described?
	7	Did the study provide estimates of the random variability in the data for the main outcomes?
	9	Were the characteristics of patients lost to follow up been described?
	10	Were actual probability values been reported for main outcomes except where the probability value is less than 0.001?
External validity	11	Were the subjects asked to participate in the study representative of the entire population from which they were recruited?
	12	Were those subjects who were prepared to participate representative of the entire population from which they were recruited?
	13	Were the staff, places and facilities where the patients were treated representative of the treatment the majority of patients receive?
Internal validity (bias)	16	If any of the results of the study were based on "data dredging" was this made clear?
	17	In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case- control studies, was the time period between the intervention and outcome the same for cases and controls?
	18	Were the statistical tests used to assess the main outcomes appropriate?
	19	Was compliance with the intervention reliable?
Internal validity (Confounding)	22	Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?
	25	Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?
	26	Were losses of patients to follow-up taken into account?
Power	$27^{a}$	Did the study have a calculation of power and was this met?
Additional internal validity (bias)	28 <sup>b</sup>	Was diagnosis of acute hamstring strain appropriate?
Additional internal validity (confounding)	29 <sup>b</sup>	Was rehabilitation controlled and supervised by the authors at least once per week?

 Table 3.3 Study quality assessment checklist modified from Downs and Black [33].

<sup>a</sup>Modified items; <sup>b</sup>Additional items

# **Data extraction**

Participant details, each study's method of HSI diagnosis, definition of RTP time, mean RTP time in days and the number of re-injuries following RTP clearance were extracted from each study. Where data were not available or reported as median rather than mean, corresponding authors were contacted for additional information. Both general guidelines and specific criteria for rehabilitation progression and RTP clearance implemented in each study were identified.

Given the wide range of specific RTP criteria, these were subsequently categorised as either clinical assessments, which are typically implemented in regular practice, or performance tests which assess the athlete's ability to complete sports-specific movements and tasks. In addition, isokinetic dynamometry and the Askling H-test were considered in their own separate categories, as they require specialised laboratory based equipment, are not typically implemented in regular clinical practice, or have only been described in the literature recently [9].

# Statistical analysis

Where individual studies reported mean RTP times and re-injuries within different intervention groups, but implemented identical rehabilitation progression and RTP criteria across interventions, the mean RTP times and overall re-injury rates for these studies were calculated. These means were used in order to investigate subsequent RTP times and re-injury rates, independent of differences between interventions within studies.

Mean RTP times for these studies were calculated using the "weighted.mean" function in R [122]. Weights were chosen as the inverse of the estimated variance in RTP time for each intervention. Overall rate of re-injury was calculated by dividing the total number of re-injuries by the total number of participants who completed re-injury follow-up in each individual study and expressing this quotient as a percentage. These results along with the categories of RTP criteria implemented by each study were then plotted in a figure created using the "ggplot2" package [145] in R [122].

# **Primary outcome**

The primary outcome of this systematic review was the mean RTP time and overall rate of reinjury for each study, in the context of the criteria implemented to progress through stages of rehabilitation and determine RTP clearance.

# **3.4. RESULTS**

# Literature search

The literature search consisted of five steps (Figure 3.1). Following full text assessment, ten studies met the eligibility criteria, however, two of these studies reported on the same data set from a large-scale intervention [30, 105]. One study analysed a smaller subset of the data that performed follow-up testing post RTP clearance [30], therefore only the study with greater participant numbers [105] was included in the review.



Figure 3.1 PRISMA flowchart outlining study selection process.

# Study quality assessment

Study quality ranged from 10 [73] to 18 [50] out of a possible score of 22, with a mean ( $\pm$  SD) score of 14.4 ( $\pm$  2.2). Full quality assessment results for each study are detailed in Table 3.4.

Reference	1	2	3	4	6	7	9	10	11	12	13	16	17	18	19	22	25	26	27	28	29	Total	%
Askling et al. [10]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	1	0	1	1	15	68
Askling et al. [11]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	1	0	1	1	15	68
Hamilton et al. [50]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	2	1	1	18	82
Kilcoyne et al. [73]	0	1	0	1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	10	45
Malliaropoulos et al.	1	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0	0	1	13	59
[79]																							
Reurink et al. [105]	1	1	1	1	1	1	0	1	0	0	0	1	1	1	0	1	0	1	2	1	0	15	68
Sherry and Best [111]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	1	1	0	0	1	15	68
Silder et al. [117]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	1	0	1	16	72
Verrall et al. [139]	1	1	1	1	1	1	1	0	0	0	0	1	0	1	0	1	1	1	0	1	0	13	59

Table 3.4 Results of itemised scoring of study quality using a modified quality assessment checklist<sup>a</sup>.

<sup>a</sup>See Table 3.3 for questions relating to the listed items.

#### Participant and study details

A total of 601 participants with an acute HSI diagnosed by either clinical examination, magnetic resonance imaging (MRI), or a combination of both within 10 days of initial injury were recruited across the included studies. These participants included a mixture of males (80.6%) and females (19.4%) participating in sports at professional, collegiate and recreational levels. Definitions of RTP time included the number of days from injury until participation in full training or availability for competition [10, 11, 105, 139], completion of rehabilitation protocol and clearance from treating sports medicine physician [50] or meeting RTP criteria [73, 79, 111, 117] as detailed in Table 3.7. Further details of participants and studies included are seen in Table 3.5.

#### Rehabilitation progression guidelines and criteria

Progression of rehabilitation exercises was only allowed within pain-free limits in six studies [10, 11, 50, 105, 117, 139], whilst one allowed up to 1-2 out of 10 pain during their running rehabilitation protocol [73]. Five studies [50, 79, 105, 111, 117] implemented specific criteria-based progressions through stages of rehabilitation, with the alleviation of pain during walking [79, 105, 111, 117], pain-free manual assessment of isometric knee flexor strength [105, 117] and pain-free normal jogging [105, 117] most common. Further details of rehabilitation progression guidelines and criteria are shown in Table 3.6.

# **RTP** criteria

A wide range of specific RTP criteria were identified across the nine included studies with painfree sprinting [73, 105, 111, 117], manual assessment of isometric knee flexor strength [10, 11, 111, 117], range of motion (ROM) tests [10, 11, 79, 105] and pain-free palpation of the injury site [10, 11, 111, 117] most common. Clinical assessments and performance tests were the most widely implemented categories of RTP criteria, used by eight [10, 11, 50, 79, 105, 111, 117, 139] and seven [50, 73, 79, 105, 111, 117, 139] of the included studies, respectively.

Four studies implemented a combination of clinical assessments and performance tests as their criteria for RTP clearance [105, 111, 117, 139]. In addition to performance tests [73] or a combination of clinical assessments and performance tests [50, 79], three studies implemented isokinetic dynamometry as part of RTP decision making [50, 73, 79]. Finally, two studies

implemented the Askling H-test as RTP criteria once no signs or symptoms of HSI were present during clinical assessments [10, 11]. Further details of the specific RTP criteria included within each of these categories can be seen in Table 3.7.

**Table 3.5** Participant and study details.

Reference	Participants	Population	Diagnosis	Re-injury follow-up
	(% male)			period
Askling et al. [10]	56 (68%)	Elite Swedish sprinters and jumpers	CE and MRI $\leq$ 5 days of injury	12 months
Askling et al. [11]	75 (92%)	Elite Swedish footballers	CE and MRI $\leq$ 5 days of injury	12 months
Hamilton et al. [50]	90 (100%)	Athletes from a range of sports at	CE and MRI $\leq$ 5 days of injury	6 months
		professional or competitive level		
Kilcoyne et al. [73]	48 (83%)	Athletes from a range of sports	$CE \le 24$ hours of injury	6 months
		competing at Division 1 collegiate		
		level		
Malliaropoulos et al.	165 (59%)	Elite track and field athletes	CE and US $\leq$ 48 hours of injury	24 months
[79]				
Reurink et al. [105]	80 (95%)	Athletes from a range of sports	CE and MRI $\leq$ 5 days of injury	12 months
		competing at recreational or		
		competitive level		
Sherry and Best	28 (75%)	Athletes from a range of sports	$CE \le 10$ days of injury	12 months
[111]				
Silder et al. [117]	29 (79%)	Athletes from a range of sports	CE and MRI $\leq 10$ days of injury	12 months
		involving high speed running		
Verrall et al. [139]	30 (100%)	Elite Australian Rules footballers	CE and MRI between 2 and 6 days of	Same and following
			injury	playing season

CE = clinical examination, MRI = magnetic resonance imaging and US = ultrasound

Ge	eneral gu	idelines	Specific criteria for progression through stages of rehabilitation									
Reference	Within	Within	Pain-	Pain-	Full knee	Pain-	Pain-free	Pain-free	Pain-free	Run at 70%	Pain-free	Pain-free
	pain-	limits of	free	free	extension	free	normal	ROM or	normal	perceived	submaximal	change of
	free	1-2/10 pain	single	bike at	in supine	high	walking	>75% of	jog	maximum	then full	direction
	limits	(no sharp	leg	150W		knee	gait	uninjured		speed	isometric	and 100%
		pain)	squat	for		march		side			knee flexor	speed run
				5mins							strength	
											assessed	
											manually	
Askling et al. [10]	$\checkmark$											
Askling et al. [11]	$\checkmark$											
Hamilton et al. [50]	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$		$\checkmark$		$\checkmark$
Kilcoyne et al. [73]		$\checkmark$										
Malliaropoulos et al.							$\checkmark$	$\checkmark$				
[79]												
Reurink et al. [105]	$\checkmark$						$\checkmark$		$\checkmark$		$\checkmark$	
Sherry and Best						$\checkmark$	$\checkmark$					
[111]												
Silder et al. [117]	$\checkmark$						$\checkmark$		$\checkmark$		$\checkmark$	
Verrall et al. [139]	$\checkmark$											
Total	6	1	1	1	1	1	4	2	2	1	2	1

**Table 3.6** General rehabilitation progression guidelines and specific criteria to progress through stages of rehabilitation.

ROM = range of motion.

	Clinical assessments			Perform	ance tests			Isokinet	Askling			
												H-test
Reference	Manual	Pain-free	ROM	"Normal"	Pain-free	Pain-free	Pain-free	"Equal"	Isokinetic	Results of	Perceived	No pain or
	assessment	palpation	tests	clinical	and	and	full	single-	strength	isokinetic	equal	insecurity
	of isometric	of injury		assessment	subjective	subjective	training	leg triple	difference	strength test	between	during
	knee flexor	site		(details of	readiness	readiness		hop for	$\leq$ 5% at	considered	limb	ballistic hip
	strength			assessment	following	following		distance	60 and		isokinetic	flexion with
				not	sprinting	agility tests			180°/s		strength	full knee
				reported)		or sports						extension in
						specific						supine
						movements						
Askling et al. [10]	$\checkmark$	$\checkmark$	$\checkmark$									$\checkmark$
Askling et al. [11]	$\checkmark$	$\checkmark$	$\checkmark$									$\checkmark$
Hamilton et al. [50]				$\checkmark$		$\checkmark$				$\checkmark$		
Kilcoyne et al. [73]					$\checkmark$						$\checkmark$	
Malliaropoulos et al.			$\checkmark$					$\checkmark$	$\checkmark$			
[79]												
Reurink et al. [105]			$\checkmark$		$\checkmark$	$\checkmark$						
Sherry and Best	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$						
[111]												
Silder et al. [117]	$\checkmark$	$\checkmark$			$\checkmark$							
Verrall et al. [139]				$\checkmark$			$\checkmark$					
Total	4	4	4	2	4	3	1	1	1	1	1	2

**Table 3.7** Specific criteria for return to play (RTP) within each category.

ROM = range of motion.

#### **RTP** times and re-injury rates

In the four studies implementing a combination of clinical assessments and performance tests as RTP criteria, mean RTP times and re-injury rates were 23 days and 34.8% [111], 26 days and 9.1% [117], 27 days and 63.3% [139] and 45 days and 34.8% [105]. Mean RTP times and rates of re-injury in the three studies implementing isokinetic dynamometry as part of RTP decision making were 12 days and 6.25% [73], 15 days and 13.9% [79] and 25 days and 9.6% [50]. In the two studies implementing the Askling H-test as RTP criteria, mean time taken to RTP and rates of re-injury were 63 days and 3.6% [10] and 36 days and 1.3% [11]. Figure 3.2 shows each study's mean RTP time, rate of re-injury and indicates the combination of RTP criteria implemented in each of these studies.



**Figure 3.2** Overall re-injury rate and mean return to play (RTP) time for each of the included studies. Mean time taken to RTP and overall rates of re-injury for each study are plotted on the x and y axis respectively. The combination of RTP criteria implemented by each study is indicated by the shape of the data point as per the key in the top right hand corner of the figure.

#### **3.5. DISCUSSION**

#### **Statement of main findings**

The main findings of this systematic review are i) progression of HSI rehabilitation is largely based around the injured individual's perception of pain and typically only allowed within pain-free limits; ii) the most commonly implemented RTP criteria, performance tests and clinical assessments, are generally based on either the injured individual's perception of pain, or a clinician's subjective interpretation, such as manually resisted strength testing; iii) studies implementing the Askling H-test had lower rates of re-injury but prolonged RTP times and iv) studies implementing isokinetic dynamometry had faster mean RTP times compared to studies implementing a combination of clinical assessments and performance tests as RTP criteria.

#### Rehabilitation progression guidelines and criteria

In all included studies the injured individual's perception of pain was used to guide rehabilitation progression to some extent, either through general progression guidelines [10, 11, 50, 73, 105, 117, 139] or specific criteria to advance through stages of rehabilitation [50, 79, 105, 111, 117]. With the exception of one study [73], which was of the lowest methodological quality, rehabilitation was kept completely pain-free, consistent with conventional clinical practice and guidelines for the treatment of muscle injury [26, 32, 34, 41, 52, 69, 78, 100, 109, 112, 134]. However, as acknowledged in some of these articles [41, 69, 78, 100], such guidelines lack a solid scientific basis, and the efficacy of remaining completely pain-free during HSI rehabilitation has never been scientifically investigated.

Specific criteria for rehabilitation progression, such as the alleviation of pain during isometric knee flexor contraction, also reflect the aforementioned treatment guidelines, which advise that isometric muscle contractions should be pain-free prior to implementing concentric before eccentric exercises [34, 41, 69, 75, 78, 100]. As mentioned above, such guidelines lack empirical evidence, leaving the possibility that this approach may unnecessarily delay and reduce exposure to eccentric exercise. This is of critical importance, as eccentric knee flexor exercise reduces HSI risk [6, 7, 102, 135], likely due to improving known risk factors such as eccentric hamstring strength [29, 96] and muscle fascicle length [128, 129]. A potential lack of exposure to eccentric exercise during rehabilitation may partly explain residual deficits in such variables seen in those

with a previous HSI [93, 130], potentially contributing to elevated risk of re-injury in this population [43, 92].

#### **RTP criteria**

The RTP decision was also heavily weighted to the resolution of signs and symptoms of HSI during performance tests and clinical assessments, consistent with recently published work [31, 136]. Being able to sprint and perform sports specific movements without pain is a logical milestone prior to RTP clearance; however, these performance tests do not directly assess any know risk factors for HSI. Therefore, although such performance tests should be included to indicate readiness to RTP, they do not necessarily provide any information as to the subsequent risk of re-injury [51].

Clinical assessments were frequently implemented as both rehabilitation progression and RTP criteria, and these have been shown to provide a relatively time and cost effective indicator of recovery from HSI [8, 59, 81]. However, the subjective nature of clinical assessments implemented by the studies in this review, such as manual muscle testing, lack reliability and sensitivity in detecting deficits in strength [16, 140]. The use of more objective measures of isometric strength, such as hand-held and externally fixed dynamometry has been shown to provide a more reliable guide to clinical recovery and may indicate risk of re-injury [8, 30]. In addition to isometric strength testing, the implementation of ROM tests may also provide a good guide to clinical recovery [81] and indicate increased risk of re-injury [30].

Compared to the prevalence of performance tests and clinical assessments, isokinetic dynamometry was only implemented as RTP criteria in three of the included studies [50, 73, 79]. The high cost, lab-based nature and technical requirements of this methodology, likely explain its low rate of implementation. Whilst potentially providing a more objective measure than manual strength assessment, the ability of isokinetic dynamometry to assess risk of initial and recurrent HSI at the individual level has been shown to be limited [131, 137].

A more recent and less frequently implemented criterion for RTP was the Askling H-test, which provides an assessment of the athlete's ability to tolerate dynamic lengthening of the hamstring muscles without pain or apprehension [9]. The H-test has been shown to be both reliable and

sensitive to detect differences in active ROM in athletes recovering from HSI [9] and can also potentially be implemented with relatively little and inexpensive equipment.

#### Rehabilitation progression and RTP criteria and subsequent RTP times and re-injury rates

It has been established that RTP times and re-injury rates following HSI are influenced by a multitude of factors such as injury type/severity [8, 24, 103] and mode of rehabilitation [10, 11, 101, 111]. The current systematic review, for the first time, provides data related to the implementation of different rehabilitation progression and RTP criteria and subsequent RTP times and re-injury rates.

The combination of the Askling H-test and clinical assessments as RTP criteria appears to be associated with the lowest risk of re-injury [10, 11]. These findings do require further validation, as the H-test has only been implemented in two studies by the same author, who is also credited with developing the assessment. These studies also demonstrated extended mean RTP times, which may be seen as too conservative in an elite sport environment, where non-medical decision modifiers often mean accepting an increased risk of re-injury instead of missing an important game [27, 48, 54, 97, 113, 138]. By comparison, studies implementing a combination of clinical assessments and performance tests were generally associated with shorter mean RTP times but increased rates of re-injury of up to nearly two thirds of participants [139]. However, it should be noted that of these studies, the study with the highest re-injury rate [139] was of low methodological quality and rehabilitation was not fully controlled by the investigators.

Despite this apparent trade-off between RTP times and re-injury rates, the implementation of isokinetic dynamometry as part of RTP criteria appears to be associated with a more desirable balance between these variables. Reduced rates of re-injury may be due to the fact that isokinetic dynamometry provides a more objective measure of eccentric knee flexor strength which is a known risk factor for HSI [29, 96]. Unfortunately, the aforementioned limitations of isokinetic dynamometry (see section 4.3), reduce the practicality of its implementation, highlighting the need to develop and implement more clinically practical and objective measures of variables such as eccentric hamstring strength.

The improved balance between RTP time and re-injury rates seen with the implementation of isokinetic dynamometry may be further reduced with more aggressive rehabilitation progression guidelines. The single study in this review to allow a small amount of pain during rehabilitation running drills also had the fastest mean RTP time and relatively low rate of re-injury [73]. There is potential that these outcomes may be due to greater exposure to rehabilitation stimuli, driving beneficial adaptation to rehabilitation [72]. However, this study was of the lowest methodological quality [73], lacked a comparison group and did not objectively measure desired adaptations, leaving this as mere speculation.

# Limitations

The major limitation of this systematic review is that RTP times and re-injury rates have been reported regardless of factors such as injury type/severity and rehabilitation intervention. Studies confirmed HSI diagnosis via either clinical examination, MRI or a combination of both, making it difficult to differentiate between structural and functional HSI, which are known to influence time to RTP and rates of re-injury [103]. In order to truly investigate time taken to achieve RTP clearance and re-injury rates in response to different rehabilitation progression and RTP criteria , the aforementioned factors must be accounted for in randomised controlled trials.

The categories chosen to group specific RTP criteria were selected by the authors and are somewhat open to interpretation. However, this categorisation allowed for easier interpretation of results due to the wide range of specific RTP criteria implemented across different studies. Mean RTP time and re-injury data should also be viewed with some caution as definition of RTP time and follow-up periods varied across the included studies. However, the definitions of RTP time have been discussed in section 3.3 and the inclusion criterion of six-month follow-up minimum should account for the majority of re-injury risk following RTP clearance. It is also acknowledged that although the original Downs and Black quality assessment has been validated [33], the modified version implemented in the current systematic review has not. These modifications are, however, similar to those implemented in another recently published systematic review [81]. Finally, our literature search was limited to articles published in the English language only, and we are not able to account for non-English literature that would have otherwise fit the inclusion criteria.

# **2.6. CONCLUSIONS**

This systematic review highlights the strong emphasis placed on the alleviation of pain to allow HSI rehabilitation progression and reliance on highly subjective clinical assessments and performance tests as RTP criteria. Implementation of the Askling H-test appears to reduce rates of re-injury, although this requires further validation, whilst implementing isokinetic dynamometry as part of RTP criteria may result in a more desirable balance between RTP times and rates of re-injury when compared to relying on a combination of clinical assessments and performance tests alone. These results suggest a need for more objective and clinically practical criteria, allowing an evidence based approach to rehabilitation progression, and potentially reducing the ambiguity involved in the RTP decision making process.

# Chapter 4 – Study 2: A novel apparatus measuring knee flexor strength during various hamstring exercises: A reliability and retrospective injury study

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#### 4.1. Linking paragraph

As identified in chapter 3, the criteria to guide rehabilitation progression and determine RTP clearance following HSI are typically based on clinical assessments and performance tests. These criteria, most commonly, are dependent upon the clinician's subjective interpretation and/or the alleviation of the injured individual's pain. Knee flexor strength was explicitly mentioned by eight of the nine studies in chapter 2 as criteria for either rehabilitation progression or RTP clearance. However, criteria for rehabilitation progression and RTP clearance related to knee flexor strength were still largely subjective. Reliance on such subjective information throughout the rehabilitation process may be due to a lack of clinically practical objective monitoring tools, particularly when considering knee flexor strength. Knee flexor strength is a variable that, if objectively monitored throughout rehabilitation, can indicate time course of clinical recovery and risk of recurrent HSI. A monitoring tool capable of objectively measuring knee flexor strength has potential use in a clinical setting as part of the RTP decision making process. Chapter 4 discusses current objective methods for knee flexor strength assessment and describes a novel apparatus, which measures knee flexor strength during a range of HSI rehabilitation exercises. The reliability of this novel apparatus is investigated along with between-leg differences in previously injured and un-injured hamstrings.

# 4.2. ABSTRACT

Study Design: Reliability and case-control injury study.

**Objectives:** To establish test re-test reliability of a novel apparatus measuring knee flexor strength during various hamstring exercises; to investigate whether these measures detect between-leg differences in males with and without history of unilateral hamstring strain injury (HSI).

**Background:** Knee flexor strength is a key variable when dealing with HSI and methodologies of objective measurement of strength are often limited to single exercises.

**Methods:** Twenty male participants without and ten male participants with previous unilateral HSI participated. Isometric knee flexor strength and peak rate of force development (RFD) at 0/0, 45/45 and 90/90 degrees of hip/knee flexion were measured, as well as force impulse during bilateral and unilateral variations of an eccentric slider and hamstring bridge, using a novel apparatus. Intraclass correlation coefficient (ICC), typical error (TE) and typical error as a coefficient of variation (%TE) were calculated for all measures. The magnitude of between-leg differences within each group were calculated using estimates of effect sizes reported as Cohen's *d* with a  $\pm$  90% confidence interval (CI).

**Results:** Moderate to high test re-test reliability was observed for isometric knee flexor strength (ICC = 0.87 to 0.92) and peak RFD (ICC = 0.87 to 0.95) across three positions and mean force impulse during the eccentric slider (ICC = 0.83 to 0.90). In those with prior HSI, large deficits were seen in the previously injured leg compared to the contralateral uninjured leg for mean force impulse during the unilateral eccentric slider (d = -1.09, 90% CI = -0.20 to -1.97), isometric strength at 0/0 (d = -1.06, 90% CI = -0.18 to -1.93) and 45/45 (d = -0.88, 90% CI = -0.02 to -1.74).

**Conclusions:** The novel apparatus provides a reliable measure of isometric knee flexor strength, peak RFD and force impulse during an eccentric slider, with deficits seen in previously injured hamstrings for these measures.

# **4.3. INTRODUCTION**

For researchers and clinicians, knee flexor strength is a variable of interest when dealing with hamstring strain injuries (HSI), which is a persistent issue in a range of sports [38, 40, 99] that has associated financial consequences [54]. Risk of HSI increases with lower eccentric knee flexor strength [95, 128], and, furthermore, greater between-leg differences in isometric knee flexor strength may indicate re-injury risk and the time-course of recovery during rehabilitation [8, 30, 81]. Despite such evidence, objective knee flexor strength measures are scarcely implemented as part of return to play criteria following HSI [56], potentially contributing to persistent deficits seen in previously injured hamstrings [93, 130].

Isokinetic dynamometry is a methodology which has been implemented as part of HSI return to play decision making [56] and provides a reliable objective measure of knee flexor strength [119]. However, the clinical utility of isokinetic dynamometry is often limited to a laboratory environment due to high cost and technical requirements. As a clinically-practical alternative, handheld dynamometry can be used to measure isometric and eccentric knee flexor strength, although its reliability is dependent on clinician strength and skill [17, 143]. To overcome clinician dependency, several studies have implemented externally fixed dynamometry to provide an objective measure of knee flexor strength which may still be clinically practical [8, 74, 91, 125, 146]. To date, reports of externally fixed dynamometry tend to measure isometric knee flexor strength at a single position and have not investigated variables such as rate of force development (RFD), also shown to be deficient in previously injured hamstrings [94].

Externally fixed dynamometry is mostly used to measure knee flexor strength during isometric tests, although quantifying force output during dynamic exercises may have additional benefits. Being able to quantify force output during dynamic hamstring exercises may improve the clinician's ability to make more objective decisions around the progression of HSI rehabilitation, a process that is typically subjective [56]. Identifying methods of quantifying force output during both bilateral and unilateral hamstring exercises, which could be employed during HSI rehabilitation, is likely of interest to clinicians.

Therefore, the purpose of this study was to establish test-retest reliability of a novel apparatus measuring isometric knee flexor strength and RFD at three hip and knee joint angles as well as left and right leg force outputs independently during bilateral and unilateral variations of an

eccentric slider and hamstring bridge. Further to this, the study also aims to determine whether these measures detect between-leg differences in males with and without history of unilateral HSI.

# 4.4. METHODS

Twenty male participants with no history of HSI were included in the control group and ten male participants with a history of at least one unilateral HSI within the past 18 months were included in the previous HSI group. Participants in both groups were recreationally active, participating in physical activity twice per week as a minimum. Following ethical approval granted by the Australian Catholic University Human Research Committee (2015-253H), all participants provided written informed consent prior to commencing testing. Injury history was obtained during a subjective interview conducted by a health professional (JH) with four year's clinical experience in musculoskeletal injury assessment and rehabilitation. Previous HSI was defined as acute onset posterior thigh pain resulting from a typical mechanism of HSI (i.e. high speed running, acceleration, deceleration, etc.), causing immediate cessation of activity and at least seven days absence from regular activity participation [120]. At the time of testing, all participants with a prior HSI had subsequently returned to their normal level of activity and both groups were free from any current lower limb or lumbo-pelvic pain or injury.

Participants in the control group attended the Australian Catholic University research laboratory on three occasions, whilst the previous HSI group attended on two occasions. Each visit was separated by seven days and lasted approximately 45 to 60 minutes. All visits consisted of isometric knee flexor contractions at three different hip/knee joint angles (0/0, 45/45 and 90/90 degrees), as well as bilateral and unilateral variations of the eccentric slider and hamstring bridge exercises. All of these measures were performed in a novel apparatus consisting of two adjustable ratchet straps hanging in parallel from a power cage, with a wired load cell (MLP-750, Transducer Techniques, Temecula CA, USA) and heel strap attached in series with each (Figure 4.1). All load cell data was sampled at 2000Hz and transferred to a laptop computer via an analogue input data acquisition card (NI9237, National Instruments, Austin TX, USA) and monitored via a custom written software visual interface (LabVIEW 2013 National Instruments,

Austin TX, USA). Offline analysis of all data was later performed using custom written code in R [122] version 3.2.4.



**Figure 4.1** Novel apparatus consisting of two adjustable ratchet straps hanging in parallel from a power cage placed at the end of a plinth (a) with two independent load cells and ankle straps attached in series with each strap (b).

Isometric knee flexor contractions were performed at 0/0, 45/45 and 90/90 degrees of hip/knee flexion while participants were supine on a plinth placed at the end of the apparatus, with an additional strap used to secure participant's pelvis to the plinth (Figure 4.2). In each position participants performed two submaximal repetitions at 50% and then 75% of perceived maximum, followed by three maximal repetitions of three to five seconds duration, with a minimum 30 seconds rest between each. Standardised instructions were given to "push your heel down into the strap, without countermovement, as fast and hard as you can, in three, two, one, go" with strong verbal encouragement provided to ensure maximal effort. Testing position and leg order was randomised for each participant during their first visit, with this order maintained for subsequent sessions and for unilateral variations of the eccentric slider and hamstring bridge.



**Figure 4.2** Positions used to perform isometric knee flexor contractions at 0/0 (a), 45/45 (b) and 90/90 (c) degrees of hip and knee flexion with an adjustable strap used to secure the participant's pelvis to the plinth.

Data for all isometric knee flexor contractions were corrected for leg weight, calculated as the resting force output collected prior to each repetition. Isometric knee flexor strength was defined as the highest recorded force output across the three repetitions for each leg, at each of the three testing positions. In addition to this, peak RFD defined as the greatest increase in force over a rolling 200ms window, from contraction onset (increase in resting force  $\geq$  4N), until the time point where peak force was achieved. Peak RFD over a 200ms window was selected as this has previously been shown to be more reliable than alternative methodologies [77, 85]. In order to identify contraction onset, the data was low pass filtered (10Hz) using a zero-lag fourth order Butterworth filter. To reduce the chance of countermovement influencing RFD [77], repetitions with a decrease in resting force  $\geq$  4N in the 200ms prior to contraction onset were removed from analysis. Identification and removal of repetitions with a countermovement was done in a systematic fashion using custom written code in R [122] to reduce risk of subjective bias. Of the remaining repetitions, the single repetition with the greatest peak RFD (N/s) for each leg in each position was used for later analysis.

Prior to commencing the eccentric slider and hamstring bridge, leg weight was calculated as the resting force output of each leg independently, with participants laying supine on the plinth, arms across their chest and heels resting in the straps of the apparatus, ensuring 0/0 degrees of hip/knee flexion (Figure 4.3a). From the position used to ascertain resting leg weight, participants got into the starting position for the eccentric slider by flexing their knees (Figure

4.3b), then lifting their hips up from the plinth creating a straight line from shoulders to knees (Figure 4.3c). For the bilateral variation, on the "go" command, participants extended both knees as slowly as possible using their knee flexors to control the movement, keeping hips elevated (Figure 4.3d-f). The unilateral variation was performed in the same way, except on the "go" command, participants lifted the contralateral leg so that active force was only being applied through the heel of the leg being assessed (Figure 4.3g-i). A repetition was deemed complete when full knee extension was reached or when hip extension could not be maintained. Three repetitions of the bilateral and unilateral eccentric slider on each leg were performed by all participants following practice repetitions. The tester (JH) had to be satisfied with technique prior to allowing participants to progress to test repetitions.



**Figure 4.3** Phases of the bilateral and unilateral eccentric slider. Position used to ascertain resting leg weight (a); participant getting into the starting position for the eccentric slider (b-c); eccentric phase of the bilateral eccentric slider (d-f); eccentric phase of the unilateral eccentric slider (g-i).

The bilateral hamstring bridge was performed from 45/45 degrees of hip/knee flexion, with participants lifting their hips from the plinth until they achieved a straight line from their shoulders to knees, before returning to the starting position (Figure 4.4a-c). The unilateral variation was performed in the same way except that the leg not being assessed was held out of the strap at approximately 90/90 degrees of hip/knee flexion (Figure 4.4d-f). Speed of each repetition was controlled by a metronome to ensure approximately a three second up (concentric) and three second down (eccentric) phase. Three repetitions of the bilateral and unilateral hamstring bridge on each leg were performed by all participants following practice repetitions. The tester (JH) had to be satisfied with technique prior to allowing participants to progress to test repetitions.



**Figure 4.4** Phases of the bilateral and unilateral hamstring bridge. Bilateral hamstring bridge from start (a), mid (b) and end (c) repetition positions; unilateral hamstring bridge from start (a), mid (b) and end (f) repetition positions.

Following correction for resting leg weight, area under the force time curve from the start to end of each eccentric slider and hamstring bridge repetition was defined as force impulse normalised to each participant's body mass (N.s/kg). The start of a bilateral eccentric slider repetition was defined as the first collected data point which coincided with the "go" command, whereas the start of a unilateral eccentric slider repetition was the point at which force of the contralateral leg

dropped below resting leg weight. The start of a hamstring bridge repetition was calculated as the point which force exceeded resting leg weight for the bilateral variation or 2 x resting leg weight for the unilateral variation. The end of a repetition for both the eccentric slider and hamstring bridge was calculated as the point which force dropped below resting leg weight for each leg independently for the bilateral variation and 2 x resting leg weight for the unilateral variation. Force impulse was calculated for each repetition with the average of the three repetitions performed for each exercise variation (termed mean force impulse), used for later analysis. It is important to note that the measure of mean force impulse involved the combination of the concentric and eccentric phases for the hamstring bridge, whereas for the eccentric slider, only the eccentric phase was used for data analysis.

To determine test re-test reliability, descriptive statistics for all measures from the dominant and non-dominant legs of the control group across three visits were screened for normal distribution, using the Shapiro-Wilk test in SPSS Version 23.0.0.3 (IBM Corporation, Chicago, IL). Intraclass correlation coefficient (ICC), typical error (TE) and typical error as a co-efficient of variation (%TE) were calculated using a custom spreadsheet, with log-transformed data reported for non-normally distributed measures [57]. Based on previous studies of similar test re-test reliability data [91, 130], an ICC  $\geq$  0.90 was considered to be high, between 0.80 and 0.89 moderate and  $\leq$  0.79 poor. Minimum detectable change at a 95% confidence interval (MDC<sub>95</sub>) was calculated as TE x 1.96 x  $\sqrt{2}$ .

Within each group, between-leg comparisons were performed using data from the second visit, to account for an anticipated learning effect from visits one to two. The magnitude of between-leg differences were calculated using estimates of effect sizes reported as Cohen's *d* with a  $\pm$  90% confidence interval (CI) using the "effsize" package [132] in R [122]. Cohen's *d* of  $\geq$ 0.8 was considered large;  $\geq$ 0.5 and <0.8 moderate;  $\geq$ 0.2 and <0.5 small, and <0.2 trivial. Where the 90% CI overlapped both the positive ( $\geq$ 0.2) and negative ( $\leq$ -0.2) thresholds of a small effect simultaneously, were defined as unclear [14]. To provide a relative comparison of between-leg differences across all measures, asymmetry was calculated as the non-dominant leg divided by the dominant leg in the control group and the previously injured leg divided by the uninjured leg in the previous HSI group and expressed as a percentage. In the control group, leg dominance

was determined by asking participants which leg they prefer to kick a ball with. Due to recently discussed limitations in the selective reporting of p-values [142], these were not calculated as part of primary statistical analysis but can be found in supplementary material.

## 4.5. RESULTS

For clarity, all data are reported as mean  $\pm$  standard deviation unless otherwise stated. Participants' age, stature and mass were 24 $\pm$ 4 years, 178 $\pm$ 7cm, 79 $\pm$ 10kg in the control group and 24 $\pm$ 4 years, 182 $\pm$ 8cm, 86 $\pm$ 9kg in the previous HSI group. Median time from most recent HSI was 9 months, ranging from 1 to 15 months.

Test re-test reliability ranged from moderate to high for isometric strength (ICC = 0.87 to 0.92; TE% = 6.2 to 8.1) and peak RFD (ICC = 0.87 to 0.95; TE% = 9.9 to 12.4) across the three positions assessed and for mean force impulse during the unilateral eccentric slider (ICC = 0.87 to 0.90; TE% = 16.4 to 17.4). Mean force impulse during the bilateral eccentric slider was moderately reliable (ICC = 0.83 to 0.87; TE% = 20.2 to 21.2) and ranged from poor to high during the unilateral (ICC = 0.78 to 0.92; TE% = 4.8 to 7.1) and bilateral (ICC = 0.57 to 0.81, TE% = 8.5 to 13.8) variations of the hamstring bridge. All test re-test reliability data can be found in Table 4.1.

Among participants with prior HSI, large deficits were seen in the previously injured leg compared to contralateral uninjured leg for mean force impulse during the unilateral eccentric slider (d = -1.09, 90% CI = -0.20 to -1.97), isometric strength at 0/0 (d = -1.06, 90% CI = -0.18 to -1.93) and 45/45 (d = -0.88, 90% CI = -0.02 to -1.74), as well as peak RFD at 45/45 (d = -0.88, 90% CI = -0.02 to -1.74). Moderate deficits were seen in the previously injured leg compared to the contralateral uninjured leg for peak RFD at 0/0 (d = -0.75, 90% CI = 0.10 to -1.59), isometric strength at 90/90 (d = -0.69, 90% CI = 0.15 to -1.54) and mean force impulse during the bilateral bridge (d = -0.65, 90% CI = 0.19 to -1.49). In the control group, a small effect of leg dominance at 0/0 was seen for peak RFD (d = -0.48, 90% CI = 0.07 to -1.04) and isometric strength (d = -0.40, 90% CI = 0.15 to -0.96). All other between-leg differences were unclear (Supplementary Table 4.1), with a summary of between-leg asymmetry in percentage terms for all measures shown in Figure 4.5.

Measure	Visit 1	Visit 2	Visit 3	ICC	TE	TE%	MDC <sub>95</sub>
	(mean±SD)	(mean±SD)	(mean±SD)	(95% CI)	(95% CI)	(95% CI)	20
Isometric							
Strength (N)							
0/0 Dominant	$249\pm49$	$251 \pm 48$	$243 \pm 46$	0.87	17.8	8.1	49.2
				(0.74-0.94)	(14.3-24.1)	(6.5-11.2)	
0/0 Non-dominant	$239\pm46$	$242 \pm 41$	$235 \pm 42$	0.91	13.8	6.2	38.4
				(0.81-0.96)	(11.1-18.8)	(5.0-8.6)	
45/45 Dominant	$337 \pm 69$	$325 \pm 61$	$332\pm69$	0.89	23.5	7.3	65.1
				(0.77-0.95)	(18.9-31.9)	(5.8-10)	
45/45 Non-dominant	$328 \pm 67$	$328 \pm 61$	$327 \pm 72$	0.92	20.4	6.7	56.5
				(0.82-0.96)	(16.4-27.7)	(5.4-9.2)	
90/90 Dominant	$346 \pm 75$	$334 \pm 69$	$340 \pm 68$	0.91	22.2	7.2	61.4
				(0.81-0.96)	(17.8-30.1)	(5.8-9.9)	
90/90 Non-dominant	$341 \pm 70$	$334 \pm 67$	$336 \pm 65$	0.90	22.7	8.1	63.0
				(0.79-0.96)	(18.3-30.9)	(6.5-11.2)	
Isometric							
Peak RFD (N/s)							
0/0 Dominant	$873 \pm 235$	$873 \pm 258$	$828 \pm 236$	0.90	82.0	10.6	227.4
				(0.79-0.96)	(66.0-111.5)	(8.5-14.7)	
0/0 Non-dominant	$835 \pm 240$	$818 \pm 253$	$836 \pm 225$	0.90	81.2	12.2	225.0
				(0.79-0.96)	(65.4-110.3)	(9.7-16.9)	
45/45 Dominant	$1113 \pm 398$	$1057 \pm 321$	$1102 \pm 334$	0.95	86.2	9.9	239.0
				(0.89-0.98)	(69.4-117.2)	(7.9-13.7)	
45/45 Non-dominant	$1077 \pm 358$	$1062 \pm 327$	$1066 \pm 361$	0.92	107.3	12.4	297.4
				(0.82-0.96)	(86.4-145.8)	(9.9-17.2)	
90/90 Dominant	$1202 \pm 300$	$1205 \pm 331$	$1214 \pm 368$	0.88	121.8	12.4	337.6
				(0.75-0.95)	(96.8-165.0)	(9.7-17.1)	
90/90 Non-dominant	$1216 \pm 332$	$1161 \pm 354$	$1177 \pm 366$	0.92	102.4	11.6	284.0
				(0.84-0.97)	(81.4-138.8)	(9.1-16.1)	
Eccentric Slider							
Mean Force Impulse (N.s/kg)							
Bilateral Dominant	$11.9 \pm 6.6$	$14.0 \pm 7.0$	$15.6 \pm 7.9$	0.87*	2.7	20.2	7.5
				(0.74-0.95)	(2.1-3.7)	(15.7-28.3)	
Bilateral Non-dominant	$12.1 \pm 5.8$	$13.7 \pm 6.0$	$15.4 \pm 7.0$	0.83*	2.6	21.2	7.2
				(0.66-0.93)	(2.1-3.6)	(16.5-29.8)	
Unilateral Dominant	$18.1 \pm 9.7$	$22.7 \pm 10.9$	$23.5 \pm 11.0$	0.87*	3.2	17.4	8.9
	10.0 10.1		22.4.44.5	(0.74-0.95)	(2.5-4.2)	(13.8-24.4)	o <b>F</b>
Unilateral Non-dominant	$19.2 \pm 10.1$	$22.7 \pm 11.7$	$23.4 \pm 11.5$	0.90*	3.1	16.4	8.5
				(0.79-0.96)	(2.5-4.2)	(13.0-22.9)	
Hamstring Bridge Mean							
Force Impulse (N.s/kg)	(1, 1)	67.10	65.10	0.57*	07	12.0	2.0
Bilateral Dominant	$6.1 \pm 1.2$	$6.7 \pm 1.0$	$6.5 \pm 1.0$	0.5/*	0.7	13.8	2.0
D'lataral Nam da '	(7,1)	$c_0 + 1.4$		(0.28-0.79)	(0.6-1.01)	(11.0-19.3)	1 7
Bilateral Ivon-dominant	$0.7 \pm 1.2$	$0.9 \pm 1.4$	$0.7 \pm 1.1$	$0.81^{\circ}$	0.5	8.5 (6 9 11 7)	1.5
Unilotoral Dominant	12.2 + 1.0	12.0 + 2.1	125 10	(0.02-0.91)	(0.4-0.7)	(0.8-11./)	27
Unnateral Dominant	$13.3 \pm 1.9$	$13.9 \pm 2.1$	$13.3 \pm 1.9$	(0.70)	1.0	(5707)	2.1
Unilatoral Non dominant	130 + 22	14 - 21	13.0 + 2.1	(0.37 - 0.90)	(0.0-1.3)	(3.7-9.7)	17
Chinateral Non-dominant	$13.7 \pm 2.2$	14 - 2.1	$13.7 \pm 2.1$	(0.32)	(0.5-0.8)	+.0 (3.9-6.6)	1./

Table 4.1 Test re-test reliability of the dominant and non-dominant legs in the control group.

Abbreviations: ICC, intraclass correlation coefficient; MDC<sub>95</sub>, minimal detectable change at 95% confidence level; TE, typical error; TE%, typical error as a coefficient of variation.\*Indicates ICC taken from log-transformed data due to non-normal distribution



**Figure 4.5** Between-leg asymmetry for all measures within each group. Median (middle line) and interquartile range (box) between-leg asymmetry (%), with whiskers extending 1.5 x interquartile range from quartile 1 and 3 respectively and dots indicate outliers more than 1.5 x interquartile range from the box. Negative values indicate between-leg asymmetry in favour of the dominant or contralateral uninjured leg in the control and previous HSI group respectively.

**Supplementary Table 4.1** Between-leg comparisons for all measures, within each group. Between-leg asymmetry (%), effect sizes reported as Cohen's d with a  $\pm$  90% confidence interval (CI), raw and Holm's adjusted p-values obtained from paired t-tests for all between-leg comparisons within each group. Negative values indicate between-leg asymmetry/difference in favour of the dominant or contralateral uninjured leg in the control and previous HSI group respectively.

Measure	Asymmetry % (mean ± SD)	Cohen's <i>d</i> (90% CI)	Raw p value	Adjusted p value
Control $(n = 20)$				
Isometric Strength 0/0	$-2.8 \pm 9.2$	-0.40	0.088	0.790
		(0.15 to -0.96)		
Isometric Strength 45/45	$1.6 \pm 12.2$	0.05	0.809	1.000
		(0.60 to -0.49)		
Isometric Strength 90/90	$0.6 \pm 14.2$	-0.02	0.937	1.000
		(0.53 to -0.56)		
Peak RFD 0/0	$-5.7 \pm 13.1$	-0.48	0.045	0.446
		(0.07 to -1.04)		
Peak RFD 45/45	$1.9\pm14.9$	0.04	0.857	1.000
		(0.59 to -0.51)		
Peak RFD 90/90	$-3.3 \pm 15.8$	-0.24	0.305	1.000
		(0.32 to -0.81)		
Eccentric Slider	$1.6 \pm 16.1$	-0.13	0.573	1.000
Bilateral		(0.43 to -0.70)		
Eccentric Slider	$0.3 \pm 17.8$	0.01	0.962	1.000
Unilateral		(0.56 to -0.53)		
Hamstring Bridge	$4.4 \pm 22.9$	0.13	0.582	1.000
Bilateral		(0.67 to -0.42)		
Hamstring Bridge	$1.9 \pm 10.6$	0.12	0.584	1.000
Unilateral		(0.67 to -0.42)		
Previous HSI (n = 10)				
Isometric Strength 0/0	$-10.8 \pm 10.0$	-1.06	0.009	0.078
		(-0.18 to -1.93)		
Isometric Strength 45/45	$-12.5 \pm 14.5$	-0.88	0.021	0.168
		(-0.02 to -1.74)		
Isometric Strength 90/90	$-8.6 \pm 12.5$	-0.69	0.056	0.279
		(0.15 to -1.54)		
Peak RFD 0/0	$-9.2 \pm 18.9$	-0.75	0.043	0.256
		(0.10 to -1.59)		
Peak RFD 45/45	$-14.5 \pm 15.7$	-0.88	0.021	0.168
		(-0.02 to -1.74)		
Peak RFD 90/90	$-2.5 \pm 22.1$	-0.40	0.234	0.404
		(0.42 to -1.23)		
Eccentric Slider	$-13.8 \pm 27.0$	-0.64	0.074	0.279
Bilateral		(0.20 to -1.48)		
Eccentric Slider	$-26.0 \pm 20.7$	-1.09	0.007	0.075
Unilateral		(-0.20 to -1.97)	0.0.50	0.5=0
Hamstring Bridge	$-11.0 \pm 18.3$	-0.65	0.069	0.279
Bilateral	• • • • •	(0.19 to -1.49)	0.000	0.404
Hamstring Bridge	$-2.9 \pm 9.0$	-0.44	0.202	0.404
Unilateral		(0.39 to -1.26)		

#### 4.6. DISCUSSION

The main findings of the current study are that i) the novel apparatus was moderately to highly reliable when measuring isometric knee flexor strength and peak RFD across three positions, as was mean force impulse during an eccentric slider; and ii) individuals with prior HSI display large deficits in the previously injured leg compared to their contralateral uninjured leg for isometric knee flexor strength, peak RFD and mean force impulse during a unilateral eccentric slider.

When measuring isometric knee flexor strength, test re-test reliability of the current apparatus is comparable to previous investigations implementing externally fixed dynamometry [8, 146] with the advantage of employing a range of hip/knee joint angles. In contrast to other retrospective investigations reporting an absence of between-leg deficits in isometric knee flexor strength [105, 130], moderate to large deficits were seen in the previous HSI group. Such findings may be partly explained by the range of hip/knee joint angles employed in the current study, which allowed for assessment of isometric knee flexor strength at longer hamstring muscle lengths involving hip flexion, compared to a prone position with no hip flexion [105, 130].

The supine testing position also enabled analysis of isometric RFD, as the force output could be detected from a position of complete rest, allowing more accurate identification of contraction onset and countermovement [77]. Peak RFD over a 200ms window was analysed, as this requires simpler offline analysis and is more reliable than other RFD analysis methodologies [77, 85], improving potential for future clinical implementation with automated analysis. It is unclear from the current findings whether peak RFD provides any clinically useful information additional to isometric knee flexor strength, as peak RFD deficits found in previously injured hamstrings were of a similar or lesser magnitude to deficits in isometric strength. Nevertheless, given the moderate to high reliability of peak RFD, implementation of the current apparatus in future studies may be warranted in populations where knee flexor RFD may be of interest, such as those with acute HSI [94] or anterior cruciate ligament injury [87].

In addition to isometric strength and RFD, the current study reports for the first time, the measure of force impulse of the left and right legs independently during two exercises, the eccentric slider and hamstring bridge. Whilst independent knee flexor force output of the left and right legs have previously been objectively measured during the bilateral Nordic hamstring

exercise (NHE) [91], the current apparatus allows objective measurement of force output during both bilateral and unilateral exercises. Another key difference between the NHE and the exercises employed in the current study is that the eccentric slider and hamstring bridge are submaximal in nature, which may have application for clinicians. For example, monitoring force impulse during the submaximal bilateral eccentric slider may provide an objective guide for progression to maximal eccentric knee flexor exercises during HSI rehabilitation such as the NHE. Furthermore, instantaneous force output can be displayed, providing the clinician and patient visual feedback on between-leg contributions when performing the eccentric slider and hamstring bridge during HSI rehabilitation.

The major difference between the two exercises employed in the current study was that the eccentric slider only assessed the eccentric phase which was performed as slowly as possible, whereas the hamstring bridge involved both a concentric and eccentric phase with repetition speed controlled. As such, TE% of mean force impulse during the eccentric slider was higher compared to the hamstring bridge, but allowed for greater differentiation between previously injured and uninjured hamstrings, reflected in the relatively higher ICCs. Therefore, caution should be taken when interpreting subtle between-leg differences in mean force impulse during the eccentric slider, although large between-leg deficits such as those seen in the previous HSI group during the unilateral variation may still be detected.

The novel apparatus used in this study utilised commercially available equipment that is relatively inexpensive (cost < \$1000USD) and is not confined to a laboratory setting unlike isokinetic or externally fixed dynamometry. It is acknowledged that the methods of data analysis employed in the current study require some technical expertise, however, ongoing development of custom written code using free and open source R software [122] will allow for simpler automated analysis, improving potential for clinical utility.

The current study has some limitations. Firstly, the study included recreationally active participants who performed a minimum of two days of physical activity per week, however the type, volume and/or intensity of exercise beyond these minimum requirements was not controlled for. Secondly, retrospective injury history and details of rehabilitation were restricted to subjective reporting. As a result, the severity of previous HSI and exposure to stimulus for adaptation are unknown, with both of these factors likely to influence subsequent knee flexor
strength and function. Thirdly, as with any retrospective investigation, it is also unknown whether the between-leg deficits seen in the previous HSI group were a result or cause of initial injury. Fourthly, it is acknowledged that muscles such as gastrocnemius and gracilis also contribute to knee flexor force output in addition to the hamstrings, whilst the contribution of the hip extensors during the hamstring bridge and eccentric slider cannot be directly quantified. Finally, measures of knee flexor strength in the current study were not compared to gold standard tools such as isokinetic dynamometry.

## **4.7. CONCLUSION**

The novel apparatus is capable of objectively measuring both isometric knee flexor strength and peak RFD across a range of hip/knee joint angles, as well as force impulse during an eccentric slider, with moderate to high reliability. Large between-leg deficits were observed in previously injured hamstrings for isometric knee flexor strength, peak RFD and mean force impulse during the unilateral eccentric slider when using the apparatus. It is hoped that future implementation of such an apparatus will improve the ability of both clinicians and researchers to objectively monitor knee flexor strength in clinical populations of interest such as those with a HSI and improve rehabilitation outcomes.

# Chapter 5 – Study 3: Exercise-specific progression criteria emphasising accelerated eccentric loading during hamstring strain injury rehabilitation

Publication statement:

This chapter is comprised of the following paper under preparation for submission to the *British Journal of Sports Medicine:* 

**Hickey JT,** Rio E, Timmins RG, Maniar N, Pitcher CA, Williams MD, Opar DA. Exercisespecific progression criteria emphasising accelerated eccentric loading during hamstring strain injury rehabilitation.

## 5.1. Linking paragraph

As discussed in chapter 1, previously injured hamstrings often display persistent deficits in eccentric knee flexor strength and BFlh fascicle length even after completion of rehabilitation and RTP clearance. These deficits likely contribute to the elevated risk of future HSI in previously injured hamstrings and suggest failings of current rehabilitation and RTP practices.

Pressure to expedite RTP times, combined with conservative approaches to HSI rehabilitation progression reduces time available for exposure to eccentric loading. As outlined in chapter 3, the progression of HSI rehabilitation exercises is typically guided by clinical assessments and performance tests mostly based on the clinician's subjective interpretation. In general this approach lacks specificity to the exercises they are allowing progression towards. Guidelines such as delaying the introduction of eccentric loading, until the alleviation of pain and/or between-leg deficits  $\geq 10\%$  in isometric knee flexor strength, lack evidence to either support or refute their clinical efficacy.

The focus of chapter 5 is to describe exercise-specific progression criteria as part of a HSI rehabilitation protocol designed to accelerate the introduction of eccentric loading. Supporting data is provided to compare the clinical efficacy of conventional guidelines for the introduction of eccentric loading and exercise-specific progression criteria during HSI rehabilitation. The novel apparatus described in chapter 4 is implemented to objectively measure isometric knee flexor strength and force impulse during rehabilitation exercises.

## **5.2. ABSTRACT**

**Background:** Clinicians are under pressure to achieve timely return to play (RTP) and minimise re-injury risk for athletes following hamstring strain injuries (HSIs). Whilst eccentric exercise reduces risk of HSI and accelerates RTP, conventional guidelines for the introduction of eccentric loading during HSI rehabilitation, such as alleviation of pain and between-leg deficits  $\geq$ 10% during isometric knee flexor contractions, lack evidence.

**Objectives:** To describe a HSI rehabilitation protocol with exercise-specific progression criteria and provide data highlighting how early eccentric exercise can be tolerated.

**Methods:** Forty-three men with an acute HSI participated in a fully supervised rehabilitation protocol twice per week, which was progressed using exercise-specific criteria. The introduction of eccentric loading was defined as the first rehabilitation session where the Nordic hamstring exercise (NHE) and unilateral eccentric slider exercise were performed. The number of days from acute HSI to the first rehabilitation session where eccentric loading was introduced was reported. Participants rating of pain and between-leg force output during isometric knee flexor strength assessments, eccentric slider exercise variations and the NHE were reported during the first session where eccentric loading was introduced.

**Results:** Eccentric loading was introduced in a median time of 5 days (range = 1 to 17 days) following acute HSI, despite concurrent pain and/or between-leg deficits  $\geq 10\%$  present during isometric knee flexor strength assessments in 39 of the 43 participants (91%). Throughout the rehabilitation period, pain and/or between-leg deficits  $\geq 10\%$  remained present in 16 of the 43 participants (37%), despite all participants being exposed to eccentric loading with no adverse events.

**Conclusion:** Waiting for the alleviation of pain and between-leg deficits during isometric knee flexor strength assessments may unnecessarily delay introduction of eccentric loading during HSI rehabilitation. Clinicians cognisant of timely RTP, who are looking to accelerate the introduction of eccentric loading, should consider implementing exercise-specific progression criteria during HSI rehabilitation.

## **5.3. INTRODUCTION**

The goal of rehabilitation following acute hamstring strain injury (HSI) is to return the injured athlete to their previous level of function with minimal risk of re-injury [52]. Performance, financial and organisational pressures [48, 54] often compel clinicians to attempt to achieve these rehabilitation goals in an expedited manner. Accelerated return to play (RTP) reduces time available for rehabilitation stimulus, potentially contributing to persistent deficits in hamstring muscle structure and function [45, 76, 81, 93, 94, 130] and elevated risk of future HSI [43, 92]. With brief convalescence desirable for key stakeholders involved in the RTP decision [5, 27, 113], clinicians must implement risk mitigating interventions which can be administered in a safe and timely manner during HSI rehabilitation.

There is compelling evidence that eccentric exercise reduces the risk of HSI [3, 6, 102, 135] and drives positive adaptations in hamstring muscle structure and function [4, 18, 21, 129]. Emphasising hamstring lengthening through exercises involving eccentric bias, over concentrically biased exercises, reduces RTP times and is associated with low re-injury rates following HSI [10, 11]. Consequently, eccentric loading is being increasingly advocated during HSI rehabilitation [23, 109, 112, 134], although little empirical evidence exists to guide the timing of its introduction or exercise progression.

Criteria-based HSI rehabilitation protocols recommend passing certain milestones prior to introducing eccentric loading and progressing different exercises [84, 131]. These progression criteria are typically based on resolution of pain during clinical assessments [56, 84, 131], and the general guideline to only perform exercises in the absence of pain [56]. Following acute HSI, it is widely recommended that eccentric loading be delayed until isometric knee flexor strength is  $\geq$ 90% of the uninjured leg and pain-free [56, 84, 109, 112]. However, no direct evidence exists to support or refute these criteria.

Therefore, the aims of this study were to 1) describe exercise-specific progression criteria as part of a HSI rehabilitation protocol; 2) investigate whether the introduction and progression of rehabilitation exercises can be accelerated if performed up to a pain-threshold rather than remaining pain-free; 3) determine whether exercise-specific progression criteria can accelerate introduction of eccentric loading prior to the resolution of pain and/or strength deficits during isometric knee flexor contractions.

## **5.4. METHODS**

## **Participants**

This study was a secondary observational analysis of data collected from participants performing HSI rehabilitation as part of a larger randomised controlled trial, which will be detailed in chapter 6 (ANZCTR12616000307404). Ethical approval was granted by the Australian Catholic University Human Research Committee (2015-307H). Potential participants provided informed written consent prior to undergoing an initial clinical assessment conducted by a health professional with five years' experience in musculoskeletal injury assessment and rehabilitation (JTH).

To be included in the study, participants had to be aged between 18 and 40 years and have an acute HSI confirmed via initial clinical assessment within seven days of suspected injury. Acute HSI was confirmed based on three pre-determined criteria [84] 1) clear HSI mechanism (eg. high speed running, kicking, bending over) causing acute posterior thigh pain and the cessation of activity; 2) localised pain on palpation of the injured hamstring muscle and 3) localised pain at the site of injury during isometric knee flexor contraction. Potential participants were excluded if they presented with posterior thigh pain consistent with other conditions, including hamstring tendinopathy and referred lower back pain, or if the severity of their injury warranted surgical opinion. An independent physiotherapist (ER) with 15 years' experience in sports injury clinical practice and research verified participant eligibility by reviewing subjective and objective data collected during initial clinical assessments.

## Randomisation

Participants who met inclusion criteria were stratified for sex and history of HSI, prior to random allocation to either a pain-free or pain-threshold rehabilitation group. Participants allocated to the pain-free group were only permitted to perform and progress rehabilitation exercises in the complete absence of pain, which had to be rated 0 on a 0-10 numeric rating scale (NRS). In contrast, those in the pain-threshold group were permitted to perform and progress rehabilitation exercises in the exercises in the pain-threshold group were permitted to perform and progress rehabilitation exercises in the pain-threshold group were permitted to perform and progress rehabilitation exercises in the progress rehabilitation exercis

The pain-threshold of  $\leq 4$  on the 0-10 NRS was selected as a slightly more conservative version of the pain monitoring model which allowed pain rated  $\leq 5$  out of 10 during patellofemoral joint pain and Achilles tendinopathy rehabilitation [115, 124]. The 0-10 NRS was explained to all

participants in the context of localised pain at the site of injury where 0 represented "absolutely no pain" and 10 was the "worst pain imaginable". Participants provided written informed consent before commencing their allocated rehabilitation protocol. The presence of an alternative intervention was concealed to reduce the possibility of contamination between groups.

## **Rehabilitation protocol**

All participants performed a progressive rehabilitation protocol twice per week, fully supervised by the lead investigator (JTH). The rehabilitation protocol included moderate to long length hip dominant exercises with a concentric and eccentric phase and short to moderate length knee dominant exercises which were eccentrically biased. Hip dominant exercises included a hamstring bridge (Figure 5.1) and 45° hip extension (Figure 5.2) and knee dominant exercises included an eccentric slider (Figure 5.3) and Nordic hamstring exercise (NHE) (Figure 5.4).



**Figure 5.1** Bilateral and unilateral variations of the hamstring bridge. Concentric phase of the (ab) bilateral and (c-d) unilateral hamstring bridge, where participants were instructed to push their heels into the bench until they achieved a straight line from their shoulders to knees. For the eccentric phase of the (b-a) bilateral and (d-c) unilateral hamstring bridge, participants were instructed to slowly control their hips back to the starting position. During the unilateral variation, participants were instructed to maintain approximately 90° of hip and knee flexion to reduce the influence that hip flexor muscles may have on performing the movement.



**Figure 5.2** Bilateral and unilateral variations of the  $45^{\circ}$  hip extension. Eccentric phase of the (ab) bilateral and (c-d) unilateral  $45^{\circ}$  hip extension, where participants were instructed to lower themselves towards the floor as far as possible whilst maintaining a neutral spine. For the concentric phase of the (b-a) bilateral and (d-c) unilateral  $45^{\circ}$  hip extension, participants were instructed to use their hamstrings and glutes to extend their hips and return to the starting position. During the unilateral variation, the contralateral leg was removed from the machine to isolate the training leg.



**Figure 5.3** Bilateral and unilateral variations of the eccentric slider performed in supine on a standard plinth with the participant's arms across their chest and heels in straps of an externally fixed dynamometry setup to measure knee flexor force. Each bilateral repetition commenced with the participant bringing their heels in towards their hips (a-b); lifting their hips from the plinth (b-c); and then (c-d) participants were instructed to resist knee extension as slowly as possible until either full knee extension was reached or for as long as hip extension could be maintained. The unilateral eccentric slider was performed in the same way except once (c) participants hips were elevated, they were instructed to (e) lift the contralateral non-exercising leg so no tension was applied to that strap and (e-f) resist knee extension as slowly as possible with the exercising leg.



**Figure 5.4** The Nordic hamstring exercise performed on a device with hooks used to secure participant's ankles in position and objectively measure knee flexor force. Participants were instructed to (a-c) lower themselves towards the ground as slowly and as low as possible with their arms across their chest using their knee flexor muscles to resist. When participants could not lower themselves any further they were instructed to (d) catch themselves with their hands and return slowly the starting position without using their knee flexors.

Rehabilitation commenced immediately following the initial clinical assessment, with all participants attempting bilateral variations of the hamstring bridge,  $45^{\circ}$  hip extension and eccentric slider. Participants were asked to rate any localised pain at the site of injury according to the 0-10 NRS during performance of each exercise, with technique and range of motion closely monitored by the lead investigator. Each exercise was progressed based on three criteria (Figure 5.5), if the participant could perform the exercise 1) through full range of motion, 2) for

the prescribed repetition range and 3) within their group's pain limits. Successful completion of each exercise was defined as meeting all three of these criteria.



**Figure 5.5** Exercise-specific progression criteria and prescribed repetition ranges for each exercise variation in the rehabilitation protocol.

The bilateral hamstring bridge and 45° hip extension were both progressed to unilateral variations. The bilateral eccentric slider was progressed to both a unilateral variation and the NHE, which was defined as the introduction of eccentric loading. The NHE was introduced at this time point as the bilateral eccentric slider replicated the knee dominant, eccentric only action of the NHE at a submaximal intensity. Knee flexor force output of the injured and uninjured legs were objectively measured during performance of both eccentric slider variations and the NHE using custom-built, externally-fixed dynamometry with published reliability [55, 91].

A total of three sets of each type of exercise (hamstring bridge, 45° hip extension, eccentric slider and NHE) were permitted to be performed each rehabilitation session. For example, if progression criteria were met for the bilateral hamstring bridge after the first set, a further two sets could be performed unilaterally within that rehabilitation session. Once exercises were progressed to unilateral variations, they were performed by both the injured and uninjured legs.

## Isometric knee flexor strength assessments

A member of the research team blinded to group allocation (DAO, NM or RGT) assessed isometric knee flexor strength during the initial clinical assessment and prior to each subsequent rehabilitation session. Isometric knee flexor strength of the injured and contralateral uninjured leg was measured using custom-built, externally-fixed dynamometry with published reliability, as described in chapter 4 [55]. The custom-built externally fixed dynamometry consisted of two adjustable straps hanging from a power cage, with a wired load cell (MLP-750, Transducer Techniques, Temecula CA, USA) and heel strap attached in series with each. Contractions were performed in supine on a plinth at 0/0 and 90/90 degrees of hip/knee flexion with the participant's heel in one of the straps hanging from the power cage. Participant's hips were secured to the plinth using an adjustable strap. In each position the uninjured leg was tested prior to the injured leg [8], with a warm-up repetition at 50% and 75% of perceived maximal effort followed by three maximal effort isometric knee flexor contractions of three to five seconds duration, with a minimum 30 second inter-trial rest.

Standardised instructions were given to "push your heel down into the strap, from complete rest without lifting up your heel, as hard and fast as you can". Strong, standardised verbal encouragement was provided to ensure maximal effort. When performing isometric knee flexor contractions on the injured leg, the additional instruction of contracting "to an intensity that you feel comfortable with" was given. Participants were asked to report any pain localised to the site of injury on the 0-10 NRS with the peak pain score and maximal force output recorded in each position.

## **Outcome measures**

The number of participants within each group successfully completing each exercise and achieving pain-free isometric knee flexor strength  $\geq$ 90% compared to the contralateral uninjured

leg were reported relative to days from acute HSI. The number of days from acute HSI to introduction of eccentric loading was reported within each group. For the first rehabilitation session where eccentric loading was introduced, participant's rating of pain on the 0-10 NRS and injured knee flexor force output was reported in percentage terms relative to the contralateral uninjured leg for isometric knee flexor strength assessments, both eccentric slider variations and NHE.

## 5.5. RESULTS

Of 52 potential participants screened for eligibility, 43 met inclusion criteria and were randomly allocated to either the pain-free (n = 22) or pain-threshold (n = 21) group (Table 5.1). All potential participants screened were men. No adverse events were reported when performing exercises throughout rehabilitation. All participants successfully completed the bilateral hamstring bridge, bilateral eccentric slider, both variations of the 45° hamstring bridge and the NHE during rehabilitation. The unilateral hamstring bridge was successfully completed by 18 of the 22 participants (82%) in the pain-free group and 19 of the 21 participants (90%) in the pain-threshold group. The unilateral eccentric slider was successfully completed by 19 of the 22 participants (86%) in the pain-free group and all participants in the pain-threshold group. Pain-free isometric knee flexor strength  $\geq$ 90% compared to the contralateral uninjured leg was achieved by 12 of the 22 participants (55%) in the pain-free group and 15 of the 21 participants (71%) in the pain-threshold group (Figure 5.6).

	Dain free	Pain-
Variable	Fam-free	threshold
	(n = 22)	(n = 21)
Age (years)	$27.4\pm5.2$	$24.9\pm5.3$
Height (cm)	$180.1\pm7.5$	$182.2 \pm 8.2$
Mass (kg)	86.5 ± 13.5	$86.3\pm9.2$
Sport (days per week)	3 ± 1	3 ± 1
Sport (Australian football/other)	18/4	14/7
Prior hamstring strain injury (yes/no)	16/6	14/7
Initial clinical assessment (days from injury)	3 ± 2	3 ± 1
Activity at time of injury (match/training)	14/8	15/6
Injury location (lateral/medial)	18/4	15/6
Pain at time of injury (0-10 NRS)	$5.7 \pm 2.0$	$5.8 \pm 1.5$
Peak palpation pain (0-10 NRS)	$3.1 \pm 1.7$	$3.6 \pm 2.0$
Peak palpation pain distance from ischium (cm)	$20.2\pm6.7$	$19.6 \pm 6.4$
Total length of palpable pain (cm) $5.5 \pm 3.4$ $5.8 \pm 4$		$5.8 \pm 4.4$
Isometric knee flexor pain 0/0 (0-10 NRS) $3.7 \pm 2.8$ $3.1 \pm 2$		3.1 ± 2.6
Isometric knee flexor pain 90/90 (0-10 NRS) $4.5 \pm 2.6$ $4.8 \pm 2.6$		$4.8\pm2.1$
Isometric knee flexor strength 0/0 (%)	$70.1\pm26.9$	$66.8\pm26.8$
Isometric knee flexor strength 90/90 (%)	$60.1\pm25.2$	$60.1\pm26.4$

**Table 5.1** Baseline participant characteristics and results of initial clinical assessment reported as mean  $\pm$  SD or absolute number of participants within each group.

N = Newtons; % = relative to uninjured leg, NRS = numeric rating scale



**Figure 5.6** The number of days from acute HSI taken to successfully complete each exercise, within each group. Proportion of participants within each group (%) is shown on the y-axis relative to the number of days from acute HSI on the x-axis.

Eccentric loading was introduced in a median time of 6 (range = 1 to 17) and 4 (range = 1 to 11) days from acute HSI in the pain-free and pain-threshold groups, respectively. During the first session that eccentric loading was introduced three key observations were made (Figure 5.7) 1) 18 of the 22 participants (82%) in the pain-free group and all participants in the pain-threshold group were still reporting pain during isometric knee flexor strength assessments and/or had strength deficits  $\geq 10\%$  2) 13 of the 22 participants (59%) in the pain-free and 17 of the 22 participants (81%) in the pain-threshold group were able to successfully complete the unilateral eccentric slider; 3) 19 of the 22 participants (91%) in the pain-free and 21 of the 22 participants (95%) in the pain-threshold group were able to successfully complete the NHE.



**Figure 5.7** Participant's rating of pain and between-leg knee flexor force during the first session that eccentric loading was introduced. Participant's rating of pain on the 0-10 numeric rating scale (NRS) is shown in the top panel and knee flexor force of the injured leg relative to the contralateral uninjured leg (horizontal dotted line representing 90%) is shown in the bottom panel. Each dot represents an individual participant, with the median shown as the solid horizontal line within each group.

## **5.6. DISCUSSION**

The major findings of this study are that 1) exercise-specific progression criteria accelerates the introduction of eccentric loading during HSI rehabilitation in a way that is safe and well tolerated by participants; 2) successful completion of exercises and introduction of eccentric loading was further accelerated when HSI rehabilitation was performed and progressed up to a pain-threshold rather than remaining pain-free and 3) it is not necessary to delay the introduction of eccentric loading until isometric knee flexor strength is  $\geq$ 90% of the contralateral uninjured leg and pain-free.

There are two key features that differentiate the current rehabilitation protocol from the majority of those reported in the HSI literature. Firstly, progression of rehabilitation was based on each participant's ability to perform exercises rather than pain or between-leg deficits during independent clinical assessments such as isometric knee flexor contractions [84, 131]. Secondly, each exercise was progressed individually rather than as a group based on the stage of rehabilitation the participant was deemed to be in [84, 131]. To date, only two studies have utilised exercise-specific progression criteria [10, 11]. However, unlike the current study, rehabilitation was restricted to begin no earlier than five days following acute HSI and only performed in the complete absence of pain [10, 11]. By removing time as a restriction, 47% of participants were exposed to eccentric loading prior to five days from acute HSI. In addition to this, participants in the pain-threshold group were able to successfully complete eccentric loading in the presence of pain rated  $\leq 4$  out of 10 with no adverse effects.

For the first time following acute muscle injury, pain-threshold rehabilitation has been shown to safely accelerate successful completion of exercises and introduction of eccentric loading compared to the conventional practice of remaining pain-free [56]. Although relatively novel for acute muscle injury, pain-threshold rehabilitation has been shown to be safe and beneficial for chronic and post-operative musculoskeletal conditions [114, 118, 124]. This study provides proof of concept warranting further investigation of the utility of exercise-specific progressions up to a pain-threshold during HSI rehabilitation.

Although it has been suggested that isometric knee flexor strength should be  $\geq 90\%$  of the contralateral uninjured leg and pain-free, prior to introducing eccentric loading [84], data from the current study highlights limitations in such criteria. In fact, 37% of participants in the current study would not have been exposed to eccentric loading during rehabilitation had the alleviation of pain and between-leg deficits  $\geq 10\%$  during isometric knee flexor strength assessments been implemented as progression criteria.

Objective monitoring of isometric knee flexor strength during HSI rehabilitation has value as a prognostic tool and indicator of re-injury risk when measured in concert with other clinical variables [8, 59, 81]. However, in isolation, between-leg strength cut-offs may inappropriately delay exposure to eccentric loading and fail to indicate risk of first-time and recurrent HSI at the individual level [131, 137]. The culmination of these recent findings and those of the current study reinforce the value of exercise-specific progression criteria in accounting for individual variation during HSI rehabilitation.

Despite reporting pain during isometric knee flexor contractions and producing <90% of the force of the contralateral uninjured leg, the majority of participants reported no pain and demonstrated knee flexor force  $\geq 90\%$  during eccentric exercises. The mechanism explaining discrepancies between isometric and eccentric knee flexor contraction modes in terms of pain and between-leg force output remains unknown. It should be noted that isometric knee extension has been shown to induce analgesia in those with patellar tendinopathy [107]. Consequently, as isometric knee flexor strength assessments were always performed prior to rehabilitation sessions, it is possible that this resulted in an analgesic effect during subsequent eccentric exercise. However, isometric knee flexor contractions in the current study were three to five seconds in duration compared to 45 seconds in the patellar tendinopathy study [107]. In addition, generalising evidence from tendon to muscle should be done with caution. Further research is needed to elucidate potential mechanisms for discrepancies in pain and force outputs during isometric and eccentric contractions in injured skeletal muscle. Regardless of potential mechanisms, these findings challenge conventional clinical guidelines for acute muscle injury rehabilitation that suggests isometric contractions should be pain free and symmetrical in strength prior to implementing eccentric exercise [52, 68, 78, 112].

There were limitations of the current study. Acute HSI was confirmed by clinical assessment without supporting diagnostic imaging. However, it has been recently shown that magnetic resonance imaging provides no additional value on top of clinical assessments in acute HSI prognosis [59, 141]. In addition, confirming acute HSI via clinical assessment increases the external validity of the current study for clinicians without access to diagnostic imaging. Another limitation is that although no adverse effects were reported when performing the current rehabilitation protocol, the longer term outcomes of accelerated eccentric loading are at this stage unknown. Chapter 6 will investigate the effect this rehabilitation protocol has on time from HSI to RTP clearance, rates of re-injury and hamstring muscle structure and function.

## **5.7 CONCLUSION**

The findings of the current study challenge conventional guidelines for the progression of exercises and introduction of eccentric loading during HSI rehabilitation. Clinicians should reconsider the need for the alleviation of pain and/or between-leg deficits  $\geq 10\%$  during isometric knee flexor contractions prior to introducing eccentric loading during HSI rehabilitation. By implementing exercise-specific progression criteria, clinicians will be able to accelerate the introduction of eccentric loading during HSI rehabilitation whilst under pressure to achieve timely RTP.

## Chapter 6 – Study 4: Pain-free versus pain-threshold rehabilitation following acute hamstring strain injury: a randomised controlled trial

Publication statement:

This chapter is comprised of the following manuscript under preparation for submission to the *British Journal of Sports Medicine:* 

**Hickey JT,** Timmins RG, Maniar N, Rio E, Hickey, PF, Williams MD, Opar DA. Pain-free versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial.

## 6.1. Linking paragraph

As outlined in chapter 3, it is typically recommended that rehabilitation exercises only be performed and progressed within pain-free limits. This conventional clinical practice of pain-avoidance, however, lacks scientific comparison to alternative approaches. As such, there is currently no evidence to support or refute the efficacy of the conventional clinical practice of pain-free rehabilitation following acute muscle injury. The following double-blind randomised controlled trial aims to investigate whether allowing rehabilitation to be performed and progressed up to a pain-threshold rather than remaining pain-free alters the outcomes of HSI rehabilitation. The rehabilitation protocol and exercise-specific progression criteria detailed in chapter 5 are implemented in this study. The novel device described in chapter 4 is implemented to objectively measure knee flexor isometric strength and force impulse during HSI rehabilitation exercises.

#### 6.2. ABSTRACT

**Background:** Conventional guidelines recommend that hamstring strain injury (HSI) rehabilitation should only be performed and progressed in the complete absence of pain, despite lack of scientific comparison to alternative approaches.

**Objective:** This study aimed to investigate whether performing and progressing rehabilitation up to a pain-threshold alters time from HSI to RTP clearance, hamstring muscle structure and function and re-injury compared to remaining pain-free.

**Methods:** Forty-three men with an acute HSI were randomly allocated to either a pain-free (n=22) or pain-threshold (n=21) rehabilitation group. All participants completed a fully supervised progressive rehabilitation protocol twice per week. Pain had to be rated 0 on a 0-10 numeric rating scale (NRS) during exercise in the pain-free group. Participants in the pain-threshold group were permitted to perform and progress rehabilitation if they rated pain  $\leq$ 4 on a 0-10 NRS during exercise. Days from HSI to RTP clearance & re-injuries in the following six months were reported, along with biceps femoris long head (BFlh) fascicle length and isometric knee flexor strength.

**Results:** The median number of days from HSI to RTP clearance was 15 (95% CI = 13 to 17) in the pain-free group and 17 (95% CI = 11 to 24) in the pain-threshold group, which was not significantly different (p = 0.37). Both groups significantly increased BFlh fascicle length from initial clinical assessment to RTP clearance, although these improvements at two-month followup, were on average 0.91cm (95% CI = 0.34 to 1.48) greater in the pain-threshold group. The pain-threshold group achieved greater improvements in isometric knee flexor strength at 90/90 degrees of hip/knee flexion compared to the pain-free group at RTP clearance by an average of 15% (95% CI = 1 to 28) and two-month follow-up by an average of 15% (95% CI = 1 to 29). In the six months following RTP clearance, two re-injuries occurred in the both the pain-free (12%) & pain-threshold (10%) group.

**Conclusion:** This study has shown, for the first time, that allowing exercise to be performed and progressed up to a pain-threshold, results in equivalent time from HSI to RTP clearance and similar rates of re-injury to the conventional practice of pain avoidance, with additional benefits for hamstring muscle structure and function.

## **6.3. INTRODUCTION**

Hamstring strain injuries (HSIs) remain the most prevalent cause of time lost from competition in a range of sports [22, 38, 40, 99], with associated performance [48] and financial consequences [54]. Acutely following HSI, isometric strength and range of motion (ROM) deficits occur [8, 81, 105] and if persistent at return to play (RTP), can increase the risk of reinjury [30]. Following RTP clearance, previously injured hamstrings often display deficits in eccentric strength [76, 91, 93, 131] and biceps femoris long head (BFlh) fascicle length [130], both of which are modifiable risk factors for HSI [19, 96, 128, 137]. Regardless of whether these deficits were a cause or result of initial injury, they likely contribute to elevated risk of future HSI [43, 92], suggesting inadequacies in conventional rehabilitation practices.

Rehabilitation following acute HSI has been widely investigated via randomised controlled trials [1, 10, 11, 25, 50, 80, 84, 105, 111, 117], cohort studies [73, 79, 133] and systematic reviews [56, 82, 101]. Despite a variety of protocols, the guideline to only perform and progress rehabilitation exercises in the complete absence of pain is consistently implemented [56]. The recommendation to remain pain-free during rehabilitation is based on conventional guidelines for the treatment of acute muscle injuries [41, 68-71, 75, 78]. Such guidelines are largely informed by classical laboratory-based animal studies conducted over 40 years ago [60-64, 66], highlighting a need for contemporary investigations following acute muscle injury in humans.

There is suggestion that pain avoidance, particularly during early HSI rehabilitation, may limit exposure to an adequate stimulus for adaptation to variables such as eccentric strength and BFlh fascicle length [45]. For chronic or postoperative musculoskeletal conditions, allowing exercise to be performed up to a pain-threshold is safe [12, 44, 86, 114, 124, 126] and may improve outcomes compared to remaining pain-free [115, 118]. Despite the potential benefits of allowing exercise up to a pain-threshold, pain-free rehabilitation remains conventional practice with no study ever investigating divergent instructions about acceptable levels of pain during acute muscle injury rehabilitation.

Therefore, the aim of this study was to investigate whether allowing rehabilitation to be performed and progressed up to a pain-threshold alters hamstring muscle structure and function, time taken to achieve RTP clearance and rates of re-injury compared to remaining pain-free following acute HSI.

## **6.4. METHODS**

## Study design

This study was a single-centre, double-blind randomised controlled trial, designed and conducted at the Australian Catholic University in Melbourne, Australia. The Australian Catholic University Human Research Committee (2015-307H) granted ethical approval and the trial was registered with the Australian New Zealand Clinical Trials Registry (ANZCTR12616000307404).

## Participant recruitment and eligibility

Between February 2016 and May 2017 men and women aged 18 to 40 years were invited to undergo an initial clinical assessment within seven days of suspected acute HSI. Potential participants were recruited via contact made with sporting clubs and sports injury clinics around Melbourne and via social media advertisement. Informed written consent was provided by potential participants prior to undergoing a subjective interview and series of clinical assessments to confirm presence of acute HSI.

Potential participants had to meet all pre-determined eligibility criteria (Table 6.1) [84] to be included in the study. If potential participants presented with signs and symptoms of other causes of posterior thigh pain (hamstring tendinopathy, referred lower back pain etc.) or if the severity of their injury warranted surgical opinion, they were excluded from the study. An independent physiotherapist (ER) with 15 years' experience in sports injury clinical practice and research verified participant eligibility by reviewing relevant subjective interview and clinical assessment data.

 Table 6.1 Eligibility criteria for study inclusion.

Men and women aged 18 to 40 years

Acute onset posterior thigh pain associated with clear injury mechanism (eg. high speed running, kicking, bending over etc.) causing cessation of activity

Present for initial clinical assessment within seven days of suspected injury

Pain on palpation of the injured muscle

Pain localised to the site of injury during isometric knee flexor contraction

#### Randomisation

If eligible, participants were randomly allocated to either a pain-free or pain-threshold rehabilitation group after completion of their initial clinical assessment. A four-block randomisation approach, with stratification for previous HSI and gender was implemented. Four folders marked either 1) male/previous HSI, 2) male/first-time HSI, 3) female/previous HSI or 4) female/first-time HSI; each contained four sealed envelopes, two for both the pain-free and pain-threshold group. The lead investigator (JH) selected an envelope from the relevant folder which indicated either allocation to a pain-free of pain-threshold rehabilitation group. Envelopes were only replaced in their respective folders once all four had been selected.

Participants allocated to the pain-free group were only permitted to perform and progress rehabilitation in the complete absence of pain, rated 0 on a 0-10 numeric rating scale (NRS). In contrast, those in the pain threshold group were permitted to perform and progress rehabilitation in the presence of pain rated  $\leq 4$  on the 0-10 NRS. The 0-10 NRS was explained to all participants in the context of localised pain at the site of injury where 0 represented "absolutely no pain" and 10 was the "worst pain imaginable". Upon allocation, participants were informed only of the pain limits for performance and progression of rehabilitation applicable to their respective group. Participants provided written informed consent prior to commencing their respective rehabilitation protocol.

#### Blinding

All objective outcome measures were collected by members of the research team (DO, NM and RT) who were blinded to group allocation for the duration of the study. In addition, all participants were blinded to the presence of the alternative intervention, to reduce the possibility of cross-group contamination.

## Initial subjective interview

Injury details, demographic data and relevant injury history were all ascertained from an initial subjective interview. The subjective interview was conducted by the lead investigator (JH) a health professional with five years' clinical experience in musculoskeletal injury assessment and rehabilitation. Upon completion of the subjective interview, participants were asked to complete the 17 item Tampa Scale for Kinesiophobia (TSK) to assess fear of movement.

#### **Clinical assessments**

During each participant's initial visit to confirm presence of acute HSI and prior to each subsequent rehabilitation session, a series of clinical assessments were conducted. These clinical assessments were administered by members of the research team (DO, NM or RT) who were blinded to group allocation. Firstly, ultrasound images were acquired to ascertain biceps femoris long head (BFlh) architecture with participants at rest in a prone position (hips and knees in neutral). The same blinded investigator (RT) with published reliability (ICC = 0.96 to 0.98; %TE = 2.1 to 3.4) and experience [130] collected and later analysed all ultrasound images offline (MicroDicom, Version 0.7.8, Bulgaria). The scanning site was determined as the halfway point between the ischial tuberosity and knee joint fold, along the line of the BFlh. Images were taken along the longitudinal axis of the BFlh belly on the injured then contralateral uninjured leg utilising a 2-D, B-mode ultrasound (frequency, 12Mhz; depth, 8cm; field of view, 14 x 47mm) (GE Healthcare Vivid-*i*, Wauwatosa, U.S.A).

For each image, six points were digitised as described by Blazevich and colleagues [15], after which muscle thickness (MT) was defined as the distance between the superficial and intermediate aponeurosis of the BFlh. A fascicle of interest, which was the clearest and could be seen across the entire field of view, was then outlined and marked on the image. Pennation angle (PA) was defined as the angle between this fascicle and the intermediate fascicle. Aponeurosis angle (AA) was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal reference line across the captured image. Fascicle length (FL) was determined as the length of the outlined fascicle between the intermediate and superficial aponeurosis and reported in absolute terms (cm). As the entire fascicle was not visible in the field of view, fascicle length was estimated via a validated equation [15].

$$FL = sin (AA + 90^{\circ}) x MT/sin(180^{\circ} - (AA + 180^{\circ} - PA))$$

Participants remained in a prone position where the injured muscle was palpated to determine injury location and pain. The assessor palpated along the length of the injured muscle to identify the location of peak palpation pain. Participants were asked rate their pain on the 0-10 NRS with the peak value was recorded. The distance from the ischial tuberosity to the site of peak

palpation pain and the total cranio-caudal length of palpable pain were also measured in centimetres (cm) [8, 144].

Hamstring ROM was assessed via the passive straight leg raise (PSLR) [8, 110] and active knee extension (AKE) tests [49, 106]. For both the PSLR and AKE a digital inclinometer was placed on the anterior tibial border just below the tibial tuberosity to objectively measure the angle of hip flexion or knee extension respectively at the point of onset of localised pain or maximal tolerable stretch. Participants were asked to rate their pain on the 0-10 NRS if they experienced localised pain at the site of injury during either the PSLR or AKE tests. Three trials of the PSLR and AKE were performed on the uninjured then injured leg, with the highest ROM value and peak pain score recorded for each test.

Isometric knee flexor strength was assessed with the participant laying supine at 0/0 and 90/90 degrees of hip/knee flexion using a novel apparatus with published reliability, as described in chapter 4 [55]. In each position the uninjured leg was tested prior to the injured leg, with two warm-up repetitions at 50% then 75% of perceived maximal effort followed by three maximal effort isometric knee flexor contractions with a minimum 30 second inter-trial rest. Standardised instructions were given to "push your heel down into the strap, from complete rest without lifting up your heel, as fast and hard as you can, in three, two, one, go" with strong verbal encouragement provided to ensure maximal effort. When performing contractions with the injured leg, the additional instruction of contracting "to an intensity that you feel comfortable with" was given. Participants were asked to report any pain localised to the site of injury on the 0-10 NRS with the peak pain score recorded in each position. For each day of testing, isometric knee flexor strength at both 0/0 and 90/90 was defined as the highest recorded force output across the three repetitions for each leg, at each position. Isometric knee flexor strength of the injured leg was reported in percentage terms, relative the participant's contralateral uninjured leg at initial clinical assessment.

## Rehabilitation

All participants commenced rehabilitation immediately following their initial assessment confirming presence of HSI and subsequent group allocation. All participants performed a rehabilitation protocol with exercise-specific progression criteria, as outlined in chapter 5, within

their group's respective pain limits. In addition to these exercises, a nine stage progressive running protocol was implemented based on the work of Silder et al. [117], with acceleration, hold and deceleration phases of varying intensity and distance (Table 6.2). Rehabilitation was performed twice per week, with all sessions fully supervised by the same investigator (JH) until RTP clearance criteria were met.

**Table 6.2** Nine stage progressive running protocol. Participants commenced at stage 1 once participants could walk within their group's respective pain-limits. Participants progressed to the next stage once they could perform three repetitions within their group's respective pain-limits. No more than nine repetitions were permitted to be performed in a single rehabilitation session.

Stage	Acceleration phase	Hold phase	Deceleration phase
	(Intensity/distance)	(Intensity/distance)	(Intensity/distance)
1	Walk/20m	Jog/10m	Walk/20m
2	Walk/15m	Jog/20m	Walk/15m
3	Walk/10m	Jog/30m	Walk/10m
4	Jog/20m	Run/10m	Jog/20m
5	Jog/15m	Run/20m	Jog/15m
6	Jog/10m	Run/30m	Jog/10m
7	Run/20m	Sprint/10m	Run/20m
8	Run/15m	Sprint/20m	Run/15m
9	Run/10m	Sprint/30m	Run/10m

Walk = regular gait; Jog <50% of perceived maximal running speed; Run <70% perceived maximal running speed; Sprint >90% of perceived maximal running speed.

Pre-determined criteria (Table 6.3) were implemented to provide RTP clearance, which were identical for all participants and based on best available evidence.[5, 136] At the completion of the rehabilitation session when all RTP clearance criteria were met, participants repeated the TSK to assess fear of movement. The lead investigator (JH) provided the same standard recommendation to all participants, that they should complete at least two full on field training sessions prior to returning to competitive sport. However, the final decision to return to competitive sport was left to the participant and where relevant, coach and medical staff at their

sporting club. This approach to return to competitive sport was implemented to account for variation in sports, levels of competition and need for shared RTP decision making [5, 27, 113]. All participants were provided with the same general advice to try and continue with one hip dominant and one knee dominant rehabilitation exercise at least once per week, although compliance was not enforced or monitored.

**Table 6.3** Criteria for return to play clearance.

No pain on palpation of the injured muscle
No pain during range of motion (ROM) assessment, with ROM ~90% of contralateral
uninjured leg

No pain during maximal effort isometric knee flexor contraction at 0/0 and 90/90 degrees of hip/knee flexion

No pain or apprehension during sprinting at 100% of perceived maximal running intensity

## **Follow-up**

Following RTP clearance, participants were contacted at least once per month, for a six month period to monitor for re-injury. Participants were instructed to contact the lead investigator if they suspected re-injury, with all attempts made to confirm presence of acute HSI via clinical assessment. However, if this was not possible re-injury was confirmed via telephone conversation with the participant and communication with relevant contacts at the participant's sporting club such as a team physiotherapist. All suspected re-injuries were verified by an independent physiotherapist (ER) who was blinded to group allocation and was provided with all available objective and subjective information.

As close to two months following RTP clearance as possible, all participants, except those who had to that point suffered a re-injury, were requested to attend a follow-up assessment. This assessment was conducted entirely by the same blinded assessor (RT, DO or NM) as during rehabilitation, with BFlh muscle architecture, isometric knee flexor strength and the TSK assessed as previously described. In addition, eccentric knee flexor strength was assessed during

performance of the unilateral eccentric slider and NHE. For the unilateral eccentric slider, mean force impulse was measured across three repetitions on the uninjured then previously injured leg and normalised to body weight (N.s/kg), as described in chapter 3 using an apparatus with published reliability [55]. For the NHE, the average of peak force (N) was calculated for the left and right legs independently across three maximal effort repetitions using a device with published reliability [91]. Mean force impulse during the unilateral slider and average peak force during the NHE were reported in both absolute terms for the previously injured leg and relative to the contralateral uninjured leg.

#### **Outcome measures**

The number of days from acute HSI until RTP clearance was recorded and participants were then followed up for a six month period. The numbers of re-injuries were reported in both absolute terms and relative to the number of participants within each group completing six-month follow-up in percentage terms. BFlh fascicle length, isometric knee flexor strength at 0/0 and 90/90 and fear of movement were reported at initial clinical assessment, RTP clearance and two months following RTP clearance. Eccentric knee flexor strength was reported two months following RTP clearance via average peak force during the NHE and mean force impulse during the unilateral eccentric slider.

#### **Statistical analysis**

An a priori sample size calculation deemed it necessary to recruit a total of 29 participants to achieve 80% power and account for 20% dropout. This sample size calculation was based on an effect size of 1.2 comparing RTP time following two different rehabilitation protocols [10, 11].

All statistical analysis was performed in R version 3.4.3 [122], using custom written code. Intention-to-treat analysis was used to investigate the treatment effect on the number of days from acute HSI to RTP clearance using a Cox proportional-hazards model. Time to RTP clearance and survival from re-injury curves were fit via the Kaplan-Meier method using the "survival" package [123]. Participants who did not meet RTP clearance criteria were censored from analysis at the time of their last completed rehabilitation session. Participants who did not complete six-month re-injury follow-up were censored at the last time-point they were contacted.

Linear mixed models were used to investigate the effect of each rehabilitation protocol (group) on BFlh fascicle length, isometric knee flexor strength and fear of movement at RTP clearance and two-month follow-up (time). Linear mixed models were fit via restricted maximum likelihood using the "lme4" package [13]. Group, time and their interaction were treated as fixed effects, with participant modelled as a random effect to account for individual variability. Residuals were plotted and checked for approximate normality and statistical significance was assessed using 95% confidence intervals (95% CI).

As eccentric knee flexor strength was only assessed at a single time-point two months following RTP clearance, average peak force during the NHE and mean force impulse during the unilateral eccentric slider were compared between groups using a one-way ANOVA and Mann-Whitney U test, respectively, with significance set to p < 0.05. The Mann-Whitney U test was used in the case of the unilateral eccentric slider due to non-normally distributed data.

#### 6.5. RESULTS

#### **Participants**

Of 52 potential participants (all men) assessed for eligibility, 43 had an acute HSI confirmed via initial clinical assessment and were randomised to either a pain-free (n = 22) or pain-threshold (n = 21) rehabilitation group (Figure 6.1). All participants were adherent to rehabilitation and met RTP clearance criteria, apart from one participant in the pain-free group. This participant ceased rehabilitation 24 days following acute HSI without meeting RTP clearance criteria and was censored from further analysis at this time-point. One participant in the pain-threshold group suffered a re-injury when attempting to sprint during the progressive running portion of the rehabilitation protocol 15 days following initial HSI. This participant continued with pain-threshold rehabilitation two days after this incident and successfully met RTP clearance criteria two weeks later, which was 29 days from the initial HSI. No other adverse events occurred throughout the rehabilitation period in either group.

Of the 21 participants in the pain-free group who successfully completed rehabilitation, five participants did not complete two-month follow-up assessments. Four of these participants could not be contacted and one participant suffered a re-injury prior to two-month follow-up assessment. In the pain-threshold group, of the 21 participants who successfully completed

rehabilitation, three participants did not complete two-month follow-up. Two participants suffered re-injuries and one participant suffered an unrelated knee injury prior to two-month follow-up assessment. Therefore, 16 participants in the pain-free group and 18 participants in the pain-threshold group performed follow-up assessments in a mean  $\pm$  SD time from RTP clearance of 65  $\pm$  7 days and 68  $\pm$  10 days, respectively. Four of the 21 participants in the pain-free group who successfully completed rehabilitation were censored from six-month re-injury analysis at the last time-point they could be contacted following RTP clearance. One participant in the pain-threshold group was censored from six –month re-injury analysis at the time-point where they suffered an unrelated knee injury following RTP clearance.



**Figure 6.1** Consort diagram showing participant flow through study from enrolment to allocation, follow-up and analysis. Explanations are given where participants were excluded from either study inclusion of subsequent analysis.

#### **Return to play clearance & re-injury**

The median number of days from HSI until RTP clearance was 15 (95% CI = 13 to 17) in the pain-free group and 17 (95% CI = 11 to 24) in the pain-threshold group, which was not significantly different (p = 0.37) (Figure 6.2a). Two participants in each group suffered re-injuries during the six months following RTP clearance (Figure 6.2b).



**Figure 6.2** Time to return to play (RTP) clearance and re-injuries during six-month follow-up within each group. Panel a) shows the percentage of participants within each group achieving RTP clearance relative to the number of days from acute hamstring strain injury. The shaded area represents the 95% confidence intervals for each group. Where the blue and orange lines intersect the horizontal dotted line indicates the median number of days from acute hamstring strain injury to return to play clearance within the pain-free and pain-threshold group respectively. The ^ symbol indicates the one participant in the pain-free group who ceased rehabilitation without achieving return to play clearance. Panel b) shows the percentage of participants within each group avoiding re-injury in the six months following return to play clearance. The vertical dotted line indicated 182.5 days or six months from return to play clearance. The X symbol indicates the four participants in the pain-free group who were lost to follow-up and the last time-point they were contactable. The O symbol represents the one participant in the pain-free group and 18 participants in the pain-free group who completed six-month follow-up without re-injury.

## Biceps femoris long head fascicle length

From initial clinical assessment to RTP clearance, BFlh fascicle length significantly improved by an average of 1.70cm (95% CI = 1.33 to 2.08) in the pain-free group (Figure 6.3a) and 1.95cm (95% CI = 1.41 to 2.48) in the pain-threshold group (Figure 6.3b), with no significant difference between the two groups (95% CI = -0.29 to 0.78). Despite a slight reduction in the two months following RTP clearance, BFlh fascicle length was still significantly greater than initial clinical assessment by an average of 0.56cm (95% CI = 0.16 to 0.97) in the pain-free group and 1.47cm (95% CI = 0.90 to 2.04) in the pain-threshold group. The difference in BFlh fascicle length from initial clinical assessment to two-month follow-up was significantly greater in the pain-threshold group than the pain-free group by an average of 0.91cm (95% CI = 0.34 to 1.48).



**Figure 6.3** Biceps femoris long head fascicle length of the injured leg within each group at initial clinical assessment, return to play clearance and two-month follow-up. Each dot represents an individual participant, dotted lines indicate change over time and the solid horizontal line shows the group median.
### Isometric knee flexor strength

Significant improvements were seen in isometric knee flexor strength at 0/0 by an average of 32% (95% CI = 22 to 41) in the pain-free group (Figure 6.4a) and 39% (95% CI = 26 to 52) in the pain-threshold group (6.4b) from initial clinical assessment to RTP clearance, with no difference between groups (95% CI = -6 to 20). Isometric knee flexor strength at 0/0 remained significantly greater than initial clinical assessment in both groups two months following RTP clearance, with no difference between groups (95% CI = -6 to 22).

Isometric knee flexor strength at 90/90 improved significantly by an average of 35% (95%CI = 26 to 44) in the pain-free group (Figure 6.4c) and 49% (95%CI = 36 to 63) in the pain-threshold group (Figure 6.4d) from initial clinical assessment to RTP clearance. This improvement was significantly greater by an average of 15% (95%CI = 1 to 28) in the pain-threshold group. Two months following RTP clearance, improvement in isometric knee flexor strength at 90/90 from initial clinical assessment remained significantly greater by an average of 15% (95%CI = 1 to 29) in the pain-threshold group.



**Figure 6.4** Isometric knee flexor strength of the injured leg at 0/0 and 90/90 relative to the contralateral uninjured leg (%) within each group at initial clinical assessment, return to play clearance and two-month follow-up. Each dot represents an individual participant, dotted lines indicate change over time and the solid horizontal line shows the group median.

# Fear of movement

According to the TSK out of a maximum score of 68 points, fear of movement significantly reduced by an average of -7 points (95% CI = -5 to -9) in the pain-free group (Figure 6.5a) and - 8 points (95% CI = -5 to -11) in the pain-threshold group (Figure 6.5b) from initial clinical assessment to RTP clearance. Between group differences in reduction of fear of movement from initial clinical assessment of -1 point (95% CI = -4 to 2) at RTP clearance and -4 points (95% CI = -6 to 0) at two-month follow-up were non-significant.



**Figure 6.5** Fear of movement according to the Tampa Scale for Kinesiophobia within each group at initial clinical assessment, return to play clearance and two-month follow-up. Each dot represents an individual participant, dotted lines indicate change over time and the solid horizontal line shows the group median.

### **Eccentric knee flexor strength**

Two months following RTP clearance, mean force impulse during the unilateral slider was not significantly different in either absolute terms (p = 0.14) or relative to the contralateral uninjured leg (p = 0.88) between the pain-free group (13.1N.s/kg ± 7.0 and 106% ± 39) and pain-threshold group (16.7N.s/kg ± 7.2 and 108% ± 18). Average eccentric knee flexor strength during the NHE was not significantly different in either absolute terms (p = 0.08) or relative to the contralateral uninjured leg (p = 0.94) between the pain-free group (398N ± 102 and 101% ± 15) and pain-threshold group (452N ± 79 and 101% ± 17) two months following RTP clearance.

### 6.6. DISCUSSION

This double-blinded, randomised controlled trial has for the first time challenged the conventional clinical practice of pain-free rehabilitation following acute muscle injury. The main findings of this study are that 1) no difference is seen between pain-free and pain-threshold rehabilitation in the number of days taken to achieve RTP clearance, nor were re-injury rates during a six-month follow-up period different; 2) deficits in BFlh fascicle length, isometric and eccentric knee flexor strength and fear of movement were all adequately addressed by the rehabilitation protocol employed, regardless of group allocation; 3) allowing this rehabilitation protocol to be performed and progressed up to a pain-threshold resulted in better maintenance of BFlh fascicle length improvements two months following RTP clearance compared to pain-free rehabilitation and 4) greater recovery of isometric knee flexor strength at 90/90 from initial clinical assessment to RTP clearance and two-month follow-up was seen in the pain-threshold group compared to pain-free group.

At face value, the lack of difference in RTP clearance time and rates of re-injury between painfree and pain-threshold rehabilitation may seem unremarkable. However, pain-free rehabilitation has, for many years, been widely recommended and accepted as best clinical practice in the treatment of acute muscle injuries [41, 68-71, 75, 78], and this study, for the first time, refutes such notions of superiority. Further, pain-threshold rehabilitation may offer some additional benefits chiefly for the maintenance of BFlh fascicle length improvements and recovery of isometric knee flexor strength. As these additional benefits were achieved in the equivalent timeframes as pain-free rehabilitation, allowing exercise to be performed and progressed up to a painthreshold may provide clinicians with an opportunity to enhance adaptation under the pressure of expedited RTP time.

Better maintenance of BFlh fascicle length improvements at two months following RTP clearance could be explained by accelerated introduction of eccentric loading in the painthreshold group, as highlighted in chapter 5. However, both groups achieved significant improvement in BFlh fascicle length from initial clinical assessment to RTP clearance, suggesting the rehabilitation protocol exposed participants to adequate eccentric loading, regardless of group allocation. These increases in BFlh fascicle length from initial clinical assessment to RTP clearance were of a similar magnitude to those previously seen in uninjured males after two weeks of eccentric knee flexor exercise [129]. In contrast to the reversal of BFlh fascicle length improvements in the study by Timmins et al. after a period of de-training [129], in the current study, BFlh fascicle length remained increased compared to initial clinical assessment in both groups. All participants in the current study were encouraged to continue with some form of eccentric loading after RTP clearance, which may have reduced the decline in BFlh fascicle length, compared to complete removal of stimulus in the study by Timmins et al. [129]. These findings support the need to continue eccentric loading beyond RTP clearance in order to maintain improvements achieved throughout rehabilitation, or at least slow the decline, in BFlh fascicle length.

Recovery of isometric knee flexor strength relative to the contralateral uninjured leg was greater in the pain-threshold group at RTP clearance and two-month follow-up at 90/90. There was, however, no difference between groups when assessing isometric knee flexor strength at 0/0. The 90/90 position was generally more pain provoking and showed larger between-leg deficits than the 0/0 position at initial clinical assessment. These findings are consistent with recent work showing greater loss of strength at 90/90 degrees of hip/knee flexion compared to shorted muscle lengths following acute HSI [144]. Participants exposed to pain-threshold rehabilitation may have been more willing to perform maximal isometric knee flexor contractions in this position as they were less likely to see pain as a barrier to exercise. However, these between-group differences in isometric knee flexor strength were observed once pain was alleviated in both groups at RTP clearance and two-month follow-up. Pain-threshold rehabilitation may therefore be preferable for clinicians looking to maximise recovery of knee flexor strength under the pressures of expedited RTP clearance.

Despite greater recovery of isometric knee flexor strength at 90/90 in the pain-threshold group at both RTP clearance and two-month follow-up, this did not appear to influence subsequent reinjury risk. There is conflicting evidence as to whether knee flexor strength around the time of RTP clearance can indicate risk of re-injury. Between-leg deficits in isometric knee flexor strength just after RTP have been associated with small increases in re-injury risk following HSI rehabilitation [30]. Arbitrary cut-offs appear to be less useful, with between leg deficits  $\geq$ 10% in isokinetic knee flexor strength not indicative of re-injury at RTP clearance following HSI rehabilitation [131]. Data from the current study supports these findings with a greater number of participants in the pain-free group displaying residual deficits of  $\geq$ 10% in isometric knee flexor strength at RTP clearance, yet re-injury rates between groups were similar. However, studies with larger sample sizes and greater numbers of re-injuries are needed to truly determine whether objectively monitoring between-leg deficits in knee flexor strength has value as an indicator of re-injury risk.

In addition to isometric strength, eccentric knee flexor strength was measured two months following RTP clearance via the unilateral eccentric slider and NHE. Both groups demonstrated relative symmetry compared to their contralateral uninjured leg at this time point. These findings are in contrast to those of chapter 4, which showed average deficits of  $\geq$ 25% in previously injured hamstrings during the unilateral eccentric slider [55]. Force output during the NHE in both groups also compares favourably to the values achieved by participants with a previous HSI in other retrospective studies employing this methodology in absolute and relative terms [91, 130]. As eccentric knee flexor strength was only included as an outcome measure two months following RTP clearance, eccentric knee flexor strength prior to RTP clearance and acute HSI is unknown. Nevertheless, the results of the current study suggest that the rehabilitation protocol employed adequately addressed eccentric knee flexor strength, regardless of whether pain is or isn't allowed during exercise performance.

The avoidance of pain during acute muscle injury rehabilitation is largely driven by fear of symptom exacerbation and/or re-injury [69]. Pain-threshold rehabilitation did result in one re-injury while attempting to sprint 15 days post HSI. It must be noted, however, that this

participant did not report any pain during any of the six preceding repetitions performed in the session where re-injury occurred. As a result, it could be argued, that had this participant been in the pain-free group, re-injury would have been just as likely during that session. Regardless of this, no adverse events were reported when exercise was allowed to be performed and progressed in the presence of pain rated  $\leq 4$  on the 0-10 NRS.

The pain-threshold of  $\leq 4/10$  was selected as a slightly more conservative limit than the painmonitoring model of  $\leq 5/10$ , previously implemented in patellofemoral joint pain and Achilles tendinopathy rehabilitation [114, 115, 124]. Selection of an appropriate pain-threshold will always be somewhat of an arbitrary task given the complex and subjective nature of pain perception [89]. Upon reflection of this study, the authors recommend that clinicians consider an individualised approach to pain-threshold rehabilitation and focus on educating the injured athlete that it is safe and effective to exercise up to a low level of pain, which they feel comfortable with, rather than using an explicit number as a limit. Exposing participants to pain during exercise did not induce fear but rather reduced fear of movement from initial clinical assessment to RTP clearance to an equivalent extent as pain-free rehabilitation. As such, the findings of the current study refute the long-held belief that pain should be completely avoided when performing exercise during acute muscle injury rehabilitation.

The methodological strengths of the current study lie in its double-blind randomised controlled trial design. Investigators collecting all outcome measures were blinded to group allocation, which reduces risk of bias and participants were blinded to the presence of an alternative intervention, which reduced risk of contamination between groups. All rehabilitation sessions were performed in the same setting fully supervised by the same investigator, with over five years' experience in musculoskeletal injury rehabilitation.

Despite these aforementioned methodological strengths, the current study is certainly not without limitations. Confirmation of acute HSI was restricted to clinical assessment, with diagnostic tools such as magnetic resonance imaging (MRI) not utilised, which may limit the ability to determine injury severity. However, it has recently been shown that MRI adds little to no value on top of clinical assessment as a prognostic tool following HSI [59, 141]. Many clinicians working with sports injuries are restricted to using clinical assessments, as described in this study, to confirm presence of acute HSI, enhancing the ecological validity of the current findings.

# **6.7. CONCLUSION**

Allowing exercise to be performed and progressed up to a pain-threshold results in equivalent time from HSI to RTP clearance and similar rates of re-injury compared to pain-free rehabilitation. Clinicians looking to maximise recovery of isometric knee flexor strength and better preserve improvements in BFlh fascicle length should consider allowing exercise rehabilitation to be performed and progressed up to a pain-threshold. Overall, it is not necessary to completely avoid pain during HSI rehabilitation and as a result, conventional guidelines for the treatment of acute muscle injury should be re-considered.

#### **Chapter 7 – General discussion, limitations and conclusion**

This program of research has detailed alternative approaches to the objective monitoring of knee flexor strength and exercise progression during HSI rehabilitation. Conventional guidelines for HSI rehabilitation, which have long been held as best clinical practice without evidence to support or refute their efficacy, have been questioned. The general concept that inadequacies exist in conventional HSI rehabilitation practices, was introduced in chapter 1, by highlighting evidence of elevated re-injury risk and persistent deficits in BFlh fascicle length and eccentric knee flexor strength in previously injured hamstrings. It is this overarching concept of shortcomings with conventional HSI rehabilitation, which has driven this program of research.

The scientific literature pertaining to HSI rehabilitation progression and RTP decision making was systematically reviewed in chapter 3. A common theme identified amongst the included studies, was the lack of objectivity involved in rehabilitation progression and RTP clearance decision making. Although knee flexor strength was explicitly mentioned in eight of the nine included studies as part of rehabilitation progression and/or RTP criteria, it was rarely measured objectively. Only three of the nine included studies implemented objective knee flexor strength measures as part of RTP decision making and did so using isokinetic dynamometry, a laboratory based and expensive methodology not readily available to the clinician dealing with HSI rehabilitation. Other studies not included in the systematic review, have shown hand-held dynamometry to be a more readily available objective measure of knee flexor strength [104, 143], however, this methodology is limited by clinician strength and skill [17, 143].

Cognisant of the limitations in objective monitoring tools, chapter 4 aimed to improve the clinician's ability to measure knee flexor strength during a range of exercises often used in HSI rehabilitation. A novel apparatus was developed utilising relatively inexpensive load cells (to measure force output) and equipment typically available to the clinician dealing with HSI rehabilitation. The novel apparatus was shown to be moderately to highly reliable when measuring isometric knee flexor strength, peak RFD and mean force impulse during an eccentric slider. Beyond merely establishing test-retest reliability, chapter 4 also highlighted the ability of this novel apparatus to identify moderate to large deficits in isometric knee flexor strength, peak RFD and mean force impulse during the ability of this novel apparatus to identify moderate to large deficits in isometric knee flexor strength, peak RFD and mean force impulse during a unilateral eccentric slider in previously injured hamstrings. This novel apparatus may improve the clinician's ability to objectively identify

deficits in both isometric and eccentric knee flexor strength during HSI rehabilitation prior to RTP clearance.

Objectively identifying deficits knee flexor strength is, however, only one piece of the HSI rehabilitation puzzle. It is the goal of HSI rehabilitation to address deficits in variables such as knee flexor strength prior to RTP clearance. Exposure to interventions that provide beneficial stimulus for adaptation is somewhat dependent on how rehabilitation is progressed, a concept introduced in chapter 1. Chapter 3 identified that HSI rehabilitation is often progressed using a wide variety of criteria, which are largely based on clinical expertise and opinion, rather than empirical evidence of their efficacy. In particular, the introduction of eccentric loading is typically delayed until the alleviation of pain during isometric knee flexor contractions. Further to this, it has been recommended that isometric knee flexor strength should be  $\geq$ 90% of the contralateral uninjured leg prior to introducing eccentric loading [83, 84]. However, the efficacy of these guidelines for the introduction of eccentric loading had not been previously investigated prior to chapter 5.

Chapter 5 described a HSI rehabilitation protocol using exercise-specific progression criteria to accelerate the introduction of eccentric loading. Utilising these exercise-specific progression criteria, eccentric loading was able to be introduced prior to the alleviation of pain and/or between-leg deficits in isometric knee flexor strength. This early introduction of eccentric loading was well tolerated by participants, which suggests that waiting for the alleviation of pain and/or strength deficits during isometric knee flexor contractions, may unnecessarily delay exposure to stimulus known to elicit beneficial adaptation. The benefits of accelerated eccentric loading were seen in chapter 6 with significant increases in BFlh fascicle length and knee flexor strength in participants with an acute HSI who completed this rehabilitation protocol.

Apart from the variety of criteria used to progress HSI rehabilitation, chapter 3 confirmed that by far the most commonly implemented guideline is to only perform and progress exercises in the complete absence of pain. Prior to chapter 6, no study had compared the outcomes of pain-free rehabilitation to an alternative approach following acute muscle injury. Chapter 6 addressed this gap in the literature through a double-blind randomised controlled trial comparing pain-free and pain-threshold HSI rehabilitation.

Pain-free and pain-threshold rehabilitation resulted in equivalent time from acute HSI to RTP clearance and both achieved significant increases in BFlh fascicle length and isometric knee flexor strength. However, pain-threshold rehabilitation resulted in greater improvements in isometric knee flexor strength at 90/90 compared to pain-free rehabilitation in the equivalent number of days from HSI to RTP clearance. Pain-threshold rehabilitation also resulted in significantly greater increases in BFlh fascicle length at two-month follow-up relative to initial clinical assessment compared to the pain-free group. In the six months following RTP clearance, both the pain-free and pain-threshold group suffered two re-injuries each. Despite a single re-injury during rehabilitation in the pain-threshold group, no adverse events were reported with the performance and progression of exercise in the presence of pain rated  $\leq 4/10$ . As such, chapter 6 questioned the long held belief that pain-free rehabilitation is best practice in the treatment of acute muscle injury and provided clinicians with evidence to support implementation of a relatively safe and effective alternative.

The concept of allowing pain during exercise rehabilitation is in itself not completely new. Approximately 20 years prior to this program of research, Thomee et al. described the pain-monitoring model, which allowed exercise to be performed in the presence of pain rated  $\leq 5/10$  out of 10 in females with patellofemoral joint pain [124]. This pain-monitoring model was then adapted by Silbernagel at al. for Achilles tendinopathy and implemented to allow eccentric overload training [115] and the continuation of sports activity [114]. In HSI rehabilitation, there is a case report on five professional Rugby League players with HSI where pain rated as "mild ache, the equivalent of 1 out of 10 on a visual analogue scale" was allowed during progressive running [53]. Along similar lines, Kilcoyne et al. allowed progressive running to be performed in the presence of pain rated up to 1-2 out of 10, but that sharp pain should be avoided [73]. More recently, Mendiguchia et al. reported that "mild discomfort" was allowed during the execution of exercises in their HSI rehabilitation algorithm [84], without reporting a numerical rating of pain.

What sets the current program of research apart from these aforementioned examples is that the double-blinded randomised controlled trial detailed in chapter 6, directly compared the outcomes of pain-free and pain-threshold rehabilitation. The rehabilitation protocol implemented in chapter 6 was identical apart from the fact that exercise was either permitted to be performed and progressed in the presence of pain rated 0 or  $\leq$  4 on the 0-10 NRS in the pain-free and pain-

threshold groups, respectively. Although the previously mentioned examples allowed pain during exercise, they either compared to a different rehabilitation protocol [84, 114, 115, 124] or did not have a control group [53, 73]. As such, chapter 6, for the first time, addressed the question whether allowing exercise to be performed and progressed up to a pain-threshold alters the outcomes of rehabilitation compared to the conventional approach of pain avoidance.

The outcomes of this program of research have numerous implications for clinicians dealing with HSI in their day-to-day practice. Allowing exercises to be performed and progressed in the presence of pain rated  $\leq 4$  was shown to be safe and resulted in some further improvements in isometric knee flexor strength and BFlh fascicle length. The key clinical implication here is however, not superiority of pain-threshold rehabilitation, but rather that it is not necessary to completely avoid pain when performing and progressing HSI rehabilitation, contrary to conventional guidelines for the treatment of acute muscle injuries.

It should be emphasised that regardless of whether pain was or wasn't allowed during performance and progression of exercise, the rehabilitation protocol first described in chapter 5 was able to address deficits in BFlh fascicle length and isometric knee flexor strength in the equivalent time from HSI to RTP clearance. In addition to this, residual deficits in BFlh fascicle length [127, 130] and eccentric knee flexor strength [55, 91], commonly seen in previously inured hamstrings, were absent from both groups two months following RTP clearance. Therefore the rehabilitation protocol described in chapter 5 appears to have addressed some of the apparent inadequacies in HSI rehabilitation suggested in chapter 1, regardless of whether pain was or wasn't allowed during exercise.

The most clinically beneficial component of the rehabilitation protocol described in chapters 5 appears to be the exercise-specific progression criteria which allowed for the accelerated introduction of eccentric loading during HSI rehabilitation. The ambiguity and lack of evidence that exists within guidelines for the progression of HSI rehabilitation was highlighted in the systematic review in chapter 3. Much of what is regularly implemented and recommended is based on expert opinion and clinical experience, rather than scientific evidence. A prime example of this is the recommendation to delay the introduction of eccentric loading until the alleviation of pain and between-leg deficits  $\geq 10\%$  during assessment of isometric knee flexor strength. The findings of chapter 5 refute these recommendations and show that it is not

necessary to wait until the alleviation pain and/or between-leg deficits  $\geq 10\%$  in isometric knee flexor strength prior to introducing eccentric loading during HSI rehabilitation. As such, clinicians should aim to progress and regress exercise rehabilitation along a continuum using exercise-specific criteria rather that independent clinical assessments such as isometric knee flexor strength tests.

This program of research was not without limitations. As chapter 3 aimed to identify HSI rehabilitation progression and RTP criteria and associations with convalescence time and reinjury rates, only studies reporting these outcome measures were included in the systematic review. Alternative rehabilitation progression and RTP criteria recommended or implemented in other studies to those in the systematic review may have, therefore, been overlooked. However, other studies describing criteria used for rehabilitation progression and RTP decision making were discussed throughout the thesis (chapters 1 and 5). The retrospective findings of chapter 4 are limited to a relatively small sample size of 10 males with history of unilateral HSI. Retrospective investigations of this nature also shed little light on whether deficits in previously injured hamstrings were a cause or result of initial HSI. History of HSI was limited to subjective reporting of the participant without confirmatory diagnostic tools such as MRI, a limitation also consistent across chapters 5 and 6. However, as many clinicians do not have access to diagnostic tools such as MRI; subjective reporting of injury history and confirmation of acute HSI via clinical assessment is the most externally valid methodology in HSI rehabilitation.

In conclusion, this program of research has not only questioned conventional clinical practices, but provided clinicians with objective tools to monitor knee flexor strength and alternative guidelines for the progression of exercise and introduction of eccentric loading during HSI rehabilitation. The main findings of this program of research will hopefully not only serve to improve HSI rehabilitation, but drive a healthy questioning of conventional clinical practices, which may lack evidence to support or refute their efficacy, in a range of musculoskeletal injuries and conditions.

## **Chapter 8 - References**

- A Hamid MS, Mohamed Ali MR, Yusof A, George J, Lee LPC. Platelet-rich plasma injections for the treatment of hamstring injuries: A randomized controlled trial. Am J Sports Med. 2014;42(10):2410-2418.
- Ahmad CS, Dick RW, Snell E, Kenney ND, Curriero FC, Pollack K, et al. Major and minor league baseball hamstring injuries: Epidemiologic findings from the major league baseball injury surveillance system. Am J Sports Med. 2014;42(6):1464-70.
- Al Attar WSA, Soomro N, Sinclair PJ, Pappas E, Sanders RH. Effect of injury prevention programs that include the Nordic hamstring exercise on hamstring injury rates in soccer players: A systematic review and meta-analysis. Sports Med. 2017;47(5):907-916.
- Alonso-Fernandez D, Docampo-Blanco P,Martinez-Fernandez J. Changes in muscle architecture of biceps femoris induced by eccentric strength training with nordic hamstring exercise. Scand J Med Sci Sports. 2018;28(1):88-94.
- Ardern CL, Glasgow P, Schneiders A, Witvrouw E, Clarsen B, Cools A, et al. 2016 consensus statement on return to sport from the first world congress in sports physical therapy, Bern. Br J Sports Med. 2016;50(14):853-64.
- 6. Arnason A, Andersen TE, Holme I, Engebretsen L,Bahr R. Prevention of hamstring strains in elite soccer: An intervention study. Scand J Med Sci Sports. 2008;18(1):40-8.
- Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. Scand J Med Sci Sports. 2003;13(4):244-50.
- 8. Askling C, Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. Br J Sports Med. 2006;40(1):40-4.
- Askling CM, Nilsson J, Thorstensson A. A new hamstring test to complement the common clinical examination before return to sport after injury. Knee Surg Sports Traumatol Arthrosc. 2010;18(12):1798-803.
- Askling CM, Tengvar M, Tarassova O, Thorstensson A. Acute hamstring injuries in swedish elite sprinters and jumpers: A prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2014;48(7):532-9.

- Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: A prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2013;47(15):953-9.
- Bandholm T, Thorborg K, Lunn TH, Kehlet H,Jakobsen TL. Knee pain during strength training shortly following fast-track total knee arthroplasty: A cross-sectional study. PLoS One. 2014;9(3):e91107.
- Bates DM, M; Bolker, B; Walker, S. Fitting linear mixed-effects models using lme4. Journal of Statistical Software. 2015;67(1):1-48.
- Batterham AM,Hopkins WG. Making meaningful inferences about magnitudes. Int J Sports Physiol Perform. 2006;1(1):50-7.
- 15. Blazevich AJ, Gill ND,Zhou S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. J Anat. 2006;209(3):289-310.
- 16. Bohannon RW. Manual muscle testing: Does it meet the standards of an adequate screening test? Clin Rehabil. 2005;19(6):662-7.
- 17. Bohannon RW. Test-retest reliability of hand-held dynamometry during a single session of strength assessment. Phys Ther. 1986;66(2):206-209.
- 18. Bourne MN, Duhig SJ, Timmins RG, Williams MD, Opar DA, Al Najjar A, et al. Impact of the nordic hamstring and hip extension exercises on hamstring architecture and morphology: Implications for injury prevention. Br J Sports Med. 2017;51(5):469-477.
- Bourne MN, Opar DA, Williams MD, Shield AJ. Eccentric knee flexor strength and risk of hamstring injuries in rugby union: A prospective study. Am J Sports Med. 2015;43(11):2663-70.
- Bourne MN, Timmins RG, Opar DA, Pizzari T, Ruddy JD, Sims C, et al. An evidencebased framework for strengthening exercises to prevent hamstring injury. Sports Med. 2018;48(2):251-267.
- Breno de ARAJ, Marques VB, Vaz MA,Baroni BM. Four weeks of Nordic hamstring exercise reduce muscle injury risk factors in young adults. J Strength Cond Res. 2017; April 26. doi:10.1519/JSC.000000000001975. [Epub ahead of print].
- Brooks JH, Fuller CW, Kemp SP,Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. Am J Sports Med. 2006;34(8):1297-306.

- Brukner P. Hamstring injuries: Prevention and treatment-an update. Br J Sports Med. 2015;49(19):1241-4.
- Brukner P,Connell D. 'Serious thigh muscle strains': Beware the intramuscular tendon which plays an important role in difficult hamstring and quadriceps muscle strains. Br J Sports Med. 2016;50(4):205-8.
- 25. Cibulka MT, Rose SJ, Delitto A,Sinacore DR. Hamstring muscle strain treated by mobilizing the sacroiliac joint. Phys Ther. 1986;66(8):1220-3.
- 26. Clanton TO,Coupe KJ. Hamstring strains in athletes: Diagnosis and treatment. J Am Acad Orthop Surg. 1998;6(4):237-248.
- 27. Creighton DW, Shrier I, Shultz R, Meeuwisse WH, Matheson GO. Return-to-play in sport: A decision-based model. Clin J Sport Med. 2010;20(5):379-85.
- Croisier JL, Forthomme B, Namurois MH, Vanderthommen M, Crielaard JM. Hamstring muscle strain recurrence and strength performance disorders. Am J Sports Med. 2002;30(2):199-203.
- Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. Am J Sports Med. 2008;36(8):1469-75.
- 30. De Vos RJ, Reurink G, Goudswaard GJ, Moen MH, Weir A, Tol JL. Clinical findings just after return to play predict hamstring re-injury, but baseline MRI findings do not. Br J Sports Med. 2014;48(18):1377-84.
- Delvaux F, Rochcongar P, Bruyere O, Bourlet G, Daniel C, Diverse P, et al. Return-toplay criteria after hamstring injury: Actual medicine practice in professional soccer teams. J Sports Sci Med. 2014;13(3):721-3.
- 32. DeWitt J,Vidale T. Recurrent hamstring injury: Consideration following operative and non-operative management. Int J Sports Phys Ther. 2014;9(6):798-812.
- 33. Downs SH,Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health. 1998;52(6):377-84.
- Drezner JA. Practical management: Hamstring muscle injuries. Clin J Sport Med. 2003;13(1):48-52.

- 35. Ekegren CL, Gabbe BJ, Donaldson A, Cook J, Lloyd D, Finch CF. Injuries in communitylevel australian football: Results from a club-based injury surveillance system. J Sci Med Sport. 2015;18(6):651-5.
- 36. Ekstrand J. Keeping your top players on the pitch: The key to football medicine at a professional level. Br J Sports Med. 2013;47(12):723-724.
- 37. Ekstrand J, Hagglund M, Walden M. Epidemiology of muscle injuries in professional football (soccer). Am J Sports Med. 2011;39(6):1226-32.
- 38. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: The UEFA injury study. Br J Sports Med. 2011;45(7):553-8.
- 39. Ekstrand J, Walden M, Hagglund M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: A 13-year longitudinal analysis of the UEFA elite club injury study. Br J Sports Med. 2016;50(12):731-7.
- 40. Elliott MC, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: A 10-year review. Am J Sports Med. 2011;39(4):843-50.
- 41. Fernandes TL, Pedrinelli A,Hernandez AJ. Muscle injury physiopathology, diagnosis, treatment and clinical presentation. Rev Bras Ortop. 2011;46(3):247-55.
- 42. Fournier-Farley C, Lamontagne M, Gendron P,Gagnon DH. Determinants of return to play after the nonoperative management of hamstring injuries in athletes: A systematic review. Am J Sports Med. 2016;44(8):2166-72.
- 43. Freckleton G,Pizzari T. Risk factors for hamstring muscle strain injury in sport: A systematic review and meta-analysis. Br J Sports Med. 2013;47(6):351-8.
- 44. Frohm A, Saartok T, Halvorsen K,Renstrom P. Eccentric treatment for patellar tendinopathy: A prospective randomised short-term pilot study of two rehabilitation protocols. Br J Sports Med. 2007;41(7):e7.
- 45. Fyfe JJ, Opar DA, Williams MD,Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. J Electromyogr Kinesiol. 2013;23(3):523-30.
- 46. Gabbe B, Finch C, Wajswelner H,Bennell K. Australian football: Injury profile at the community level. J Sci Med Sport. 2002;5(2):149-60.
- 47. Garrett WE, Jr., Safran MR, Seaber AV, Glisson RR,Ribbeck BM. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. Am J Sports Med. 1987;15(5):448-54.

- 48. Hagglund M, Walden M, Magnusson H, Kristenson K, Bengtsson H, Ekstrand J. Injuries affect team performance negatively in professional football: An 11-year follow-up of the UEFA champions league injury study. Br J Sports Med. 2013;47(12):738-42.
- 49. Hamid MS, Ali MR, Yusof A. Interrater and intrarater reliability of the active knee extension (AKE) test among healthy adults. J Phys Ther Sci. 2013;25(8):957-61.
- 50. Hamilton B, Tol JL, Almusa E, Boukarroum S, Eirale C, Farooq A, et al. Platelet-rich plasma does not enhance return to play in hamstring injuries: A randomised controlled trial. Br J Sports Med. 2015;49(14):943-950.
- 51. Hegedus EJ,Cook CE. Return to play and physical performance tests: Evidence-based, rough guess or charade? Br J Sports Med. 2015;49(20):1288-9.
- 52. Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, Thelen DG. Hamstring strain injuries: Recommendations for diagnosis, rehabilitation, and injury prevention. J Orthop Sports Phys Ther. 2010;40(2):67-81.
- 53. Herrington L. Patients with hamstring muscle strains returning to sport in less than 14 days: A case report of treatment used. Phys Ther Sport. 2000;1(137-138.
- 54. Hickey J, Shield AJ, Williams MD,Opar DA. The financial cost of hamstring strain injuries in the australian football league. Br J Sports Med. 2014;48(8):729-30.
- 55. Hickey JT, Hickey PF, Maniar N, Timmins RG, Williams MD, Pitcher CA, et al. A novel apparatus to measure knee flexor strength during various hamstring exercises: A reliability and retrospective injury study. J Orthop Sports Phys Ther. 2018;48(2):72-80.
- 56. Hickey JT, Timmins RG, Maniar N, Williams MD,Opar DA. Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: A systematic review. Sports Med. 2017;47(7):1375-1387.
- 57. Hopkins WG. Spreadsheets for analysis of validity and reliability. Sportscience. 2015;19(36-42.
- 58. Hoskins W,Pollard H. Hamstring injury management--part 2: Treatment. Man Ther. 2005;10(3):180-90.
- 59. Jacobsen P, Witvrouw E, Muxart P, Tol JL, Whiteley R. A combination of initial and follow-up physiotherapist examination predicts physician-determined time to return to play after hamstring injury, with no added value of mri. Br J Sports Med. 2016;50(7):431-9.

- 60. Jarvinen M. Healing of a crush injury in rat striated muscle. 2. A histological study of the effect of early mobilization and immobilization on the repair processes. Acta Pathol Microbiol Scand A. 1975;83(3):269-82.
- 61. Jarvinen M. Healing of a crush injury in rat striated muscle. 3. A micro-angiographical study of the effect of early mobilization and immobilization on capillary ingrowth. Acta Pathol Microbiol Scand A. 1976;84(1):85-94.
- 62. Jarvinen M. Healing of a crush injury in rat striated muscle. 4. Effect of early mobilization and immobilization on the tensile properties of gastrocnemius muscle. Acta Chir Scand. 1976;142(1):47-56.
- 63. Jarvinen M. Immobilization effect on the tensile properties of striated muscle: An experimental study in the rat. Arch Phys Med Rehabil. 1977;58(3):123-7.
- 64. Jarvinen M,Sorvari T. Healing of a crush injury in rat striated muscle. 1. Description and testing of a new method of inducing a standard injury to the calf muscles. Acta Pathol Microbiol Scand A. 1975;83(2):259-65.
- 65. Jarvinen MJ, Einola SA, Virtanen EO. Effect of the position of immobilization upon the tensile properties of the rat gastrocnemius muscle. Arch Phys Med Rehabil. 1992;73(3):253-7.
- 66. Jarvinen MJ,Lehto MU. The effects of early mobilisation and immobilisation on the healing process following muscle injuries. Sports Med. 1993;15(2):78-89.
- 67. Jarvinen TA, Jarvinen M,Kalimo H. Regeneration of injured skeletal muscle after the injury. Muscles Ligaments Tendons J. 2013;3(4):337-45.
- Jarvinen TA, Jarvinen TL, Kaariainen M, Aarimaa V, Vaittinen S, Kalimo H, et al. Muscle injuries: Optimising recovery. Best Pract Res Clin Rheumatol. 2007;21(2):317-31.
- Jarvinen TA, Jarvinen TL, Kaariainen M, Kalimo H, Jarvinen M. Muscle injuries: Biology and treatment. Am J Sports Med. 2005;33(5):745-64.
- 70. Jarvinen TA, Kaariainen M, Jarvinen M,Kalimo H. Muscle strain injuries. Curr Opin Rheumatol. 2000;12(2):155-61.
- 71. Kannus P. Immobilization or early mobilization after an acute soft-tissue injury? Phys Sportsmed. 2000;28(3):55-63.

- 72. Khan KM,Scott A. Mechanotherapy: How physical therapists' prescription of exercise promotes tissue repair. Br J Sports Med. 2009;43(4):247-52.
- 73. Kilcoyne KG, Dickens JF, Keblish D, Rue J-P, Chronister R. Outcome of grade i and ii hamstring injuries in intercollegiate athletes: A novel rehabilitation protocol. Sports Health. 2011;3(6):528-533.
- 74. Kollock RO, Jr., Onate JA, Van Lunen B. The reliability of portable fixed dynamometry during hip and knee strength assessments. J Athl Train. 2010;45(4):349-56.
- 75. Kujala UM, Orava S,Järvinen M. Hamstring injuries. Current trends in treatment and prevention. Sports Medicine (Auckland, N.Z.). 1997;23(6):397-404.
- 76. Lee MJ, Reid SL, Elliott BC,Lloyd DG. Running biomechanics and lower limb strength associated with prior hamstring injury. Med Sci Sports Exerc. 2009;41(10):1942-51.
- Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N,Duchateau J. Rate of force development: Physiological and methodological considerations. Eur J Appl Physiol. 2016;116(6):1091-116.
- 78. Maffulli N, Oliva F, Frizziero A, Nanni G, Barazzuol M, Via AG, et al. ISMuLT guidelines for muscle injuries. Muscles Ligaments Tendons J. 2013;3(4):241-9.
- Malliaropoulos N, Papacostas E, Kiritsi O, Papalada A, Gougoulias N,Maffulli N. Posterior thigh muscle injuries in elite track and field athletes. Am J Sports Med. 2010;38(9):1813-9.
- Malliaropoulos N, Papalexandris S, Papalada A, Papacostas E. The role of stretching in rehabilitation of hamstring injuries: 80 athletes follow-up. Med Scie Sports Exerc. 2004;36(5):756-759.
- Maniar N, Shield AJ, Williams MD, Timmins RG,Opar DA. Hamstring strength and flexibility after hamstring strain injury: A systematic review and meta-analysis. Br J Sports Med. 2016;50(15):909-20.
- Mason DL, Dickens VA, Vail A. Rehabilitation for hamstring injuries. The Cochrane Database Of Systematic Reviews. 2012;12(CD004575.
- Mendiguchia J,Brughelli M. A return-to-sport algorithm for acute hamstring injuries. Phys Ther Sport. 2011;12(1):2-14.

- Mendiguchia J, Martinez-Ruiz E, Edouard P, Morin JB, Martinez-Martinez F, Idoate F, et al. A multifactorial, criteria-based progressive algorithm for hamstring injury treatment. Med Sci Sports Exerc. 2017;49(7):1482-92.
- 85. Mentiplay BF, Perraton LG, Bower KJ, Adair B, Pua YH, Williams GP, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study. Plos One. 2015;10(10):e0140822.
- 86. Mikkelsen LR, Petersen AK, Mechlenburg I, Mikkelsen S, Soballe K, Bandholm T. Description of load progression and pain response during progressive resistance training early after total hip arthroplasty: Secondary analyses from a randomized controlled trial. Clin Rehabil. 2017;31(1):11-22.
- Mirkov DM, Knezevic OM, Maffiuletti NA, Kadija M, Nedeljkovic A, Jaric S. Contralateral limb deficit after ACL-reconstruction: An analysis of early and late phase of rate of force development. J Sports Sci. 2017;35(5):435-440.
- Moher D, Liberati A, Tetzlaff J, Altman DG,Group P. Preferred reporting items for systematic reviews and meta-analyses: The prisma statement. PLoS Med. 2009;6(7):e1000097.
- Moseley GL. Reconceptualising pain according to modern pain science. Phys Ther Rev. 2007;12(3):169-178.
- 90. Opar D, Drezner J, Shield A, Williams M, Webner D, Sennett B, et al. Acute injuries in track and field athletes: A 3-year observational study at the penn relays carnival with epidemiology and medical coverage implications. Am J Sports Med. 2015;43(4):816-22.
- 91. Opar DA, Piatkowski T, Williams MD,Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: A reliability and retrospective injury study. J Orthop Sports Phys Ther. 2013;43(9):636-40.
- 92. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: Factors that lead to injury and re-injury. Sports Med. 2012;42(3):209-26.
- 93. Opar DA, Williams MD, Timmins RG, Dear NM,Shield AJ. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. J Electromyogr Kinesiol. 2013;23(3):696-703.

- 94. Opar DA, Williams MD, Timmins RG, Dear NM, Shield AJ. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. Am J Sports Med. 2013;41(1):116-25.
- 95. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ,Shield AJ. Eccentric hamstring strength and hamstring injury risk in australian footballers. Med Sci Sports Exerc. 2015;47(4):857-65.
- 96. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ,Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. Med Sci Sports Exerc. 2015;47(4):857-65.
- 97. Orchard J,Best TM. The management of muscle strain injuries: An early return versus the risk of recurrence. Clin J Sport Med. 2002;12(1):3-5.
- Orchard J, Best TM, Verrall GM. Return to play following muscle strains. Clin J Sport Med. 2005;15(6):436-41.
- 99. Orchard JW, Seward H,Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian football league. Am J Sports Med. 2013;41(4):734-41.
- 100. Page P. Pathophysiology of acute exercise-induced muscular injury: Clinical implications. J Athl Train. 1995;30(1):29-34.
- 101. Pas HI, Reurink G, Tol JL, Weir A, Winters M, Moen MH. Efficacy of rehabilitation (lengthening) exercises, platelet-rich plasma injections, and other conservative interventions in acute hamstring injuries: An updated systematic review and metaanalysis. Br J Sports Med. 2015;49(18):1197-205.
- 102. Petersen J, Thorborg K, Nielsen MB, Budtz-Jørgensen E,Hölmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: A cluster-randomized controlled trial. The Am J Sports Med. 2011;39(11):2296-2303.
- 103. Pollock N, Patel A, Chakraverty J, Suokas A, James SL, Chakraverty R. Time to return to full training is delayed and recurrence rate is higher in intratendinous ('c') acute hamstring injury in elite track and field athletes: Clinical application of the British athletics muscle injury classification. Br J Sports Med. 2016;50(5):305-10.
- 104. Reurink G, Goudswaard GJ, Moen MH, Tol JL, Verhaar JA, Weir A. Strength measurements in acute hamstring injuries: Intertester reliability and prognostic value of handheld dynamometry. J Orthop Sports Phys Ther. 2016;46(8):689-96.

- 105. Reurink G, Goudswaard GJ, Moen MH, Weir A, Verhaar JAN, Bierma-Zeinstra SMA, et al. Rationale, secondary outcome scores and 1-year follow-up of a randomised trial of platelet-rich plasma injections in acute hamstring muscle injury: The Dutch hamstring injection therapy study. Br J Sports Med. 2015;49(18):1206-12.
- 106. Reurink G, Goudswaard GJ, Oomen HG, Moen MH, Tol JL, Verhaar JA, et al. Reliability of the active and passive knee extension test in acute hamstring injuries. Am J Sports Med. 2013;41(8):1757-61.
- 107. Rio E, Kidgell D, Purdam C, Gaida J, Moseley GL, Pearce AJ, et al. Isometric exercise induces analgesia and reduces inhibition in patellar tendinopathy. Br J Sports Med. 2015;49(19):1277-83.
- 108. Roberts SP, Trewartha G, England M, Shaddick G,Stokes KA. Epidemiology of time-loss injuries in English community-level rugby union. BMJ Open. 2013;3(11):e003998.
- 109. Schmitt B, Tim T,McHugh M. Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: A new concept. Int J Sports Phys Ther. 2012;7(3):333-341.
- Schneider-Kolsky ME, Hoving JL, Warren P,Connell DA. A comparison between clinical assessment and magnetic resonance imaging of acute hamstring injuries. The Am J Sports Med. 2006;34(6):1008-1015.
- 111. Sherry MA,Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. J Orthop Sports Phys Ther. 2004;34(3):116-25.
- 112. Sherry MA, Johnston TS, Heiderscheit BC. Rehabilitation of acute hamstring strain injuries. Clin Sports Med. 2015;34(2):263-284.
- Shrier I. Strategic assessment of risk and risk tolerance (STARRT) framework for returnto-play decision-making. Br J Sports Med. 2015;49(20):1311-5.
- 114. Silbernagel KG, Thomee R, Eriksson BI,Karlsson J. Continued sports activity, using a pain-monitoring model, during rehabilitation in patients with achilles tendinopathy: A randomized controlled study. Am J Sports Med. 2007;35(6):897-906.
- 115. Silbernagel KG, Thomee R, Thomee P,Karlsson J. Eccentric overload training for patients with chronic achilles tendon pain--a randomised controlled study with reliability testing of the evaluation methods. Scand J Med Sci Sports. 2001;11(4):197-206.

- Silder A, Heiderscheit BC, Thelen DG, Enright T,Tuite MJ. MR observations of longterm musculotendon remodeling following a hamstring strain injury. Skeletal Radiol. 2008;37(12):1101-9.
- 117. Silder A, Sherry MA, Sanfilippo J, Tuite M, Hetzel SJ,Heiderscheit BC. Clinical and morphological changes following 2 rehabilitation programs for acute hamstring strain injuries: A randomized clinical trial. J Orthop Sports Phys Ther. 2013;43(5):284-299.
- 118. Smith BE, Hendrick P, Smith TO, Bateman M, Moffatt F, Rathleff MS, et al. Should exercises be painful in the management of chronic musculoskeletal pain? A systematic review and meta-analysis. Br J Sports Med. 2017;51(23):1679-1687.
- 119. Sole G, Hamren J, Milosavljevic S, Nicholson H,Sullivan SJ. Test-retest reliability of isokinetic knee extension and flexion. Arch Phys Med Rehabil. 2007;88(5):626-31.
- 120. Sole G, Milosavljevic S, Nicholson HD, Sullivan SJ. Selective strength loss and decreased muscle activity in hamstring injury. J Orthop Sports Phys Ther. 2011;41(5):354-63.
- 121. Stevenson MR, Hamer P, Finch CF, Elliot B,Kresnow M. Sport, age, and sex specific incidence of sports injuries in western australia. Br J Sports Med. 2000;34(3):188-94.
- 122. Team RC, R: A language and environment for statistical computing. 2016, R foundation for statistical computing: Vienna, Austria.
- 123. Therneau T. A package for survival analysis in s version 2.38. 2015; Available from: https://CRAN.R-project.org/package=survival.
- 124. Thomee R. A comprehensive treatment approach for patellofemoral pain syndrome in young women. Phys Ther. 1997;77(12):1690-703.
- 125. Thorborg K, Bandholm T,Holmich P. Hip- and knee-strength assessments using a handheld dynamometer with external belt-fixation are inter-tester reliable. Knee Surg Sports Traumatol Arthrosc. 2013;21(3):550-5.
- 126. Thorstensson CA, Roos EM, Petersson IF,Ekdahl C. Six-week high-intensity exercise program for middle-aged patients with knee osteoarthritis: A randomized controlled trial [isrctn20244858]. BMC Musculoskelet Disord. 2005;6:27
- 127. Timmins RG, Bourne MN, Hickey JT, Maniar N, Tofari PJ, Williams MD, et al. Effect of prior injury on changes to biceps femoris architecture across an Australian football league season. Med Sci Sports Exerc. 2017;49(10):2102-2109.

- 128. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C,Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. Br J Sports Med. 2016;50(24):1524-1535.
- 129. Timmins RG, Ruddy JD, Presland J, Maniar N, Shield AJ, Williams MD, et al. Architectural changes of the biceps femoris long head after concentric or eccentric training. Med Sci Sports Exerc. 2016;48(3):499-508.
- Timmins RG, Shield AJ, Williams MD, Lorenzen C,Opar DA. Biceps femoris long head architecture: A reliability and retrospective injury study. Med Sci Sports Exerc. 2015;47(5):905-13.
- 131. Tol JL, Hamilton B, Eirale C, Muxart P, Jacobsen P,Whiteley R. At return to play following hamstring injury the majority of professional football players have residual isokinetic deficits. Br J Sports Med. 2014;48(18):1364-9.
- 132. Torchiano M, Effsize: Efficient effect size computation. 2016.
- 133. Tyler TF, Schmitt BM, Nicholas SJ,McHugh MP. Rehabilitation after hamstring-strain injury emphasizing eccentric strengthening at long muscle lengths: Results of long-term follow-up. J Sport Rehabil. 2017;26(2):131-140.
- 134. Valle X, J LT, Hamilton B, Rodas G, Malliaras P, Malliaropoulos N, et al. Hamstring muscle injuries, a rehabilitation protocol purpose. Asian J Sports Med. 2015;6(4):e25411.
- 135. van der Horst N, Smits D-W, Petersen J, Goedhart EA,Backx FJG. The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: A randomized controlled trial. The Am J Sports Med. 2015;43(6):1316-1323.
- 136. van der Horst N, van de Hoef S, Reurink G, Huisstede B,Backx F. Return to play after hamstring injuries: A qualitative systematic review of definitions and criteria. Sports Med. 2016;46(6):899-912.
- 137. van Dyk N, Bahr R, Whiteley R, Tol JL, Kumar BD, Hamilton B, et al. Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries: A 4-year cohort study. Am J Sports Med. 2016;44(7):1789-95.
- 138. Verrall GM, Brukner PD, Seward HG. 6. Doctor on the sidelines. Med J Aust. 2006;184(5):244-8.

- 139. Verrall GM, Slavotinek JP, Barnes PC, Fon GT,Esterman A. Assessment of physical examination and magnetic resonance imaging findings of hamstring injury as predictors for recurrent injury. J Orthop Sports Phys Ther. 2006;36(4):215-224.
- 140. Wadsworth CT, Krishnan R, Sear M, Harrold J,Nielsen DH. Intrarater reliability of manual muscle testing and hand-held dynametric muscle testing. Phys Ther. 1987;67(9):1342-7.
- 141. Wangensteen A, Almusa E, Boukarroum S, Farooq A, Hamilton B, Whiteley R, et al. MRI does not add value over and above patient history and clinical examination in predicting time to return to sport after acute hamstring injuries: A prospective cohort of 180 male athletes. Br J Sports Med. 2015;49(24):1579-87.
- 142. Wasserstein RL,Lazar NA. The ASA's statement on p-values: Context, process, and purpose. American Statistician. 2016;70(2):129-131.
- 143. Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. J Sci Med Sport. 2012;15(5):444-50.
- 144. Whiteley R, van Dyk N, Wangensteen A, Hansen C. Clinical implications from daily physiotherapy examination of 131 acute hamstring injuries and their association with running speed and rehabilitation progression. Br J Sports Med. 2018;52(5):303-310.
- Wickham H. Ggplot2: Elegant graphics for data analysis. Ggplot2: Elegant Graphics for Data Analysis. 2009;1-212.
- 146. Wollin M, Purdam C,Drew MK. Reliability of externally fixed dynamometry hamstring strength testing in elite youth football players. J Sci Med Sport. 2016;19(1):93-6.
- 147. Woods C. The football association medical research programme: An audit of injuries in professional football--analysis of hamstring injuries. Br J Sports Med. 2004;38(1):36-41.

# **Chapter 9 – Appendices**

# **Appendix I: Research portfolio**

### **Publications related to thesis**

 Hickey JT, Timmins RG, Maniar N, Williams MD, Opar DA. Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: A systematic review. *Sports Medicine*. 2017;47(7):1375-87

*Contribution statement:* JH was primarily responsible for the conception of the research question and study design, development and execution of search strategy, screening of articles, extraction of data, qualitative analysis, preparation of tables and figures, writing and submission of manuscript, responding to reviewer's feedback and approval of final proofs. RT assisted in the screening of full text articles, writing manuscript and response to reviewer's feedback. NM and MW assisted in writing manuscript and responding to reviewer's feedback. DO contributed to the conception of the research question and study design, development of search strategy, full text screening, quality assessment, writing manuscript and responding to reviewer's feedback.

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Approximate percentage contributions: JT Hickey 75%; RG Timmins 5%; NM Maniar 5%; MD Williams 5%; DA Opar 10%.

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

Jack Hickey

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

David Opar

Co-author signatures:

Ryan Timmins

Date: 02/03/2018

Date: 02/03/2018

Nirav Maniar

Morgan Williams

Date: 02/03/2018

Date: 02/03/2018

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 Hickey JT, Hickey PF, Maniar N, Timmins RG, Williams MD, Pitcher CA, Opar DA. A novel apparatus measuring knee flexor strength during various hamstring exercises: A reliability and retrospective injury study. *Journal of Orthopedic and Sports Physical Therapy* 2018; 46(2):72-80. Doi: 10.2519/jospt.2018.7634

*Contribution statement:* JH was primarily responsible for the development and pilot testing of the novel apparatus, conception of study design, gaining ethical approval, recruitment of participants, collection of data, analysis of data, statistical analysis, preparation of tables and figures, writing and submission of manuscript, responding to reviewer's feedback and approval of final proofs. PF was primarily responsible for the development of custom written data analysis code and assisted with statistical analysis, writing manuscript and responding to reviewer's feedback. NM assisted with the collection of data, data analysis, writing the manuscript and responding to reviewer's feedback. RT assisted in the collection of data, writing the manuscript and responding to reviewer's feedback. CP assisted in pilot testing the novel apparatus, writing the manuscript and responding to reviewer's feedback. DO was involved in the development and pilot testing of the novel apparatus, conception of study design, gaining ethical approval, writing manuscript and responding to reviewer's feedback.

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https://www.jospt.org/doi/abs/10.2519/jospt.2018.7634?code=jospt-site

Approximate percentage contributions: JT Hickey 70%; PF Hickey 5%; NM Maniar 5%; RG Timmins 5%; CA Pitcher 2.5%; MD Williams 2.5%; DA Opar 10%.

I acknowledge that my contribution to the above publication is 70%:

Jack Hickey

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

David Opar

Co-author signatures:

Pets die f

Peter Hickey

Nirav Maniar

**Ryan** Timmins



Morgan Williams

Christian Pitcher

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

## Manuscripts related to thesis currently under preparation

1. Hickey JT, Rio E, Timmins RG, Maniar N, Pitcher CA, Williams MD, Opar DA. Exercise-specific progression criteria emphasising accelerated eccentric loading during hamstring strain injury rehabilitation. *Under preparation for submission to the British Journal of Sports Medicine* 

Contribution statement: JH was primarily responsible for the development of the rehabilitation protocol, experimental design, recruitment of participants, supervising all rehabilitation sessions, collection of data, data analysis, preparation of figures and tables and writing manuscript. ER was involved in the development of the rehabilitation protocol, experimental design and writing manuscript. RT and NM assisted in the development of the rehabilitation protocol, data collection and manuscript writing. CP and MW assisted in writing the manuscript. DO was involved in the development of the rehabilitation protocol, experimental design, data collection and writing manuscript.

Approximate percentage contributions – JT Hickey 70%; E Rio 5%; RG Timmins 5%; NM Maniar 5%; CA Pitcher 2.5%; MD Williams 2.5%; DA Opar 10%.

I acknowledge that my contribution to the above manuscript is 70%:

Jack Hickey

Date: 02/03/2018

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

David Opar

Co-author signatures:

Le e

Ebonie Rio

Ryan Timmins

Nirav Maniar

**Christian Pitcher** 

Morgan Williams

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

2. Hickey JT, Timmins RG, Maniar N, Rio E, Hickey PF, Williams MD, Opar DA. Painfree versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial. *Under preparation for submission to the British Journal of Sports Medicine* 

*Contribution statement:* JH was primarily responsible for the conception of the research question, experimental design, gaining ethical approval, recruitment of participants, supervising all rehabilitation sessions, collection of data, follow-up contact with participants, data analysis, statistical analysis, preparation of figures and tables and writing manuscript. RT assisted in the conception of the research question, experimental design, recruitment of participants, collection of data, data analysis and writing of manuscript. NM assisted in the conception of the research question, experimental design, verification of participant inclusion and writing of manuscript. PH and MW assisted with statistical analysis and writing manuscript. DO was involved in the conception of the research question, experimental design, experimental design, and writing analysis and writing approval, collection of data, and writing of manuscript.

Approximate percentage contributions – JT Hickey 70%; RG Timmins 7.5%; NM Maniar 5%; E Rio 5%; PF Hickey 1.25%; MD Williams 1.25%; DA Opar 10%.

Jack Hickey

Date: 02/03/2018

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

David Opar

Co-author signatures:

Ryan Timmins

Nirav Maniar

Le e

Ebonie Rio

Petatic

Peter Hickey



Morgan Williams

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

Date: 02/03/2018

### **Conference presentations related to thesis**

 Hickey JT, Hickey PF, Maniar N, Timmins RG, Opar DA. Novel and clinically practical measures of hamstring strength: The HamSling reliability and retrospective study. *Sports Medicine Australia Conference* – Melbourne, October 2016.

*Contribution statement:* This presentation was based on the work from publication two (see above for author contributions). The presentation was designed and delivered by JH. PH, NM, RT and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Williams MD, Opar DA. Pain-free versus pain-threshold rehabilitation for hamstring strain injury. *International Conference on Sports Rehabilitation and Traumatology* – Barcelona, May 2017.

*Contribution statement:* This presentation was based on the work from manuscript under preparation two (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, MW and DO reviewed the presentation and provided feedback.

3. **Hickey JT,** Timmins RG, Opar DA. Pain-threshold rehabilitation for a recurrent hamstring strain injury. *International Conference on Sports Rehabilitation and Traumatology* – Barcelona, May 2017.

*Contribution statement:* This presentation was based on the work from manuscript under preparation one (see above for author contributions). The presentation was designed and delivered by JH. RT and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Painfree versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial. *Sports Medicine Australia Conference* – Langkawi, October 2017. *Contribution statement:* This presentation was based on the work from manuscript under preparation two (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Exercise-specific progression criteria accelerates introduction of eccentric loading during hamstring strain injury rehabilitation. *Scandinavian Congress of Medicine & Science in Sports* – Copenhagen, February 2018.

*Contribution statement:* This presentation was based on the work from manuscript under preparation one (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Painfree versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial. *Scandinavian Congress of Medicine & Science in Sports –* Copenhagen, February 2018.

*Contribution statement:* This presentation was based on the work from manuscript under preparation two (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Painfree versus pain-threshold rehabilitation following acute hamstring strain injury: A randomised controlled trial. *Research to Practice, Exercise & Sports Science Australia* – Brisbane, March 2018.
#### Invited conference presentations & workshops related to thesis

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Alternative rehabilitation guidelines for hamstring strain injury: Pre-conference workshop. *Sports Medicine Australia Conference* – Melbourne, October 2016.

*Contribution statement:* This presentation was based on the work from manuscript under preparation one (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Why does rehabilitation fail? Challenging current theories. *Sports Medicine Australia, Hamstrung: The Hamstring Injury Journey* – Melbourne, February 2017.

*Contribution statement:* This presentation was based on the work from manuscript under preparation one and two (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Objective assessment and alternative rehabilitation for hamstring strain injury. *Exercise* and Sports Science Australia, Victoria Symposium – Melbourne, June 2017.

*Contribution statement:* This presentation was based on the work from publications 1 and 2 and manuscripts under preparation one and two (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

4. **Hickey JT,** Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Hamstring strain injury rehabilitation: alternative exercise progression. *Clinical Edge,*  Sports Injuries Virtual Conference – December 2017.

*Contribution statement:* This presentation was based on the work from manuscript under preparation one (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

 Hickey JT, Timmins RG, Maniar N, Rio E, Pitcher CA, Williams MD, Opar DA. Exercise progression and pain during hamstring strain injury rehabilitation. *Sports MAP Network, High Performance Rehabilitation* – Melbourne, February 2018.

*Contribution statement:* This presentation was based on the work from manuscript under preparation one and two (see above for author contributions). The presentation was designed and delivered by JH. RT, NM, ER, CP, MW and DO reviewed the presentation and provided feedback.

# Appendix II: Ethics approval, participant information letters and consent forms

# Study 2

Australian Catholic University Human Research Committee approval number 2015-253H

# PARTICIPANT INFORMATION LETTER

PROJECT TITLE: Reliability and sensitivity of new measures assessing hamstring strength and function
PRINCIPAL INVESTIGATOR: Dr David Opar
STUDENT RESEARCHER: Mr Jack Hickey
STUDENT'S DEGREE: Doctor of Philosophy

Dear Participant,

You are invited to participate in the research project described below.

## What is the project about?

This research project will investigates the reliability of new testing measures of hamstring muscle strength and function in males with a history of hamstring strain injury. We will also investigate whether these tests are able to detect differences between previously injured and un-injured legs and following exercise causing muscle fatigue and soreness in one leg.

#### Who is undertaking the project?

This project is being conducted by Mr Jack Hickey and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr David Opar. Mr Jack Hickey has completed a Bachelor of Applied Science (Human Movement) and Master of Clinical Exercise Physiology and is an ESSA accredited exercise physiologist with over 3 years' experience in musculoskeletal injury prevention, assessment and rehabilitation. Dr David Opar has a PhD in exercise science and is internationally renowned for hamstring injury research. Both researchers have extensive experience conducting maximal strength testing procedures and at least one of the investigators will present during testing to ensure that you perform these measures with safe and correct technique.

#### Are there any risks associated with participating in this project?

Some of the proposed strength testing and exercise methods involve maximal contractions of the knee flexor muscles, and there is some minor risk of delayed onset muscle soreness (DOMS) and injury. It is important to consider, however, that you are at significantly greater risks of thigh muscle injury during normal sports training and playing than during these tests.

We minimise injury risk by ensuring that participants are not already suffering signs of current injury to these muscles or the knee when we start the test and by employing an appropriate warm-up prior to maximal efforts. If participants feel any unusual discomfort during the warm-up process they are

encouraged to discontinue the test.

It is expected that participants will experience some level of muscle fatigue and/or DOMS following the Nordic hamstring exercise which involves maximal eccentric (lengthening) knee flexor contraction. This is the body's normal reaction to this muscle contraction mode and the risk of fatigue and muscle soreness will be minimised by allowing for adequate recovery between tests.

Those who chose to participate in the second part of this study will also be exposed to exercise induced muscle fatigue and/or DOMS following an exercise protocol designed to cause fatigue and/or DOMS. This exercise protocol may involve a series of maximal eccentric muscle contractions of the knee flexors which is likely to result in DOMS.

Muscle fatigue after these tests typically lasts for less than an hour while DOMS typically appears after approximately 8 hours and reaches a peak at around 24-72 hours after the exercise. The soreness then dissipates over the subsequent 24-48 hours. DOMS is greatest after the initial familiarisation session but will decline significantly following your second and third visit to ACU.

In the unlikely evet of any soft-tissue injury, we will apply standard first aid treatment (ice, elevation and compression). If the injury impedes your ability to transport yourself home safely, alternative transportation arrangements will be organised by the investigators, at no cost to you. We will also be able to provide you with advice and assistance regarding your rehabilitation; however we are not able to provide you with primary care (i.e. physiotherapy).

#### What will I be asked to do?

Participation within the first part of this project will require you to attend the School of Exercise Science at ACU Melbourne on 3 separate occasions. The first visit will require you to become familiar with all testing procedures carried out throughout the project. Upon arrival to the lab participants will have their leg muscles prepared for placement of surface electromyography (sEMG) electrodes to monitor electrical activity of these muscles during testing. This involves the shaving a small amount of hair from the skin of the leg muscles and placement of small adhesive electrodes on the skin over the leg muscles being tested. Following this the participant will be taken through a series of strength tests involving isometric (static) strength testing of the knee flexors in three positions and three common hamstring injury prevention and rehabilitation exercises.

This procedure will then be repeated during your second and third visits to ACU. Video recording of testing procedures will take place if participant's give consent, although participants will be de-identified by recording in a side on position from the shoulders down.

Participants will then be given the option of participating in the second part of this project, which will require participants to visit ACU on a further twelve occasions. The first of these will involve an exercise protocol designed to induce muscle fatigue and/or DOMS to the knee flexor muscles. This protocol will be performed by one leg only which will be randomly selected. The following 11 visits will involve the testing procedures outlined above repeated at 1, 4, 8, 12, 24, 48, 72, 96, 120, 144 and 168 hour intervals following the maximal exercise protocol to investigate the changes in the measures over time.

#### How much time will the project take?

Each visit to ACU in of the research project should take no more than 120 minutes, with 3 visits to ACU in part A resulting in 6 hours of participation. Participation in part B will involve an additional 12 visits to ACU, each taking no more than 120 minutes resulting in an additional 24 hours of participation in part B and a cumulative total of 30 hours participation in parts A and B of this research project.

# What are the benefits of the research project?

Participation in this research project will provide you with information about your hamstring muscle strength and function. This information may provide you with an indication of how well you have recovered following your previous hamstring strain injury your level of re-injury risk in the future. By participating in this research project you will have free access to the services of an accredited exercise physiologist experienced in musculoskeletal injury prevention and rehabilitation as well as the use of equipment often only available to elite athletes. The data collected from this project will contribute to the scientific literature to do with the rehabilitation process and potentially impact on the incidence, prevalence and recurrence rates of hamstring strain injuries in the future.

## Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences. Any data collected prior to your withdrawal from the study will still be analysed and used in the study unless you request it not to be. Your decision to participate will in no way impact upon your current or future relationship with ACU (for example your grades) or with any of the investigators.

# Will anyone else know the results of the project?

It is intended that the results of this research will be included as part of Jack Hickey's thesis and will be submitted for publication within scholarly journals. All test results, comments and responses are anonymous and will be treated confidentially. All data obtained:

- Will be stored for at least 5 years by the research team.
- Will not be used for any other purpose (eg as an instructional aide).
- Can be accessed only by the research team.

# Will I be able to find out the results of the project?

All results will be available to be communicated to the participants upon their request for the data once their involvement within the program is complete. Participants are encouraged to contact the investigators once this occurs. No distribution of data to the participants will occur without this prior request. Upon the request for the data, the participants will be given an individualized e-mail, outlining the specific information obtained. If participants wish to discuss the results in more detail they will be given the opportunity to contact the researches via phone or e-mail. Participants will also be informed of the publication (pending its acceptance).

## Who do I contact if I have questions about the project?

Jack Hickey Phone: 0432 225 273 Email: <u>jthick001@myacu.edu.au</u> David Opar Phone: 03 9953 3742 Email: <u>David.Opar@acu.edu.au</u>

#### What if I have a complaint or any concerns?

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2015-253H). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics c/o Office of the Deputy Vice Chancellor (Research) Australian Catholic University North Sydney Campus PO Box 968 NORTH SYDNEY, NSW 2059 Ph.: 02 9739 2519 Fax: 02 9739 2870 Email: <u>resethics.manager@acu.edu.au</u>

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

## I want to participate! How do I sign up?

Please contact either of the research team members named above to have any questions answered or if you require further information about the project.

If you would like to participate we would like to ask you to sign a written consent form (enclosed) to confirm your agreement to participate.

Yours sincerely,

Mr Jack Hickey Dr David Opar

# PARTICIPANT INFORMATION LETTER

PROJECT TITLE: Reliability and sensitivity of new measures assessing hamstring strength and function
PRINCIPAL INVESTIGATOR: Dr David Opar
STUDENT RESEARCHER: Mr Jack Hickey
STUDENT'S DEGREE: Doctor of Philosophy

Dear Participant,

You are invited to participate in the research project described below.

#### What is the project about?

This research project will investigates the reliability of new testing measures of hamstring muscle strength and function and whether these tests are able to detect between limb differences following exercise causing muscle fatigue and soreness in one leg.

#### Who is undertaking the project?

This project is being conducted by Mr Jack Hickey and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr David Opar. Mr Jack Hickey has completed a Bachelor of Applied Science (Human Movement) and Master of Clinical Exercise Physiology and is an ESSA accredited exercise physiologist with over 3 years' experience in musculoskeletal injury prevention, assessment and rehabilitation. Dr David Opar has a PhD in exercise science and is internationally renowned for hamstring injury research. Both researchers have extensive experience conducting maximal strength testing procedures and at least one of the investigators will present during testing to ensure that you perform these measures with safe and correct technique.

#### Are there any risks associated with participating in this project?

Some of the proposed strength testing and exercise methods involve maximal contractions of the knee flexor muscles, and there is some minor risk of delayed onset muscle soreness (DOMS) and injury. It is important to consider, however, that you are at significantly greater risks of thigh muscle injury during normal sports training and playing than during these tests.

We minimise injury risk by ensuring that participants are not already suffering signs of current injury to these muscles or the knee when we start the test and by employing an appropriate warm-up prior to maximal efforts. If participants feel any unusual discomfort during the warm-up process they are encouraged to discontinue the test.

It is expected that participants will experience some level of muscle fatigue and/or DOMS following the Nordic hamstring exercise which involves maximal eccentric (lengthening) knee flexor contraction. This is the body's normal reaction to this muscle contraction mode and the risk of fatigue and muscle soreness will be minimised by allowing for adequate recovery between tests.

Those who chose to participate in the second part of this study will also be exposed to exercise induced muscle fatigue and/or DOMS following an exercise protocol designed to cause fatigue and/or DOMS. This exercise protocol may involve a series of maximal eccentric muscle contractions of the knee flexors which is likely to result in DOMS.

Muscle fatigue after these tests typically lasts for less than an hour while DOMS typically appears after approximately 8 hours and reaches a peak at around 24-72 hours after the exercise. The soreness then dissipates over the subsequent 24-48 hours. DOMS is greatest after the initial familiarisation session but will decline significantly following your second and third visit to ACU.

In the unlikely event of any soft-tissue injury, we will apply standard first aid treatment (ice, elevation and compression). If the injury impedes your ability to transport yourself home safely, alternative transportation arrangements will be organised by the investigators, at no cost to you. We will also be able to provide you with advice and assistance regarding your rehabilitation; however we are not able to provide you with primary care (i.e. physiotherapy).

#### What will I be asked to do?

Participation within the first part of this project will require you to attend the School of Exercise Science at ACU Melbourne on 3 separate occasions. The first visit will require you to become familiar with all testing procedures carried out throughout the project. Upon arrival to the lab participants will have their leg muscles prepared for placement of surface electromyography (sEMG) electrodes to monitor electrical activity of these muscles during testing. This involves the shaving a small amount of hair from the skin of the leg muscles and placement of small adhesive electrodes on the skin over the leg muscles being tested. Following this the participant will be taken through a series of strength tests involving isometric (static) strength testing of the knee flexors in three positions and three common hamstring injury prevention and rehabilitation exercises.

This procedure will then be repeated during your second and third visits to ACU. Video recording of testing procedures will take place if participant's give consent, although participants will be de-identified by recording in a side on position from the shoulders down.

Participants will then be given the option of participating in the second part of this project, which will require participants to visit ACU on a further twelve occasions. The first of these will involve an exercise protocol designed to induce muscle fatigue and/or DOMS to the knee flexor muscles. This protocol will be performed by one leg only which will be randomly selected. The following 11 visits will involve the testing procedures outlined above repeated at 1, 4, 8, 12, 24, 48, 72, 96, 120, 144 and 168 hour intervals following the maximal exercise protocol to investigate the changes in the measures over time.

## How much time will the project take?

Each visit to ACU in of the research project should take no more than 120 minutes, with 3 visits to ACU in part A resulting in 6 hours of participation. Participation in part B will involve an additional 12 visits to ACU, each taking no more than 120 minutes resulting in an additional 24 hours of participation in part B and a cumulative total of 30 hours participation in parts A and B of this research project.

## What are the benefits of the research project?

Participation in this research project will provide you with information about your hamstring muscle strength and function. By participating in this research project you will have free access to the services of an accredited exercise physiologist experienced in musculoskeletal injury prevention and rehabilitation as well as the use of equipment often only available to elite athletes. The data collected from this project will contribute to the scientific literature to do with the rehabilitation process and

potentially impact on the incidence, prevalence and recurrence rates of hamstring strain injuries in the future.

## Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences. Any data collected prior to your withdrawal from the study will still be analysed and used in the study unless you request it not to be. Your decision to participate will in no way impact upon your current or future relationship with ACU (for example your grades) or with any of the investigators.

## Will anyone else know the results of the project?

It is intended that the results of this research will be included as part of Jack Hickey's thesis and will be submitted for publication within scholarly journals. All test results, comments and responses are anonymous and will be treated confidentially.

All data obtained:

- Will be stored for at least 5 years by the research team.
- Will not be used for any other purpose (eg as an instructional aide).
- Can be accessed only by the research team.

## Will I be able to find out the results of the project?

All results will be available to be communicated to the participants upon their request for the data once their involvement within the program is complete. Participants are encouraged to contact the investigators once this occurs. No distribution of data to the participants will occur without this prior request. Upon the request for the data, the participants will be given an individualized e-mail, outlining the specific information obtained. If participants wish to discuss the results in more detail they will be given the opportunity to contact the researches via phone or e-mail. Participants will also be informed of the publication (pending its acceptance).

#### Who do I contact if I have questions about the project?

Jack Hickey Phone: 0432 225 273 Email: <u>jthick001@myacu.edu.au</u> David Opar Phone: 03 9953 3742 Email: <u>David.Opar@acu.edu.au</u>

#### What if I have a complaint or any concerns?

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2015-253H). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics c/o Office of the Deputy Vice Chancellor (Research) Australian Catholic University North Sydney Campus PO Box 968 NORTH SYDNEY, NSW 2059 Ph.: 02 9739 2519 Fax: 02 9739 2870 Email: <u>resethics.manager@acu.edu.au</u>

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

## I want to participate! How do I sign up?

Please contact either of the research team members named above to have any questions answered or if you require further information about the project.

If you would like to participate we would like to ask you to sign a written consent form (enclosed) to confirm your agreement to participate.

Yours sincerely,

Mr Jack Hickey Dr David Opar

#### CONSENT FORM Copy for Researcher / Copy for Participant to Keep

**TITLE OF PROJECT:** Reliability and sensitivity of new measures assessing hamstring strength and function – Part A

## (NAME OF) PRINCIPAL INVESTIGATOR (or SUPERVISOR): Dr David Opar

## (NAME OF) STUDENT RESEARCHER: Mr Jack Hickey

I ...... (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study encompassing three 120 minute visits to complete a series of strength tests and exercises where I may be filmed in an un-identifiable way, realising that I can withdraw my consent at any time (without adverse consequences). Should I withdraw consent at any stage, any data collected up to that point will still be included in analysis unless I request otherwise. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT:	
SIGNATURE	DATE
SIGNATURE OF PRINCIPAL INVESTIGATOR (or SUPERVISOR):	
	DATE:
SIGNATURE OF STUDENT RESEARCHER	
	DATE:

## CONSENT FORM Copy for Researcher / Copy for Participant to Keep

**TITLE OF PROJECT:** Reliability and sensitivity of new measures assessing hamstring strength and function – Part B

(NAME OF) PRINCIPAL INVESTIGATOR (or SUPERVISOR): Dr David Opar

(NAME OF) STUDENT RESEARCHER: Mr Jack Hickey

I ...... (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study encompassing twelve 120 minute visits to complete a series of strength tests and exercises where I may be filmed in an un-identifiable way, realising that I can withdraw my consent at any time (without adverse consequences). Should I withdraw consent at any stage, any data collected up to that point will still be included in analysis unless I request otherwise. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT:	
SIGNATURE	DATE
SIGNATURE OF PRINCIPAL INVESTIGATOR (or SUPERVISOR):	
	DATE:
SIGNATURE OF STUDENT RESEARCHER:	
	DATE:

## Studies 3 and 4

Australian Catholic University Human Research Committee approval number 2015-307H

# PARTICIPANT INFORMATION LETTER

PROJECT TITLE: Hamstring Strain Injury Clinical Assessment PRINCIPAL INVESTIGATOR: Dr David Opar STUDENT RESEARCHER: Mr Jack Hickey STUDENT'S DEGREE: Doctor of Philosophy

Dear Participant,

You are invited to participate in the research project described below.

#### What is the project about?

This research project will clinically assess participants aged between 18 and 40 years of age with suspected acute hamstring strain injury to confirm presence of injury.

#### Who is undertaking the project?

This project is being conducted by Mr. Jack Hickey and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. David Opar. Mr. Hickey holds a Bachelor of Applied Science (Human Movement) and Master of Clinical Exercise Physiology and is an Exercise and Sports Science Australia (ESSA) Accredited Exercise Physiologist (AEP) with over three year's clinical experience working in musculoskeletal injury assessment, rehabilitation and prevention. Dr. Opar holds a Bachelor of Applied Science (Human Movement) with Honors and PhD in exercise science and is internationally renowned for hamstring injury research. Further to this both investigators have extensive experience in carrying out assessments of hamstring function and structure.

#### Are there any risks associated with participating in this project?

Some of the proposed strength testing and exercise methods involve maximal contractions of the knee flexor muscles, and there is some minor risk of delayed onset muscle soreness (DOMS) and injury. It is important to consider, however, that you are at significantly greater risks of thigh muscle injury during normal sports training and playing than during these tests.

We minimise injury risk by employing an appropriate warm-up prior to maximal efforts. If participants feel any unusual discomfort during the warm-up process they are encouraged to discontinue the test.

Should any soft-tissue injury occur, we will apply standard first aid treatment (ice, elevation and compression). If the injury impedes your ability to transport yourself home safely, alternative transportation arrangements will be organised by the investigators, at no cost to you. We will also be able to provide you with advice and assistance regarding your rehabilitation.

#### What will I be asked to do?

Participation will require you to attend the School of Exercise Science at ACU Melbourne on one occasion for no longer than two hours within seven days of suspecting an acute hamstring strain injury. This visit will require you to undergo a series of clinical assessments to confirm presence of suspected hamstring strain injury. Upon arrival to the lab you will be asked a series of questions about your how your injury occurred, level of pain and relevant medical/injury history. Following this you will be taken through a series of clinical assessments including measuring your level of pain when pressing on the injured area, assessment of muscle structure using ultrasound, flexibility assessment and strength tests. Participants will be filmed during clinical assessments in a position where their head and face is not visible, de-identifying the participant.

## How much time will the project take?

The visit to ACU for the clinical assessment should take no more than two hours.

## What are the benefits of the research project?

Participation in this research project will provide you with an in depth clinical assessment of your suspected injury to confirm presence of acute hamstring strain injury. Regular clinical assessments of this nature generally cost in excess of \$100, in addition to this you will have access to equipment often only available to elite athletes. If acute hamstring injury is confirmed you will also be eligible for free of charge rehabilitation services.

## Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. Should you withdraw consent prior to completion of the study, any data collected prior to this point will still be used in analysis unless you specifically request otherwise. Your decision to participate will in no way impact upon your current or future relationship with ACU (for example your grades) or with any of the investigators.

#### Will anyone else know the results of the project?

It is intended that the results of this research will be included as part of Jack Hickey's thesis and will be submitted for publication within scholarly journals. All test results, comments and responses are anonymous and will be treated confidentially.

All data obtained:

- Will be stored for at least 5 years by the research team.
- Will not be used for any other purpose (eg as an instructional aide).
- Can be accessed only by the research team.

## Will I be able to find out the results of the project?

All results will be available to be communicated to the participants upon their request for the data once their involvement within the program is complete. Participants are encouraged to contact the investigators once this occurs. No distribution of data to the participants will occur without this prior request. Upon the request for the data, the participants will be given an individualized letter, outlining the specific information obtained. Participants will also be informed of the publication (pending its acceptance).

#### Who do I contact if I have questions about the project?

Jack Hickey Phone: 0432 225 273 Email: <u>ithick001@myacu.edu.au</u> David Opar Phone: 03 9953 3742 Email: <u>David.Opar@acu.edu.au</u>

## What if I have a complaint or any concerns?

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2015-307H). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics c/o Office of the Deputy Vice Chancellor (Research) Australian Catholic University North Sydney Campus PO Box 968 NORTH SYDNEY, NSW 2059 Ph.: 02 9739 2519 Fax: 02 9739 2870 Email: <u>resethics.manager@acu.edu.au</u>

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

#### I want to participate! How do I sign up?

Please contact either of the research team members named above to have any questions answered or if you require further information about the project.

If you would like to participate we would like to ask you to sign a written consent form (enclosed) to confirm your agreement to participate.

Yours sincerely,

Mr Jack Hickey Dr David Opar

# CONSENT FORM Copy for Researcher / Copy for Participant to Keep

TITLE OF PROJECT: Clinical assessment of suspected hamstring strain injury

(NAME OF) PRINCIPAL INVESTIGATOR (or SUPERVISOR): Dr David Opar

(NAME OF) STUDENT RESEARCHER: Mr Jack Hickey

I ...... (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study encompassing a two hour visit to complete an initial clinical assessment to confirm presence of acute hamstring strain injury. This will involve completing a series of clinical assessments where I may be filmed in an un-identifiable way, realising that I can withdraw my consent at any time (without adverse consequences). I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. Should I withdraw my consent prior to completion of the study, any data collected prior to this point will still be used in analysis unless I specifically request otherwise.

NAME OF PARTICIPANT:	
SIGNATURE	DATE
SIGNATURE OF PRINCIPAL INVESTIGATOR (or SUPERVISOR)	
	DATE:
SIGNATURE OF STUDENT RESEARCHER:	
	DATE:

# PARTICIPANT INFORMATION LETTER

PROJECT TITLE: Pain-free Exercise during Hamstring Strain Injury Rehabilitation
PRINCIPAL INVESTIGATOR: Dr David Opar
STUDENT RESEARCHER: Mr Jack Hickey
STUDENT'S DEGREE: Doctor of Philosophy

Dear Participant,

You are invited to participate in the research project described below.

#### What is the project about?

This research project will investigate the changes in hamstring muscle function and structure and the effect of exercising within pain-free limits during rehabilitation for acute hamstring strain injury in participants aged between 18 and 40 years of age.

#### Who is undertaking the project?

This project is being conducted by Mr. Jack Hickey and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. David Opar. Mr. Hickey holds a Bachelor of Applied Science (Human Movement) and Master of Clinical Exercise Physiology and is an Exercise and Sports Science Australia (ESSA) Accredited Exercise Physiologist (AEP) with over three year's clinical experience working in musculoskeletal injury assessment, rehabilitation and prevention. Dr. Opar holds a Bachelor of Applied Science (Human Movement) with Honors and PhD in exercise science and is internationally renowned for hamstring injury research. Further to this both investigators have extensive experience in carrying out assessments of hamstring function and structure.

#### Are there any risks associated with participating in this project?

Some of the proposed strength testing and exercise methods involve maximal contractions of the knee flexor muscles, and there is some minor risk of delayed onset muscle soreness (DOMS) and re-injury. It is important to consider, however, that you are at significantly greater risks of thigh muscle injury during normal sports training and playing than during these tests.

We minimise injury risk by employing an appropriate warm-up prior to maximal efforts. If participants feel any unusual discomfort during the warm-up process they are encouraged to discontinue the test.

Should re-injury or any other soft-tissue injury occur, we will apply standard first aid treatment (ice, elevation and compression). If the injury impedes your ability to transport yourself home safely, alternative transportation arrangements will be organised by the investigators, at no cost to you. We will also be able to provide you with advice and assistance regarding your rehabilitation.

#### What will I be asked to do?

Participation within this research project will require you to complete two to three times per week clinical assessment and rehabilitation for your acute hamstring strain injury. Clinical assessments include

measuring your level of pain when pressing on the injured area, assessment of muscle structure using ultrasound, flexibility assessment and strength tests. The rehabilitation protocol will involve a series of exercises designed to improve strength and flexibility of the hamstring muscles as well as a progressive running protocol which you will have the option of completing during an additional two supervised sessions per week at ACU or two sessions per week unsupervised in your own time. Participants will be filmed during clinical assessments and rehabilitation session in a position where their head and face is not visible, de-identifying the participant.

During this rehabilitation protocol it is required that you remain completely pain-free to avoid risk of reinjury. Should you experience any level of pain localised to the injury site during exercise you should advise the supervisor of your rehabilitation session who will adjust your rehabilitation accordingly to avoid pain.

## How much time will the project take?

Each visit to ACU for the clinical assessment and rehabilitation protocol should take no more than a total of two hours and progressive running protocol (either at ACU or in own time) no more than 30 minutes. It is a requirement of the research project to complete the clinical assessment/rehabilitation sessions two to three times per week and progressive running twice per week until pre-determined criteria are met to allow clearance to return to normal level of activity.

Following this point you will be invited to attend ACU for weekly follow-up clinical assessments for a three month period. For 24 months following return to play clearance, you will also be contacted weekly by the investigators to enquire whether any re-injury has occurred, in which case you will be required to attend ACU to undergo clinical assessment to confirm presence of suspected re-injury.

## What are the benefits of the research project?

Participation in this research project will provide you with free of charge in depth clinical assessment and rehabilitation services for your acute hamstring strain injury and rehabilitation to determine your progress through rehabilitation. In depth clinical assessment and rehabilitation of this nature generally cost in excess of \$80 per session and in addition to this you will have access to equipment often only available to elite athletes.

#### Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. Should you withdraw consent prior to completion of the study, any data collected prior to this point will still be used in analysis unless you specifically request otherwise. Your decision to participate will in no way impact upon your current or future relationship with ACU (for example your grades) or with any of the investigators.

#### Will anyone else know the results of the project?

It is intended that the results of this research will be included as part of Jack Hickey's thesis and will be submitted for publication within scholarly journals. All test results, comments and responses are anonymous and will be treated confidentially.

All data obtained:

- Will be stored for at least 5 years by the research team.
- Will not be used for any other purpose (eg as an instructional aide).
- Can be accessed only by the research team.

## Will I be able to find out the results of the project?

All results will be available to be communicated to the participants upon their request for the data once their involvement within the program is complete. Participants are encouraged to contact the investigators once this occurs. No distribution of data to the participants will occur without this prior request. Upon the request for the data, the participants will be given an individualized letter, outlining the specific information obtained. Participants will also be informed of the publication (pending its acceptance).

## Who do I contact if I have questions about the project?

Jack Hickey Phone: 0432 225 273 Email: <u>jthick001@myacu.edu.au</u> David Opar Phone: 03 9953 3742 Email: <u>David.Opar@acu.edu.au</u>

## What if I have a complaint or any concerns?

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2015-307H). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics c/o Office of the Deputy Vice Chancellor (Research) Australian Catholic University North Sydney Campus PO Box 968 NORTH SYDNEY, NSW 2059 Ph.: 02 9739 2519 Fax: 02 9739 2870 Email: <u>resethics.manager@acu.edu.au</u>

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

#### I want to participate! How do I sign up?

Please contact either of the research team members named above to have any questions answered or if you require further information about the project.

If you would like to participate we would like to ask you to sign a written consent form (enclosed) to confirm your agreement to participate.

Yours sincerely,

Mr Jack Hickey Dr David Opar

# CONSENT FORM Copy for Researcher / Copy for Participant to Keep

**TITLE OF PROJECT:** Effect of pain-free exercise on rehabilitation of acute hamstring strain injury

## (NAME OF) PRINCIPAL INVESTIGATOR (or SUPERVISOR): Dr David Opar

## (NAME OF) STUDENT RESEARCHER: Mr Jack Hickey

I ...... (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study encompassing two to three times per week two hour visits to complete follow-up clinical assessment and rehabilitation until pre-determined criteria to return to normal activity is given. This will involve a series of clinical assessments and exercises at an intensity which should not cause any level of self-rated pain where I may be filmed in an un-identifiable way. I also consent to completing an additional twice per week progressive running protocol either supervised at ACU or in my own time.

Once return to play clearance has been given I agree to attend ACU for weekly follow up clinical assessment for a period of three months and to be contacted weekly for a period of 24 months to enquire about potential re-injury, realising that I can withdraw my consent at any time (without adverse consequences). I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. Should I withdraw my consent prior to completion of the study, any data collected prior to this point will still be used in analysis unless I specifically request otherwise.

NAME OF PARTICIPANT:	
SIGNATURE	DATE
SIGNATURE OF PRINCIPAL INVESTIGATOR (or SUPERVISOR):	
	DATE:
SIGNATURE OF STUDENT RESEARCHER:	

DATE:....

# PARTICIPANT INFORMATION LETTER

 PROJECT TITLE: Pain-threshold Exercise during Hamstring Strain Injury Rehabilitation
PRINCIPAL INVESTIGATOR: Dr David Opar
STUDENT RESEARCHER: Mr Jack Hickey
STUDENT'S DEGREE: Doctor of Philosophy

Dear Participant,

You are invited to participate in the research project described below.

## What is the project about?

This research project will investigate changes in hamstring muscle function and structure as well as the effect of exercising to a 4/10 pain-threshold during rehabilitation for acute hamstring strain injury in participants aged between 18 and 40 years of age.

#### Who is undertaking the project?

This project is being conducted by Mr. Jack Hickey and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. David Opar. Mr. Hickey holds a Bachelor of Applied Science (Human Movement) and Master of Clinical Exercise Physiology and is an Exercise and Sports Science Australia (ESSA) Accredited Exercise Physiologist (AEP) with over three year's clinical experience working in musculoskeletal injury assessment, rehabilitation and prevention. Dr. Opar holds a Bachelor of Applied Science (Human Movement) with Honors and PhD in exercise science and is internationally renowned for hamstring injury research. Further to this both investigators have extensive experience in carrying out assessments of hamstring function and structure.

## Are there any risks associated with participating in this project?

As you will be permitted to exercise to a 4/10 pain-threshold during exercises, it is expected that you will experience some pain or discomfort throughout the rehabilitation of your hamstring injury. It is not required that you experience pain during all exercises or even at all, however the guideline of 4/10 has been set as an acceptable limit which you will be permitted to exercise up to. It is important to note however that this rating of 4/10 is somewhat subjective in nature and is determined entirely by you the participant. There is evidence that exercising to a pain-threshold of 5/10 is safe and effective in other injuries however it has not yet been reported in acute hamstring strain injury, therefore a certain level of risk of re-injury may be present.

We have aimed to minimise re-injury risk by selecting a pain-threshold (4/10) which is lower than what has previously been shown to be safe in other injuries (5/10). We will also ensure that participants employ safe and appropriate exercise technique.

Some of the proposed strength testing and exercise methods involve maximal contractions of the knee flexor muscles, and there is some minor risk of delayed onset muscle soreness (DOMS) and injury. It is important to consider, however, that you are at significantly greater risks of thigh muscle injury during normal sports training and playing than during these tests. We will also ensure that adequate warm-up is employed prior to maximal efforts to minimise risk of re-injury or DOMS.

Should re-injury or any other soft-tissue injury occur, we will apply standard first aid treatment (ice, elevation and compression). If the injury impedes your ability to transport yourself home safely, alternative transportation arrangements will be organised by the investigators, at no cost to you. We will also be able to provide you with advice and assistance regarding your rehabilitation.

#### What will I be asked to do?

Participation within this research project will require you to complete two to three times per week clinical assessment and rehabilitation for your acute hamstring strain injury. Clinical assessments include measuring your level of pain when pressing on the injured area, assessment of muscle structure using ultrasound, flexibility assessment and strength tests. The rehabilitation protocol will involve a series of exercises designed to improve strength and flexibility of the hamstring muscles as well as a progressive running protocol which you will have the option of completing during an additional two supervised sessions per week at ACU or two sessions per week unsupervised in your own time. Participants will be filmed during clinical assessments and rehabilitation session in a position where their head and face is not visible, de-identifying the participant.

The intensity of the exercises in the rehabilitation protocol will be guided by your level of pain. Exercising to a moderate level of pain during rehabilitation has been shown to be safe and effective in other musculoskeletal injuries, therefore if you experience pain up to and including 4/10 during exercise you will be encouraged to continue. However if you experience pain in excess of this, you are required to inform the supervisor of your rehabilitation who will adjust your rehabilitation accordingly to limit pain to 4/10 or less.

#### How much time will the project take?

Each visit to ACU for the clinical assessment and rehabilitation protocol should take no more than a total of two hours and progressive running protocol (either at ACU or in own time) no more than 30 minutes. It is a requirement of the research project to complete the clinical assessment/rehabilitation sessions two to three times per week and progressive running twice per week until pre-determined criteria are met to allow clearance to return to normal level of activity.

Following this point you will be invited to attend ACU for weekly follow-up clinical assessments for a three month period. For 24 months following return to play clearance, you will also be contacted weekly by the investigators to enquire whether any re-injury has occurred, in which case you will be required to attend ACU to undergo clinical assessment to confirm presence of suspected re-injury.

#### What are the benefits of the research project?

Participation in this research project will provide you with free of charge in depth clinical assessment and rehabilitation services for your acute hamstring strain injury and rehabilitation to determine your progress through rehabilitation. In depth clinical assessment and rehabilitation of this nature generally cost in excess of \$80 per session and in addition to this you will have access to equipment often only available to elite athletes.

#### Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. Should you withdraw consent prior to completion of the study, any data collected prior to this point will still be used in analysis unless you specifically request otherwise. Your decision to participate will in no way impact upon your current or future relationship with ACU (for example your grades) or with any of the investigators.

#### Will anyone else know the results of the project?

It is intended that the results of this research will be included as part of Jack Hickey's thesis and will be submitted for publication within scholarly journals. All test results, comments and responses are anonymous and will be treated confidentially.

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- Will not be used for any other purpose (eg as an instructional aide).
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#### Who do I contact if I have questions about the project?

Jack Hickey Phone: 0432 225 273 Email: <u>jthick001@myacu.edu.au</u> David Opar Phone: 03 9953 3742 Email: <u>David.Opar@acu.edu.au</u>

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Yours sincerely,

Mr Jack Hickey Dr David Opar

# CONSENT FORM Copy for Researcher / Copy for Participant to Keep

**TITLE OF PROJECT:** Effect of pain-threshold exercise on rehabilitation of acute hamstring strain injury

(NAME OF) PRINCIPAL INVESTIGATOR (or SUPERVISOR): Dr David Opar

(NAME OF) STUDENT RESEARCHER: Mr Jack Hickey

I ...... (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study encompassing two to three times per week two hour visits to complete follow-up clinical assessment and rehabilitation until pre-determined criteria to return to normal activity is given. This will involve a series of clinical assessments and exercises at an intensity allowing up to and including 4/10 self-rated pain where I may be filmed in an un-identifiable way. I also consent to completing an additional twice per week progressive running protocol either supervised at ACU or in my own time.

Once return to play clearance has been given I agree to attend ACU for weekly follow up clinical assessment for a period of three months and to be contacted weekly for a period of 24 months to enquire about potential re-injury, realising that I can withdraw my consent at any time (without adverse consequences). I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. Should I withdraw my consent prior to completion of the study, any data collected prior to this point will still be used in analysis unless I specifically request otherwise.

NAME OF PARTICIPANT:	
SIGNATURE	DATE
SIGNATURE OF PRINCIPAL INVESTIGATOR (or SUPERVISOR):	
	DATE:
SIGNATURE OF STUDENT RESEARCHER:	
	DATE: