Utilising field-based technology to explore the relationship between high-speed running biomechanics and hamstring strain injury

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Statement of Originality

This is to certify that, to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.
I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Signature:

Lisa Nicole Wolski

Date: 18 June 2025

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List of Abbreviations

HSI	Hamstring Strain Injury
DOMS	Delayed Onset Muscle Soreness
POC	Point of Contact
TRIPP	Translating Research into Injury Prevention Practice
NHE	Nordic Hamstring Exercise
FIFA	Fédération Internationale de Football Association
MAS	Motion Analysis System
SD	Standard deviation

NA	Not applicable
NR	Not reported
NS	No significant difference
FVP	Force-velocity profiling
V3D	Visual 3D
RMSE	Root Mean Square Error
ICC	Intraclass Correlation Coefficient
F0	Theoretical maximum horizontal force at null velocity
V0	Theoretical maximum velocity under zero load
Pmax	Maximal mechanical power output
FV Slope	Linear F-V relationship slope
RFmax	Ratio of horizontal component of ground reaction force (RF) maximum value (%)
Drf	Rate of decrease in RF (%);
Vopt	Speed at maximal power output
ANCOVA	Analysis of Covariance
CI	Confidence Interval
L	Left
R	Right
ASIS	Anterior superior iliac spine
PSIS	Posterior superior iliac spine
GT	Greater trochanter
TH	Thigh
LAT	Lateral
MED	Medial
TTUB	Tibial tuberosity
HFIB	Head of fibula
LMAL	Lateral malleolus
MMAL	Medial malleolus
MT	Metatarsal joint
HLX	Hallux
ML	Medial lateral
AP	Anterior posterior
SWC	Smallest Worthwhile Change
MWC	Moderate Worthwhile Change
LWC	Largest Worthwhile Change
TE	Typical Error of Measurement
CV%	Coefficient of Variation Percentage

Abstract

Hamstring strain injury (HSI) poses a significant problem for athletes and sporting organisations. As one of the top injuries in sports involving high-speed running, it attracts great attention both in academia and the clinical realm. From an organisational perspective, the HSI burden is pronounced, especially due to its high recurrence rate. As a result, increasing pressure is placed on sports medicine professionals to deliver successful injury prevention and recovery programs. To date, the majority of the HSI prevention research focuses on hamstring strength, but the evidence and results 'on the ground' are indecisive. Noting the primary mechanism for HSI in field-based sports is non-contact high-speed running, this thesis aimed to explore the relationship between high-speed running biomechanics and HSI. Sprint coaches anecdotally exhibit a wealth of knowledge in this space, but the translation to the clinical realm seems to be lacking. Thus, an investigation into the association between high-speed running and HSI may 'bridge the gap', and subsequently inform injury prevention programs.

First, a systematic review (Chapter 2) was conducted to summarise the existing evidence on the relationship between running biomechanics and HSI, and to direct any spatiotemporal, kinematic, and kinetic aspects requiring further investigation. Evaluation of the twelve included studies revealed emerging evidence for a relationship between running biomechanics and HSI; however, there were significant concerns regarding the study quality. Further, significant variability was noted between studies in terms of protocol and methodology, reducing the ability to determine a definitive synopsis. It was recommended that more research is needed with validated measures of running biomechanical analysis.

Before further research could be conducted in this space, the methodological considerations for quantifying running biomechanics were explored (Chapter 3). The exploration and utilisation of portable technology became critical constituents of this research, ensuring that the biomechanical variables investigated reflected those of real-world, field-based settings. This led to extensive pilot testing before validation of an inertial measurement unit (IMU) system against the gold standard, the 3D Motion Analysis System (MAS), over incremental high-speed running (Chapter 4). IMU kinematic variables of interest that were identified as valid and reliable were anterior pelvic tilt and hip flexion at point of contact (POC), as well as stride time. Knee flexion and shank inclination angle at POC were inaccurately and inconsistently measured by the IMU system when compared to the MAS. Thus only, anterior tilt and hip flexion could go on to be confidently quantified by the portable IMU system for subsequent field-based observational research.

The culminating field-based observational research study (Chapter 5) was of combined cross-sectional and prospective cohort study design. The IMU system, as well as force-velocity profiling (FVP), a previously validated novel portable method for characterising the kinetics of acceleration, were utilised as methods for quantifying running biomechanics. Participants were aged between 17 and 50 years, actively participated in a sport involving sprinting, and did not have a current medical condition or injury affecting their ability to sprint pain-free. Inopportunely, restrictions imposed by COVID-19 adversely impacted recruitment in the study, resulting in a limited sample size. Twenty-three sprinters were recruited and tested at baseline, before a one-year surveillance period. Baseline testing consisted of a single maximum-effort 40m sprint from a crouched start. The first

30m was used for FVP calculation, and 6 consecutive steps in the later upright phase of the sprint were used for kinematic evaluation via the IMU system. For cross-sectional analysis, the history of HSI was based on self-report only. For prospective cohort analysis, the one-year surveillance period involved weekly text message reporting. If a HSI in the preceding week was suspected, the participant was assessed by an independent physiotherapist. Thirteen of the 23 participants had a history of HSI at baseline. Two participants went on to sustain HSIs within the surveillance period; both were classified as recurrent injuries. Although the sample size was small, the findings present a case for further investigation. At a cross-sectional level, participants with a history of HSI demonstrated increased anterior pelvic tilt at POC when compared to controls. Prospectively, the two participants who sustained a HSI exhibited a velocity-orientated profile, when compared to controls. Although these key findings are comparable to that of other studies, our observational study was the first of its kind to conduct both FVP and IMU kinematic analysis in a field-based settings. As such, the study may be considered a good feasibility trial, offering several lessons learnt in the practical implementation of such novel technologies.

Author Attribution Statement

This thesis includes three publications. Chapter 2, 4 and 5 are published manuscripts.

Chapter 2 of this thesis includes the publication:

Wolski, L., Pappas, E., Hiller, C., Halaki, M., & Fong Yan, A. (2021). Is there an association between high-speed running biomechanics and hamstring strain injury? A systematic review. Sports Biomechanics, 23(10), 1313-1339. doi: 10.1080/14763141.2021.1960418

I was the lead and corresponding author on this paper. I contributed to conceptualisation of the paper and writing (original draft preparation, review and editing). I responded to comments from reviewers during the publication process, with input from my supervisors.

Chapter 4 of this thesis includes the publication:

Wolski, L., Halaki, M., Hiller, C. E., Pappas, E., & Fong Yan, A. (2024). Validity of an Inertial Measurement Unit System to Measure Lower Limb Kinematics at Point of Contact during Incremental High-Speed Running. Sensors (Basel, Switzerland), 24(17), 5718. doi: 10.3390/s24175718

I was the lead and corresponding author on this paper. I contributed to the conceptualisation of the paper, ethics applications, methodology, data curation, analysis, investigation, project administration, visualisation and writing (original draft preparation, review and editing). I responded to comments from reviewers during the publication process, with input from my supervisors.

Chapter 5 of this thesis includes the publication:

Wolski, L., Halaki, M., Hiller, C. E., Pappas, E., & Fong Yan, A. (2025). Utilising Inertial Measurement Units and Force–Velocity Profiling to Explore the Relationship Between Hamstring Strain Injury and Running Biomechanics. Sensors, 25(5), 1518. doi: 10.3390/s25051518

I was the lead and corresponding author on this paper. I contributed to the conceptualisation of the paper, ethics applications, methodology, data curation, analysis, investigation, project administration, visualisation and writing (original draft preparation, review and editing). I responded to comments from reviewers during the publication process, with input from my supervisors.

No content produced by generative AI tools has been used in the preparation of this thesis.

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As supervisors for the candidature upon which this thesis is based, we can confirm that the authorship attribution statements above are correct.

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It is with great relief and satisfaction that I declare this thesis ready for submission. I first reached out to Professor Evangelos Pappas in 2015, oblivious to the onerous, yet rewarding journey that was to come.

I underestimated the benefits this research study has afforded me. From delivery of international presentations and domestic lectures, to working with elite athletes; I never would have imagined the multiple doors that would open. The skills I have learnt have already proved invaluable to both career and life. But none of this would have been possible without the generous support of my supervisors.

To my primary supervisor Alycia, thank you for your ongoing patience, flexibility and open mind. Being remote for most of my candidature wasn't easy, but the weekly phone calls and your prompt responsiveness to emails made me feel constantly connected to the university. Evangelos, I wouldn't have started this journey if it wasn't for your humble guidance and mentorship. Thank you for your advice no matter where in the world you were! Claire, your feedback was always so timely. I am so grateful for your practical recommendations when obstacles were faced. Mark, your breadth of knowledge is inspirational. In particular, thank you for your calm nature through the most challenging periods in the lab and patience in helping me navigate complex data sets.

This PhD was my 'after-hours' hobby. I ambitiously continued to serve full-time for the Australian Defence Force through the entire candidature. Three interstate removals, coupled with various postings over the last 9 years didn't help with study time allocation. During heavy travel and high-tempo periods, I was forced to suspend my candidature twice. Even during this suspension my supervisors remained available, motivating me to continue no matter what the pace.

On a personal note, I want to thank my best friend Catherine. You've been my biggest supporter, pushing me to 'keep going' those weekends I didn't feel like studying. You were always so understanding of all the catch ups I had to cancel because I had to 'get something done'. Likewise, thank you to my family- Mum, Dad, Michael, Brooke and Jo. Your unwavering support for everything I choose to do is sincerely appreciated.

This research is obviously not without limitations. I have developed empathy for fellow research students and academics as one thing I've learnt is that it is not that easy to execute what you set out to do! The process from idea conception to research translation is unwieldly (certainly not agile in nature!). Nevertheless, I look forward to sharing this journey through this thesis and the 'next steps' that will come.

Preface

Publications Related to this Thesis

Wolski, L., Pappas, E., Hiller, C., Halaki, M., & Fong Yan, A. (2021). Is there an association between high-speed running biomechanics and hamstring strain injury? A systematic review. *Sports Biomech*, 23(10), 1313-1339. doi: 10.1080/14763141.2021.1960418

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Wolski, L. Running drills: As part of hamstring injury management. The nuts and bolts. Journal Article. *Sport Health*. 2020;38(1):26-29. doi: 10.3316/informit.237341120323269

Paper Presentations Related to this Thesis

Wolski, L., Pappas, E., Hiller, C., Halaki, M., & Fong Yan, A. Are aberrant running biomechanics a risk factor for hamstring strain injury? A systematic review. Paper presented at: Sports Medicine Australia National Conference; 13-18 Oct 2018; Perth, Australia.

Poster Presentations Related to this Thesis

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Wolski, L., Halaki, M., Pappas, E., Hiller, C., & Fong Yan, A. Sprint Acceleration Force-Velocity Profiles in Track and Field Athletes With and Without Hamstring Injury. Poster presented at: Australasian Biomechanics Virtual Conference; 06-07 Dec 2021.

Other Publications and Presentations During Candidature

Wolski, L. Optimising Hamstring Injury Prevention and Rehab in Sports involving Sprinting. Lecture presented for: Australian Physiotherapy Association; 19 Apr 2018; Perth, Australia.

Wolski, L & Shelley, L. Learn to drill Like Bolt! Running Drills for Hamstring Injury Management. Workshop presented at: High Performance Sport New Zealand; 10 Jun 2019; Auckland, New Zealand.

Wolski, L. Optimising Hamstring Injury Prevention and Rehab in Sports involving Sprinting. Lecture presented for: Australian Physiotherapy Association; 19 Jul 2019; Sydney, Australia.

Wolski, L. Hamstring Symposium Speaker. Presented at: Sports Medicine Australia National Conference; 23-26 Oct 2019; Sunshine Coast, Australia.

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Permissions for Photograph and Image Use

Photographs and images in this thesis have permission for use (as per Appendix 1).

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2017 Optimising Running Mechanics, Australian Physiotherapy Association | Melbourne, Australia
2017 MATLAB Fundamentals, MathWorks | Perth, Australia
2017 Examination and Treatment of Running Injuries', Prof Brian Heidersheit | Melbourne, Australia
2019 Injury Prevention for Physiotherapists, Australian Physiotherapy Association | Sydney, Australia
2020 Performance Health Management, University of Canberra | Sydney, Australia

Chapter 1: Introduction

1.1 Preface

'This PhD journey started at Arafura Stadium in Darwin, Northern Territory (also known as the 'top end' of Australia). A locum Physiotherapy job whilst travelling had eventuated into a permanent position working at the Darwin Naval base. As an amateur sprinter, the athletics track at Arafura Stadium became my regular 'stomping ground'. I had returned to full training following my second hamstring strain in the previous year but was struggling to get back to previous speed. Fortunately, on this particular day Patrick Johnson was at the track and after watching me warm up, decided to come over and have a chat.

To provide context, Patrick Johnson is an Australian legend in the athletics world. In 2003, he broke Matt Shirvington's Australian 100 m record to become the first and only Australian to run sub-10 seconds. The record still stands today.

Figure 1.1: Patrick Johnson (*Image permission details located in Appendix 1*)

Patrick proceeded to confidently point out flaws in my sprinting technique. He informed that if I hadn't already done so, I would strain my hamstring if I kept running the way I was. The Olympian willingly prescribed drills and coaching cues to reduce my 'overstride', and increase my trunk/pelvic stability. I eagerly took on the advice, dutifully conducting the drills at every subsequent session and conscientiously implemented the cues suggested for my running technique.

This may be a coincidence but that season, I went on to run personal bests in the 100 m and 200 m, compete at Australian Open National Championships, and not had any hamstring issues since. As a physiotherapist, this really got me thinking. The role of running technique (quantified through biomechanics) is rarely acknowledged in hamstring injury management during physiotherapy education.

Following extensive discussions with sprint coaches and other sports physiotherapists, it became apparent there was a divergence of beliefs between the two groups in the role that biomechanics may play in hamstring strain injury. Sprint coaches tended to offer anecdotes of the typical running profile of the athlete with history of hamstring strain injury and described practical coaching methods to address it. Sports physiotherapists inclined to focus more on the evidence-based information in the literature, highlighting the role of early detection of at-risk groups, appropriate load management and strengthening.

This is obviously a very generalist outlook on the views of the two professional groups. As a clinician, I decided I wanted to investigate the potential role of running technique training on hamstring injury prevention a little more. I came across the great work of Professor Evangelos Pappas, an esteemed researcher utilising biomechanical, epidemiological and clinical approaches to musculoskeletal injury. After reaching out to him detailing my intent to research, he agreed to meet.

I proposed development of a running technique feedback tool that we could test as an intervention for prevention of Hamstring Strain Injury (HSI). Evangelos advised that we needed to better understand whether a relationship exists between hamstring strain injury and running biomechanics first. He explained that much work is needed before we can skip to implementation.

And so, the work begins….'

1.2 Chapter Outline

This chapter details the background information gathered, starting with understanding hamstring anatomy and physiology, before detailing hamstring pathophysiology and the mechanism of high-speed running HSI. HSI epidemiology and current evidence-based strategies for prevention will then be discussed, and the role of running biomechanics in muscle strain injuries will be introduced. Finally, once the aforementioned context is presented, thesis aims will be outlined.

1.3 The Hamstring Muscle Group

1.3.1 Hamstring Anatomy and Physiology

The posterior thigh muscles, known as the 'hamstrings' consist of the semitendinosus, semimembranosus and biceps femoris muscles (Figure 1.2, and Table 1.1).

The semitendinosus shares its tendinous origin with the long head of biceps femoris forming the sizeable conjoint tendon (measuring on average 2.7 cm superoinferiorly and 1.8 cm transversely).[1] At the proximal musculotendinous junction, the semitendinosus muscle belly separates from the biceps femoris to run posteromedially. The distal tendon is the longest of the hamstrings and unites with the gracilis tendon at insertion (forming two thirds of the 'pes anserine' at the medial knee).[2] It is postulated that semitendinosus' long distal tendon length predisposes the muscle to rupture.[3] This long distal tendon is also commonly grafted for anterior cruciate ligament reconstruction, which can lead to ongoing issues associated with knee flexion weakness in athletes.[4]

The semimembranosus has a flat crescent-shaped origin arising from the inferomedial impression of the ischial tuberosity.[2] The muscle descends to form the longest proximal tendon origin of the

hamstrings (average measuring on average 31.9 cm cranial-caudally), with the muscle belly located anterior to the long head of the biceps and semitendinosus. Before insertion at the medial condyle, slips may be present to the femur and adductor magnus.[5]

With two heads, the biceps femoris lives up to its name. After splitting from the conjoint tendon, the long head extends posterolaterally (30 deg angle in coronal plane, 45 deg knee flexed to 90 deg).[6] The gluteus maximus covers a significant portion of the muscle belly and proximal tendon (combined with the conjoint tendon has an average length of 27.1 cm).[6] The deep short head of the biceps femoris arises from the linear aspera of the femur and merges to the long head at the distal aponeurosis before forming a joint narrow tendon inserting at the lateral femoral condyle and head of fibula.[2]

	ORIGIN	INSERTION	NERVE SUPPLY	BLOOD SUPPLY
Semitendinosus	Ischial tuberosity (inferomedial impression)	Superior, medial tibial surface	Tibial division of the sciatic nerve (L5, S1, S2)	Medial circumflex femoral artery, first perforating artery. Accessory supply from inferior gluteal and inferior medial genicular arteries
Semimembranosus	Ischial tuberosity (superolateral impression)	Posterior aspect of medial condyle	Tibial division of the sciatic nerve (L5, S1, S2)	All perforating arteries (predominantly first), and branches of the gluteal and popliteal arteries. Accessory contribution from inferior gluteal artery
Long Head of Biceps Femoris	Ischial tuberosity (inferomedial impression)	Head of fibula and lateral tibial condyle	Tibial division of the sciatic nerve (L5, S1, S2)	First and second perforating arteries. Accessory supply from inferior gluteal, medial circumflex and superior lateral genicular arteries
Short Head of Biceps Femoris	Linear aspera (lateral lip)		Common fibular division of the sciatic nerve (L5, S1, S2)	Second and third perforating artery, and the superior lateral genicular artery

Table 1.1: Origin, insertion, nerve supply and blood supply of the hamstrings[2]

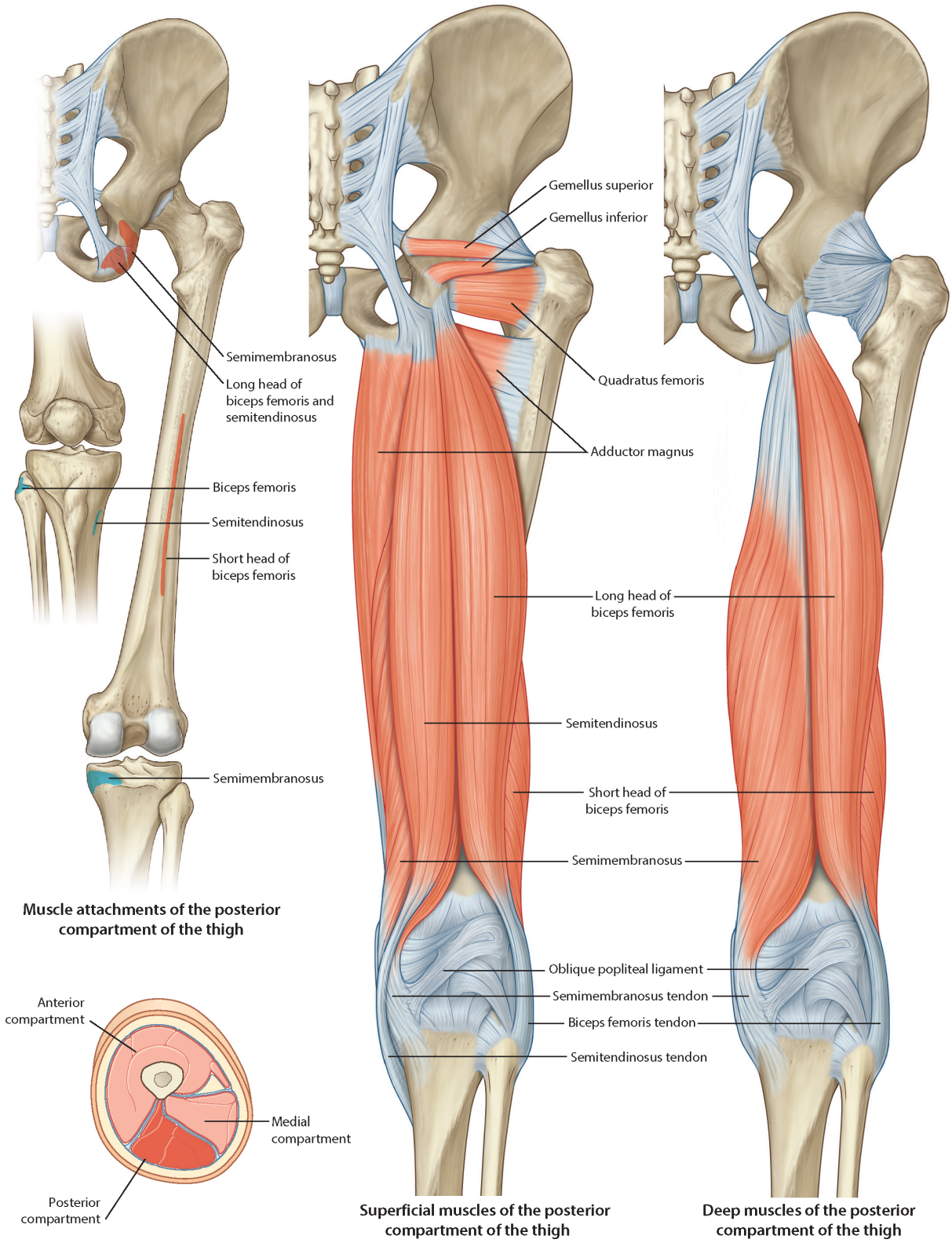

Figure 1.2: Right posterior thigh with hamstrings bony attachment detail on left - origins in red, insertions in blue. Reprinted with permission from Gray's Atlas Anatomy (*Image permission details located in Appendix 1*)[7]

Understanding muscle fibre physiology is important to fully appreciate the actions and role of the respective muscle group. Each hamstring muscle has a discrete arrangement of muscle fibre bundles or fascicles.[8] Muscle fibres comprise numerous myofibrils (the muscle contractile element). Myofibrils consist of multiple sarcomeres connected by a 'Z' line. Each sarcomere is composed of various actin and myosin protein filaments which overlap in synergy for muscle contraction.[9] Muscle fibres can be divided into slow or fast-twitch muscle types. Slow-twitch fibres are for endurance or low-intensity exercises such as long-distance running. Fast-twitch fibres on the other hand, enable short, high-intensity efforts such as sprinting or powerlifting.[10] Cadaver studies have revealed a higher proportion of fast-twitch muscle fibres in the hamstring muscles,[11] supporting the hamstrings' role in force production.

In the semitendinosus, muscle fibres are orientated longitudinally, forming a fusiform shape. The short head of biceps femoris consists of muscle fibres in a slanted trapezoid shape with fibres decreasing in length as the muscle descends distally. Muscle fibres in the long head of biceps femoris and semimembranosus are of hemi-pennate morphology connecting on the deep aspect to the origin tendon, and the insertional tendon superficially.[12] Hemi-pennate muscles have obliquely attached, shorter muscle fibres that contribute less to total muscle length and increase the physiological cross-sectional area, optimising them for force production rather than large range of motion.[12] This ability to generate significant force is of particular relevance when considering the role of the hamstrings in high speed running, and consequent injury risk.

1.3.2 Hamstrings Actions and Function Role in High-Speed Running

Crossing the hip and the knee, the primary actions of the hamstrings are knee flexion and hip extension. The hamstrings have various adjunct stability functions too. In a semi-flexed position, they act to stabilise the knee with the biceps femoris a lateral tibial rotator, and the semimembranosus and semitendinosus a medial tibial rotator.[2] Owing to their pelvic origin at the level of the hip joint, the hamstrings also act to stabilise the hip joint by limiting hip flexion unless the knee is flexed.[13] Moreover, the hamstrings play a role in trunk postural stability. They are fairly inactive during symmetrical standing but any movement of the centre of gravity in front of the hip joint transverse axis (forward sway, trunk lean or bending) results in hamstring contraction.[2]

1.3.3 The Hamstrings' Role in High-Speed Running

The hamstrings play a particularly important role in high-speed running. For the purposes of consistent language, the running phases are defined in Figure 1.3. With increasing speed (from 80-100%), the biceps femoris long head exhibits the greatest increase in muscle activity of the hamstring muscles. This occurs during terminal swing when the hamstrings reach peak force and peak length.[14-16] At this point, the primary function of the hamstrings is to eccentrically decelerate hip flexion and knee extension in preparation for point of contact (POC).[17] From POC to midstance, the hamstrings function to stabilise the knee[18] and overcome negative horizontal (braking) force by concentrically extending the hip.[19] At midstance, horizontal forces turn positive (propulsion) with the hamstrings enduring a smaller, second eccentric peak as they elongate with rapid knee extension before toe off.[17] After toe-off, the hamstrings enter a recovery phase before mid to terminal swing when they again prepare the limb for contact.[20]

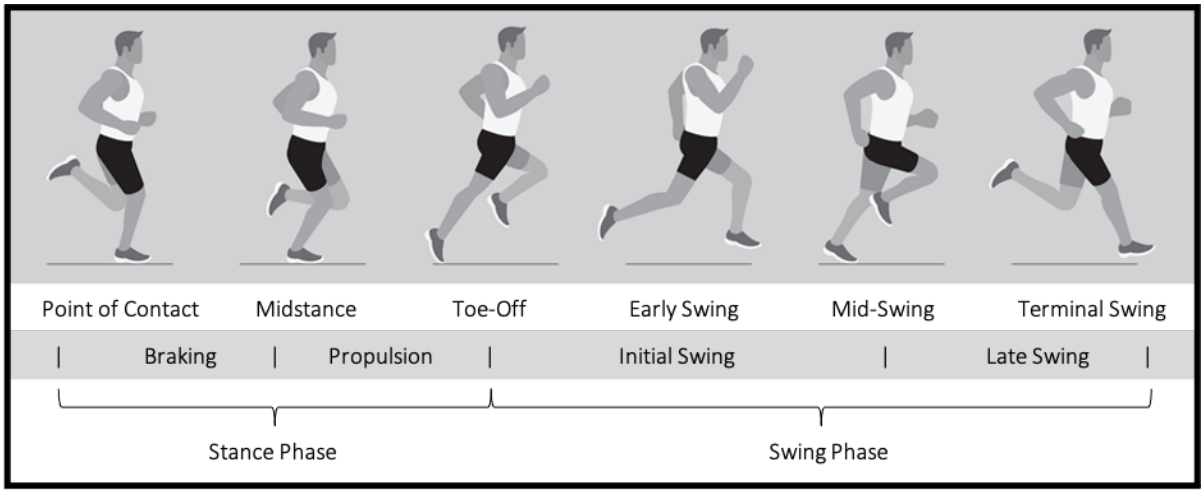

Figure 1.3: Running Phases *(Adapted with Permission from Kalkhoven et al 2020)*[21]

1.4 The HSI Problem

Hamstring injury mechanism is generally well-known by anyone who watches sport. Most would be able to describe the cliché dramatic footage of an athlete pulling up and hopping before falling to the ground grasping the back of their thigh.

1.4.1 HSI Grading, Classification and Mechanisms

The most common hamstring pathology associated with athletes is HSI. The muscle becomes strained when significant force results in muscle fibre and surrounding connective tissue failure. Traditionally, clinicians broadly grade muscle injuries into a three-tiered system according to severity; minor, moderate or severe.[22] More recently, alternative proposed grading methods incorporate prognosis based on location within the muscle unit. The most frequent site of injury is at the musculotendinous junction,[23] the weakest point of the muscle as the interface between flexible muscle fibres and stiff tendon fibres.[8] The British Athletics Muscle Injury Classification grades injuries as 1-4 (small, moderate, extensive, complete) with a, b or c denoting location (myofascial, musculotendinous or intratendinous respectively). There is also grade 0 for muscle soreness with the suffices ‘a’ or ‘b’. Localised muscle soreness with no MRI findings is graded 0a. Generalised muscle soreness or delayed onset muscle soreness (DOMS) is graded 0b (where the MRI may be normal or characteristic of DOMS).[24]

HSI can be further classified by the nature of the significant force imposed. The hamstrings are subject to high amounts of total tension. Total tension is the summation of active tension generated by contractile forces and passive tension generated by stretch on connective tissues.[22] Accordingly, two distinct pathophysiologic mechanisms of HSI have been identified; the stretch type and the high-speed running type.[25,26] Upon subjective examination, athletes typically can recall the point in time when the injury occurred. Stretching type injuries occur when the hamstrings elongate and it may occur during slow or fast end range movements.[27-29] HSI of the high-speed running type are more common[30-32] and frequently sustained during non-contact sprinting.[33] Both types are summarised in Table 1.2.

	MECHANISM	LOCATION	PROGNOSIS
High-Speed Running Type	May present during acceleration, maximal sprinting or deceleration. Injury most likely occurs during terminal swing[34]	Long head biceps femoris *(Commonly proximal musculotendinous junction)*[35]	Generally greater acute functional impairment[25] but shorter rehabilitation period (median 16 weeks, range 6-50 weeks)[26]
Stretch Type	Occurs when hamstrings elongate during slow or fast movements such as kicking, splits, sliding tackle[25]	Semimembranosus *(Typically proximal tendon closer to ischial tuberosity)*[27]	Usually mild initial symptoms[25] but rehabilitation longer (median 50 weeks, range 30-76 weeks)[26]

Table 1.2: Summary of the HSI Types. *Note: Most common presentation of each type described. Prognosis will vary depending on length of damage and proximity to the ischial tuberosity*[27,35]

This thesis will focus on HSI of the high-speed running type which typically affects the biceps femoris. [23,35,36] As comprehensively described in recent systematic and literature reviews, [37,38] there is much debate about the exact running phase in which a HSI occurs. Muscle actuated forward dynamic simulation [39] and analysis of real-time HSI [40,41] reveal the hamstring to be most susceptible to injury during late swing. Eccentric activity of a lengthened muscle increases muscle damage risk due to increased sarcomere strain.[42] Thus, it is likely that the mechanism of HSI is one of muscle damage as a result of repetitive eccentric contractions (rather than large force production), exceeding muscle capacity leading to a clinical muscle strain.[43]

1.4.2 HSI Incidence, Prevalence and Burden

For any sport that involves high-speed running or sprinting, there is generally a high risk of sustaining an HSI. The incidence is particularly high in track and field,[44,45] with HSI accounting for 50% of all injuries in sprinters.[46] It is also the most prevalent injury in Australian Football League (AFL)[47] and Gaelic football,[48] and the most common muscle injury in soccer.[30,49-53] HSI is also highly frequent in cricket,[54] Rugby Union,[55,56] Rugby League[57] and North American football.[58] A recent systematic review and meta-analysis investigating field-based sports (soccer, rugby union, field hockey, Gaelic football and AFL) reported an HSI incidence of 0.67 per 1000 exposure hours. This incidence was significantly greater during match play (3.57 per 1000 hours) compared to training (0.43 per 1000 hours). HSI prevalence was 9.8% over a 9-month period, which further increased by 6.4% for every year of increased mean cohort age. These figures have not significantly changed over the last 30 years.[59]

HSI is not only prevalent but it also has a high recurrence rate (up to 68%),[60] devastating athletes and teams. It is estimated that almost one-third of athletes who sustain an HSI will reinjure within one year of returning to sport.[61] Even if these athletes with a history of HSI do not reinjure in the first year, they still go on to be 2.7 times more likely to sustain another HSI than those without a lifetime history.[62] Decreased athlete availability (readiness to play) has a detrimental effect on team performance, potentially resulting in individual mental health issues[63] and organisational financial burden. A ten-year study of Australian Rules Football reported that total HSI, on average, costs each AFL club the equivalent of one athlete's annual salary per season.[64] Each season, a soccer team

consisting of 25 players will typically sustain five hamstring injuries, accounting for greater than 80 lost training or match days.[51] The high occurrence and recurrence rate of HSI severely affects performance, emphasising the necessity of risk factor management and prevention strategy implementation to preserve player health and ensure team stability.

1.4.3 HSI Risk Factors

Recognising the risk factors for HSI is critical for developing effective injury prevention strategies. While older age and previous HSI are the two most important risk factors,[62] there are other risk factors that should be considered. Various potential connections also exist between HSI risk factors.

In the sports performance realm, the term 'exposure' is frequently used to describe the intensity and duration of physical activity, contributing to the overall workload experienced by the athlete. Exposure includes the amount of time spent in training or competition/match, including a breakdown of specified tasks engaged in.[65] HSI researchers are particularly interested in athlete exposure to high-speed running as a modifiable risk factor for HSI.[62] Greater high-speed running exposure and playing positions with larger running demands are associated with an increased risk of HSI.[62] Sudden increases in high-speed running load predispose to HSI, possibly due to physical fatigue and eccentrically induced muscle damage associated with repeated sprints.[66] On the contrary, not enough high-speed running exposure can also increase HSI risk. A recent study of professional football players reported that reductions in high-speed running distance, playing time and running distance in the one and two matches before the HSI are associated with increased HSI risk.[67] This difference in findings may be explained by a specific level of high-speed running exposure being protective in nature.[68]

Hamstring flexibility and strength are other modifiable risk factors frequently considered in the HSI literature. While there is conflicting evidence that factors related to lower limb mobility (flexibility, range of motion etc.) are associated with an increased risk of HSI,[62] limited evidence exists that greater active knee extension deficit following return to play increases the risk of subsequent HSI.[69] Likewise, a meta-analysis revealed limited or conflicting evidence that baseline hamstring strength measures are associated with HSI as a stand-alone risk factor.[62] Emerging evidence demonstrates a relationship between match exposure and, hamstring strength and associated pain levels during testing. Isometric hamstring strength and associated subjective pain score were both significantly lower immediately and at 24 hours post-match when compared to pre-match levels. Noting this association between risk factors, hamstring strength testing procedures may be more predictive of HSI if employed more regularly than just at baseline.[70]

A history of HSI is not the only injury record associated with increased risk of HSI. Strong evidence exists that a history of anterior cruciate ligament and calf strain injury is highly associated with a greater risk of subsequent HSI. Increased HSI susceptibility following musculoskeletal injury may be related to ongoing strength deficits, reduced high-speed running exposure, and/or altered running biomechanics.[62] The previously injured hamstring muscle can undergo structural[71,72] and neurological[73] maladaptation leading to persistent deficits in its ability to tolerate stress and strain.[62] When combined with physical changes associated with increasing age,[74] the risk for recurrent HSI is concerning. As such, effective injury prevention strategies are increasingly important.

1.4.4 HSI Prevention – Models and Current Strategies

Prevention encompasses various activities aimed at reducing injury risk or preventing injury progression. As per Figure 1.4, prevention strategies can be classified into one of three stages on the 'Prevention Continuum' according to the 'Natural History of Disease / Injury'; Primary, Secondary and Tertiary.[75] Primary prevention involves interventions during the susceptibility stage, before an injury occurs, such as wearing a mouth guard in contact sports. Secondary prevention focuses on identifying injuries or diseases at their earliest stages, before symptoms appear, like skin cancer screening. Tertiary prevention occurs during the clinical stage, managing an injury post-diagnosis to slow or stop its progression and prevent recurrences. For example, using an ankle brace post sprain upon return to sport.[76]

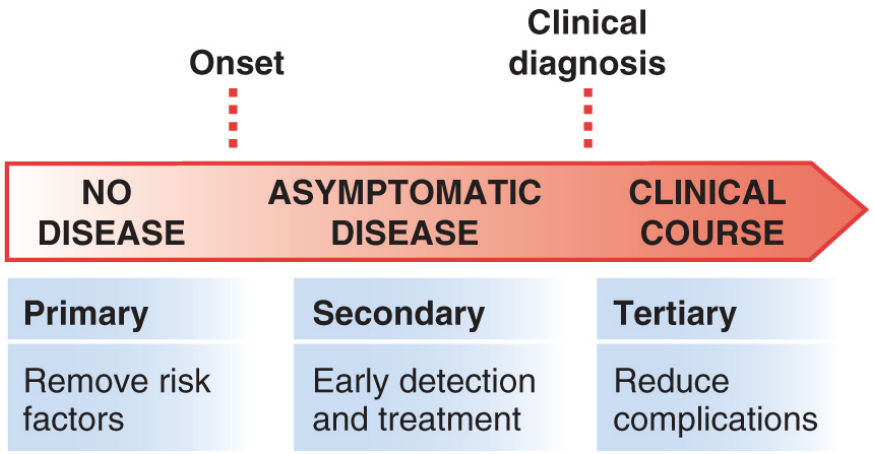

Figure 1.4: 'Prevention Continuum' or Natural History of Disease. Reprinted with permission from Clinical Epidemiology: The Essentials (*Image permission details located in Appendix 1*)[75]

Development and implementation of preventative strategies is not simple. A staged approach is required to ensure evidence-based, informed decision making. In 1992, van Mechelen and colleagues developed a four-stage model for sports injury prevention strategy implementation. Stage 1 focuses on understanding the problem/s through injury surveillance.[77] Stage 2 explores injury mechanism and risk factors, prior to development and implementation of injury prevention strategies in Stage 3. Stage 4 evaluates injury prevention strategy effectiveness through repeated injury surveillance. Finch later expanded on this work in her six stage Translating Research into Injury Prevention Practice (TRIPP) Framework, incorporating practical application and implementation factors.[78] TRIPP Stages 1 and 2 are the same as van Mechelen's. For Stage 3, rather than skipping to implementation, TRIPP's model expands by including a step for carefully investigating injury problem solutions, with the aim of developing appropriate prevention strategies. TRIPP Stage 4 involves injury prevention strategy evaluation in a controlled environment, before assessing factors for protocol translation to practical or 'real-world' settings in TRIPP Stage 5. Lastly, TRIPP Stage 6 encompasses practical implementation and evaluation.

The stages of the TRIPP model serve as handy classifiers for preventative research study categorisation. Aforementioned sections summarise the HSI literature within TRIPP Stage 1 (Section 1.4.2) and TRIPP Stage 2 (1.4.1 and 1.4.3). Acknowledging that TRIPP Stage 3 does not fall within the epidemiological phases, work within Stage 3 is most likely unpublished. Often researchers go straight to TRIPP Stage 4, not fully understanding the multi-faceted reasons behind the mechanisms

and risk factors for injury.[78] The majority of these implementation studies at TRIPP Stage 4 level assess effectiveness of prevention strategies through quantification of risk factor data (e.g. strength or flexibility metrics), as opposed to actual injury surveillance data.[79] For example, in a recent systematic review and meta-analysis evaluating independent HSI prevention strategies, only four of 108 included studies reported injury incidence data.[80]

So, what evidence exists within TRIPP Stage 4 (injury prevention strategies evaluated against injury data) for HSI prevention?

All of the four aforementioned studies implemented a hamstring strengthening program for HSI prevention in field-based sports (soccer and AFL). HSIs were still present in the interventional groups, however when compared to their respective control groups, there were significantly reduced HSIs.[81-84] Three of the four studies utilised the 'Nordic Hamstring Exercise' (NHE), a simple eccentric training exercise conducted in kneeling (lower legs secured) where the athlete attempts to resist forward-falling.[82-84] One of these studies also reported a positive tertiary prevention outcome (reductions in recurrent injury).[83] The fourth study prescribed resisted concentric and eccentric knee flexion in the prone position.[81]

Hamstring strengthening exercises have also been used within comprehensive prevention programs for both primary and tertiary prevention. Programs developed by the Fédération Internationale de Football Association (FIFA 11 and 11+) have been reported to reduce the incidence of HSI in soccer players. These programs include a combination of running, agility, strength, plyometric, balance, core, coordination and neuromuscular exercises.[85,86] Within the tertiary space, a multifactorial criteria-based algorithm for HSI rehabilitation effectively reduced recurrent HSI in soccer players, when compared to a general protocol. The multifactorial algorithm consisted of criteria-based progression of manual therapy, flexibility work, gluteus exercises, hamstring strengthening, plyometrics, ankle stabilisation drills, lumbopelvic control exercises and running technique sessions.[87] While running technique is addressed in programming, there is a lack of reporting on whether running technique (quantified through biomechanical analysis) plays a role in HSI. This highlights a potential gap in literature and presents an opportunity for research to better inform prevention programs.

1.5 Running Biomechanics and HSI

1.5.1 Running-Related Biomechanical Risk Factors and Injury Prevention

There are a reasonable number of studies in the literature that consider the role of running biomechanics on running-related injuries. Although the existing prospective evidence associating biomechanical variables to the risk of running-related injuries is limited and inconsistent,[88] evidence for altering biomechanics through running or gait retraining prevention is fairly well reported.[89,90]

Biomechanical running-related risk factors investigated in the literature include a variety of lower limb kinematic, impact-related, plantar pressure variables, and a limited amount of spatiotemporal variables.[88] Some studies report on overall running-related injuries,[91-95] while others target injuries such as plantar fasciopathy, Achilles tendinopathy, medial tibial stress syndrome,[96] iliotibial band syndrome[97] or patellofemoral syndrome.[98-100] Upon pooling results, a systematic review reported the

only consistency between studies was evidence (considered limited) that female recreation runners with greater peak hip adduction were at risk of developing patellofemoral or iliotibial band pain.[88]

Like the HSI prevention programs discussed in the previous Section (1.4.4), most running re-training prevention programs assess efficacy through risk factor quantification or surrogate outcomes e.g. specific spatiotemporal, kinematic or kinetic differences, rather than impact on injury incidence, pain or functional outcome. [89,101,102] A systematic review and metanalyses into the effects of gait retraining in distance runners found only two studies that reported on injury.[101] At one year the injury incidence was reduced following gait retraining in both studies.[103,104] One of these studies implemented eight gait-retraining sessions over 2 weeks concentrating on lowering vertical impact peak. [103] The other study, significantly smaller and including males only, implemented gait retraining focusing on avoiding rear-foot strike, reducing impact and lower-limb alignment.[104]

Barton et al synthesised evidence with expert opinion on running re-training to treat specific running related injuries. The running variables used as an intervention was based on a theoretical understanding of aberrant running mechanics that may have contributed the injury. For HSI, the experts recommended reducing overstride, knee extension at point of contact and anterior pelvic tilt, as well as promoting swing phase hip and knee flexion.[90] As mentioned in Section 1.3.3, the hamstrings play an important role in preparing the lower limb for POC[17] and successively overcome braking forces in the transition to midstance.[19] Better understanding of biomechanical variables and their association with HSI risk, will inform whether this understanding can be adopted in development of HSI prevention programs.

1.5.2 Biomechanical Analysis Considerations

An important consideration for future research in this space is the accuracy and practicality of the biomechanical data collection method. The gold standard for biomechanical analysis is the 3-dimensional Motion Analysis System (MAS).[105] While the MAS allows for exceptional detail of spatiotemporal, kinematic, and kinetic biomechanical variables, environmental constraints limit its ability to truly represent movement in functional, real-world scenarios.[6] A persistent challenge for practitioners and coaches is identifying a valid and reliable portable method for running analysis in field settings.[5] These factors have been carefully considered in determining research aims and objectives presented next.

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opposed to 'football boots' because the laboratory surface is Mondo, their biomechanical findings recorded may not reflect how they truly run out field in real-life settings. A persistent challenge, however, for practitioners and coaches is identifying a valid and reliable portable method for running analysis in these field settings.[5] These factors have been carefully considered in determining research aims and objectives presented next.

1.6 Thesis Plan

1.6.1 Thesis Aims

The aim of this research was to investigate the relationship between high-speed running and HSI, and explore whether variations in running biomechanics may contribute to the development of HSI. It is hypothesised that the running technique may predispose athletes to HSI and/or be a contributing factor to recurrence. This proposed research nests within Stage 2 of the TRIPP framework, i.e. exploration of multi-faceted injury aetiology, before preventative measures can be developed in Stage 3.[78]

The secondary aim of this thesis was to investigate how the use of portable technology can aid in understanding the complex relationship between running biomechanics and HSI. To effectively translate and apply research findings in real-world conditions, health and performance staff must be confident that the biomechanical analysis method used in research is valid, reliable, and replicable in field-based settings.[5] This research aimed to explore the use of field-based methods for running biomechanical analysis to enable research within Stage 2 of the TRIPP framework. Ultimately, the results of this thesis aim to inform the development of HSI preventative strategies (TRIPP Stage 3).

1.6.2 Thesis Objectives

In order to achieve the research aims, the thesis objectives were to:

i. Review and summarise the relationship between running biomechanics and HSI through a systematic review of the literature. This was to enable identification of gaps in the literature, and direct what spatiotemporal, kinematic and kinetic aspects required further investigation. (Chapter 2)
ii. Explore the methodological considerations for quantifying running biomechanics, and develop/propose an appropriate system for field-based running analysis. This subsequently advised requirements for validation. (Chapter 3)
iii. Validate a field-based system for high-speed running analysis. (Chapter 4)
iv. Investigate variances in high-speed running biomechanics as a risk factor for HSI. (Chapter 5)

1.7 References

1. Miller SL, Gill J, Webb GR. The proximal origin of the hamstrings and surrounding anatomy encountered during repair: a cadaveric study. *J Bone Joint Surg*. 2007;89(1):44-48. doi:10.2106/JBJS.F.00094
2. Drake R, Vogl AW, Mitchell AWM. Lower limb. *Gray's anatomy for students*. 3rd ed. Elsevier; 2014:chap 6.
3. Koulouris G, Connell D. Evaluation of the hamstring muscle complex following acute injury. *Skelet radiol*. 2003;32(10):582-589. doi:10.1007/s00256-003-0674-5

4. Ferretti A, Conteduca F, Morelli F, Masi V. Regeneration of the semitendinosus tendon after its use in anterior cruciate ligament reconstruction: a histologic study of three cases. *Am J Sports Med*. 2002;30(2):204-207. doi:10.1177/03635465020300021001
5. Woodley SJ, Mercer SR. Hamstring muscles: architecture and innervation. *Cells Tissues Organs*. 2005;179(3):125-141. doi:10.1159/000085004
6. Terry GC, LaPrade RF. The biceps femoris muscle complex at the knee: its anatomy and injury patterns associated with acute anterolateral-anteromedial rotatory instability. *Am J Sports Med*. 1996;24(1):2-8.
7. Drake RL, Vogl W, Mitchell AWM, Tibbitts RM, Richardson PE, Horn A. Thigh: posterior compartment muscles. *Gray's atlas of anatomy*. 3rd ed. Elsevier; 2021:293-384:chap 6.
8. Linklater JM, Hamilton B, Carmichael J, Orchard J, Wood DG. Hamstring injuries: anatomy, imaging, and intervention. *Semin Musculoskelet Radiol*. 2010;14(02):131-161. doi:10.1055/s-0030-1253157
9. Garrett W, Best T. Anatomy, physiology, and mechanics of skeletal muscle. *J Orthop Sci*. 1994:89-125.
10. Komnos GA, Menetrey J. Biomechanical properties of orthopedic materials: muscle. In: Koh J, Zaffagnini S, Kuroda R, Longo UG, Amirouche F, eds. *Orthopaedic biomechanics in sports medicine*. 1st ed. Springer International Publishing; 2021:91-97.
11. Garrett Jr W, Califf J, Bassett F. Histochemical correlates of hamstring injuries. *Am J Sports Med*. 1984;12(2):98-103.
12. Kumazaki T, Ehara Y, Sakai T. Anatomy and physiology of hamstring injury. *Int J Sports Med*. 2012;33(12):950-954. doi:10.1055/s-0032-1311593
13. Kopydlowski NJ, Weber AE, Sekiya JK. Functional anatomy of the hamstrings and quadriceps. In: Kaeding CC, Borchers JR, eds. *Hamstring and quadriceps injuries in athletes: a clinical guide*. Springer US; 2014:1-14.
14. Silder A, Thelen DG, Heiderscheit BC. Effects of prior hamstring strain injury on strength, flexibility, and running mechanics. *Clin Biomech*. 2010;25(7):681-6. doi:10.1016/j.clinbiomech.2010.04.015
15. Schache GA, Dorn WT, Blanch DP, Brown TNA, Pandy GM. Mechanics of the human hamstring muscles during sprinting. *Med Sci Sports Exerc*. 2012;44(4):647-658. doi:10.1249/MSS.0b013e318236a3d2
16. Nagano Y, Higashihara A, Takahashi K, Fukubayashi T. Mechanics of the muscles crossing the hip joint during sprint running. *J Sports Sci*. 2014;32(18):1722-1728. doi:10.1080/02640414.2014.915423
17. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech*. 2008;41(15):3121-6. doi:10.1016/j.jbiomech.2008.09.005
18. Cleather DJ. An important role of the biarticular hamstrings is to exert internal/external rotation moments on the tibia during vertical jumping. *J Theor Biol*. 2018;455:101-108. doi:10.1016/j.jtbi.2018.07.013
19. Stanton P, Purdham C. Hamstring injuries in sprinting - the role of eccentric exercise. *J Orthop Sports Phys Ther*. 1989;10(9):343-349. doi:10.2519/jospt.1989.10.9.343
20. Howard RM, Conway R, Harrison AJ. Muscle activity in sprinting: a review. *Sports Biomech*. 2018;17(1):1-17. doi:10.1080/14763141.2016.1252790
21. Kalkhoven JT, Sides DL, McLean B, Watsford ML. The evidence indicates that the hamstrings do not behave isometrically during the swing phase of the sprint cycle: a narrative review. *SportRxiv*. 2020;doi:10.31236/osf.io/8ujt2
22. Brukner P, Clarsen B, Cook J, et al. *Brukner & Khan's clinical sports medicine: injuries*. 5th ed. McGraw-Hill Education LLC; 2017.
23. De Smet AA, Best TM. MR imaging of the distribution and location of acute hamstring injuries in athletes. *AJR Am J Roentgenol*. Feb 2000;174(2):393-9. doi:10.2214/ajr.174.2.1740393

24. Pollock N, James SLJ, Lee JC, Chakraverty R. British athletics muscle injury classification: a new grading system. *Br J Sports Med*. 2014;48(18):1347-1351. doi:10.1136/bjsports-2013-093302
25. Askling CM, Heiderscheit BC. Acute hamstring muscle injury: types, rehabilitation, and return to sports. In: Doral MN, Karlsson J, eds. *Sports injuries: prevention, diagnosis, treatment and rehabilitation*. 2nd ed. Springer; 2015:2137-2147.
26. 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):40-44.
27. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during slow-speed stretching: clinical, magnetic resonance imaging, and recovery characteristics. *Am J Sports Med*. 2007;35(10):1716-1724. doi:10.1177/0363546507303563
28. Askling CM, Tengvar M, Saartok T, Thorstensson A. Proximal hamstring strains of stretching type in different sports: injury situations, clinical and magnetic resonance imaging characteristics, and return to sport. *Am J Sports Med*. 2008;36(9):1799-1804 6p. doi:10.1177/0363546508315892
29. Askling CM, Koulouris G, Saartok T, Werner S, Best TM. Total proximal hamstring ruptures: clinical and MRI aspects including guidelines for postoperative rehabilitation. journal article. *Knee Surg Sports Traumatol Arthrosc*. March 01 2013;21(3):515-533. doi:10.1007/s00167-012-2311-0
30. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson A. 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. doi:10.1136/bjsm.2002.002352
31. Gabbe BJ, Bennell KL, Finch CF, Wajswelner H, Orchard JW. Predictors of hamstring injury at the elite level of Australian football. *Scand J Med Sci Sports*. 2006;16(1):7-13. doi:10.1111/j.1600-0838.2005.00441.x
32. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med*. 2006;34(8):1297-1306. doi:10.1177/0363546505286022
33. Elliott MC, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: a 10-year review. *Am J Sports Med*. Apr 2011;39(4):843-50. doi:10.1177/0363546510394647
34. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Spratford W, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. *Scand J Med Sci Sports*. 2019;29(8)doi:10.1111/sms.13437
35. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. *Am J Sports Med*. 2007;35(2):197-206 10p. doi:10.1177/0363546506294679
36. Thelen DG, Chumanov ES, Hoerth DM, et al. Hamstring muscle kinematics during treadmill sprinting. *Med Sci Sports Exerc*. 2005;37(1):108-114 7p. doi:10.1249/01.MSS.0000150078.79120.C8
37. Huygaerts S, Cos F, Cohen DD, et al. Mechanisms of hamstring strain injury: interactions between fatigue, muscle activation and function. *Sports*. 2020;8(5)doi:10.3390/sports8050065
38. Danielsson A, Horvath A, Senorski C, et al. The mechanism of hamstring injuries - a systematic review. *BMC Musculoskelet Disord*. 2020;21(1):641-641. doi:10.1186/s12891-020-03658-8
39. Thelen DG, Chumanov ES, Best TM, Swanson SC, Heiderscheit BC. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. *Med Sci Sports Exerc*. 2005;37(11):1931-1938 8p. doi:10.1249/01.mss.0000176674.42929.de
40. Heiderscheit BC, Hoerth DM, Chumanov ES, Swanson SC, Thelen BJ, Thelen DG. Identifying the time of occurrence of a hamstring strain injury during treadmill running: a case study. *Clin Biomech*. Dec 2005;20(10):1072-8. doi:10.1016/j.clinbiomech.2005.07.005
41. Schache AG, Wrigley TV, Baker R, Pandy MG. Biomechanical response to hamstring muscle strain injury. *Gait Posture*. Feb 2009;29(2):332-8. doi:10.1016/j.gaitpost.2008.10.054
42. Lieber RL, Friden J. Mechanisms of muscle injury gleaned from animal models. *Am J Phys Med*. Nov 2002;81(11 Suppl):S70-9. doi:10.1097/01.PHM.0000029771.92757.2F

43. Lieber RL, Friden J. Muscle damage is not a function of muscle force but active muscle strain. *J Appl Physiol*. 1993;74(2):520-526.
44. Bennell KL, Crossley K. Musculoskeletal injuries in track and field: incidence, distribution and risk factors. *Aust J Sci Med Sport*. Sep 1996;28(3):69-75.
45. Edouard P, Arnal P, Gimenez P, et al. Athletic injury prevention: determinants of sprint performance. *Ann Phys Rehabil Med*. September 2016;59:e22-e23. doi:10.1016/j.rehab.2016.07.054
46. Brubaker CE, James SL. Injuries to runners. *Am J Sports Med*. 1974;2(4):189 - 198.
47. 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*. Apr 2013;41(4):734-41. doi:10.1177/0363546513476270
48. Murphy JC, O'Malley E, Gissane C, Blake C. Incidence of injury in Gaelic football: a 4-year prospective study. *Am J Sports Med*. 2012;40(9):2113-2120. doi:10.1177/0363546512455315
49. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk factors for injuries in football. *Am J Sports Med*. Jan-Feb 2004;32(1 Suppl):5S-16S. doi:10.1177/0363546503258912
50. Dauty M, Collon S. Incidence of injuries in French professional soccer players. *Int J Sports Med*. 2011;32(12):965-969.
51. Ekstrand J, Hagglund M, Walden M. Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med*. Jun 2011;39(6):1226-32. doi:10.1177/0363546510395879
52. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med*. Jun 2011;45(7):553-8. doi:10.1136/bjsm.2009.060582
53. Hagglund M, Walden M, Ekstrand J. Injuries among male and female elite football players. *Scand J Med Sci Sports*. Dec 2009;19(6):819-27. doi:10.1111/j.1600-0838.2008.00861.x
54. Orchard JW, Kountouris A, Sims K. Risk factors for hamstring injuries in Australian male professional cricket players. *J Sport Health Sci*. September 2017;6(3):271-274. doi:10.1016/j.jshs.2017.05.004
55. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. *Br J Sports Med*. 2005;39(10):757-766. doi:10.1136/bjsm.2005.018135
56. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 2 training Injuries. *Br J Sports Med*. 2005;39(10):767-775. doi:10.1136/bjsm.2005.018408
57. O'Connor D. NRL injury report 2011. *Sport Health*. 2012;30(1):12-22. doi:10.3316/informit.502856237550053
58. Feeley BT, Kennelly S, Barnes RP, et al. Epidemiology of national football league training camp injuries from 1998 to 2007. *Am J Sports Med*. Aug 2008;36(8):1597-603. doi:10.1177/0363546508316021
59. Maniar N, Carmichael DS, Hickey JT, et al. Incidence and prevalence of hamstring injuries in field-based team sports: a systematic review and meta-analysis of 5952 injuries from over 7 million exposure hours. *Br J Sports Med*. 2023;57(2):109-116. doi:10.1136/bjsports-2021-104936
60. Diemer WM, Winters M, Tol JL, Pas HIMFL, Moen MH. Incidence of acute hamstring injuries in soccer: a systematic review of 13 studies involving more than 3800 athletes with 2 million sport exposure hours. *J Orthop Sports Phys Ther*. 2021;51(1):27-36. doi:10.2519/jospt.2021.9305
61. 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*. Feb 2010;40(2):67-81. doi:10.2519/jospt.2010.3047
62. Green B, Bourne MN, van Dyk N, Pizzari T. Recalibrating the risk of hamstring strain injury (HSI): a 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. *Br J Sports Med*. 2020;54(18):1081-1088. doi:10.1136/bjsports-2019-100983

63. Kerr ZY, Prim J, DeFreese JD, et al. Musculoskeletal injury history is associated with lower physical and mental health in a historical cohort of former National Football League players. *J Sport Rehabil*. 01 Jul. 2021 2021;30(5):760-767. doi:10.1123/jsr.2020-0231
64. 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. doi:10.1136/bjsports-2013-092884
65. Soligard T, Schwellnus M, Alonso J-M, et al. How much is too much? (Part 1) International Olympic committee consensus statement on load in sport and risk of injury. *Br J Sports Med*. 2016;50(17):1030-1041. doi:10.1136/bjsports-2016-096581
66. Howatson G, Milak A. Exercise-induced muscle damage following a bout of sport specific repeated sprints. *J Strength Cond Res*. 2009;23(8):2419-2424. doi:10.1519/JSC.0b013e3181bac52e
67. Moreno-Pérez V, Del Coso J, López-Del Campo R, et al. Reduced match exposure in the previous 2 matches accounts for hamstring muscle injury incidence in professional football players. *Sports health*. 2024;16(1):109-114. doi:10.1177/19417381231158117
68. Silva JR, Magalhães JF, Ascensão AA, Oliveira EM, Seabra AF, Rebelo AN. Individual match playing time during the season affects fitness-related parameters of male professional soccer players. *J Strength Cond Res*. 2011;25(10):2729-2739. doi:10.1519/JSC.0b013e31820da078
69. De Vos R-J, Reurink G, Goudswaard G-J, 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):1377-1384. doi:10.1136/bjsports-2014-093737
70. Wollin M, Thorborg K, Pizzari T. The acute effect of match play on hamstring strength and lower limb flexibility in elite youth football players. *Scand J Med Sci Sports*. 2017;27(3):282-288. doi:10.1111/sms.12655
71. Silder A, Heiderscheit BC, Thelen DG, Enright T, Tuite MJ. MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skelet radiol*. 2008;37(12):1101-1109. doi:10.1007/s00256-008-0546-0
72. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *Br J Sports Med*. 2016;50(23):1467-1472. doi:10.1136/bjsports-2015-094881
73. Fyfe JJ, Opar DA, Williams MD, Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. *J Electromyogr Kinesiol*. 2013;23(3):523-530. doi:10.1016/j.jelekin.2012.12.006
74. Narici MV, Maffulli N, Maganaris CN. Ageing of human muscles and tendons. *Disabil Rehabil*. 2008;30(20-22):1548-1554. doi:10.1080/09638280701831058
75. Fletcher GS. *Clinical epidemiology the essentials*. 6th ed. vol 6th. Wolters Kluwer; 2020.
76. Jacobsson J, Timpka T. Classification of prevention in sports medicine and epidemiology. *Sports Med*. Nov 2015;45(11):1483-7. doi:10.1007/s40279-015-0368-x
77. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med*. 1992;14(2):82-99. doi:10.2165/00007256-199214020-00002
78. Finch C. A new framework for research leading to sports injury prevention. *J Sci Med Sport*. May 2006;9:3-9. doi:10.1016/j.jsams.2006.02.009
79. Afonso J, Reurink G, Clemente FM, Ramirez-Campillo R, Pizzari T, Andrade R. Revisiting the hamstring injury prevention and rehabilitation literature: filling the gaps. *Br J Sports Med*. 2023;58(5):243-244. doi:10.1136/bjsports-2023-106878
80. Rudisill SS, Varady NH, Kucharik MP, Eberlin CT, Martin SD. Evidence-based hamstring injury prevention and risk factor management: a systematic review and meta-analysis of randomized controlled trials. *Am J Sports Med*. 2023;51(7):1927-1942. doi:10.1177/03635465221083998

81. 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):244-250. doi:10.1034/j.1600-0838.2003.00312.x
82. Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian football. *J Sci Med Sport*. 2006;9(1):103-109. doi:10.1016/j.jsams.2006.02.001
83. 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. *Am J Sports Med*. 2011;39(11):2296-2303. doi:10.1177/0363546511419277
84. 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. *Am J Sports Med*. 2015;43(6):1316-1323. doi:10.1177/0363546515574057
85. Al Attar WSA, Soomro N, Pappas E, Sinclair PJ, Sanders RH. Adding a post-training FIFA 11+ exercise program to the pre-training FIFA 11+ injury prevention program reduces injury rates among male amateur soccer players: a cluster-randomised trial. *J Physiother*. 2017;63(4):235-242. doi:10.1016/j.jphys.2017.08.004
86. Nouni-Garcia R, Carratala-Munuera C, Orozco-Beltran D, Lopez-Pineda A, Asensio-Garcia MR, Gil-Guillen VF. Clinical benefit of the FIFA 11 programme for the prevention of hamstring and lateral ankle ligament injuries among amateur soccer players. *Inj prev*. 2018;24(2):149-154. doi:10.1136/injuryprev-2016-042267
87. Mendiguchia J, Martinez-Ruiz E, Edouard P, et al. A multifactorial, criteria-based progressive algorithm for hamstring injury treatment. *Med Sci Sports Exerc*. 2017;49(7):1482-1492. doi:10.1249/MSS.0000000000001241
88. Ceyssens L, Vanelderen R, Barton C, Malliaras P, Dingenen B. Biomechanical risk factors associated with running-related injuries: a systematic review. journal article. *Sports Med*. April 26 2019;doi:10.1007/s40279-019-01110-z
89. Agresta C, Brown A. Gait retraining for injured and healthy runners using augmented feedback: a systematic literature review. *J Orthop Sports Phys Ther*. 2015;45(8):576-584. doi:10.2519/jospt.2015.5823
90. Barton CJ, Bonanno DR, Carr J, et al. Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion. *Br J Sports Med*. 2016;50(9):513-526. doi:10.1136/bjsports-2015-095278
91. Dudley RI, Pamukoff DN, Lynn SK, Kersey RD, Noffal GJ. A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners. *Hum Mov Sci*. 2017;52:197-202. doi:10.1016/j.humov.2017.02.007
92. Bredeweg SW, Kluitenberg B, Bessem B, Buist I. Differences in kinetic variables between injured and noninjured novice runners: A prospective cohort study. *J Sci Med Sport*. 2013;16(3):205-210. doi:10.1016/j.jsams.2012.08.002
93. Bredeweg SW, Buist I, Kluitenberg B. Differences in kinetic asymmetry between injured and noninjured novice runners: A prospective cohort study. *Gait Posture*. 2013;38(4):847-852. doi:10.1016/j.gaitpost.2013.04.014
94. Kuhman DJ, Paquette MR, Peel SA, Melcher DA. Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Hum Mov Sci*. 2016;47:9-15. doi:10.1016/j.humov.2016.01.013
95. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Kinetic risk factors of running-related injuries in female recreational runners. *Scand J Med Sci Sports*. 2018;28(10):2164-2172. doi:10.1111/sms.13228
96. Brund RBK, Rasmussen S, Nielsen RO, Kersting UG, Laessoe U, Voigt M. Medial shoe-ground pressure and specific running injuries: a 1-year prospective cohort study. *J Sci Med Sport*. 2017;20(9):830-834. doi:10.1016/j.jsams.2017.04.001

97. Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech*. 2007;22(9):951-956. doi:10.1016/j.clinbiomech.2007.07.001
98. Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc*. 2013;45(6):1120-1124. doi:10.1249/MSS.0b013e31828249d2
99. Thijs Y, Tiggelen DV, Roosen P, Clercq DD, Witvrouw E. A prospective study on gait-related intrinsic risk factors for patellofemoral pain. *Clin J Sport Med*. 2007;17(6):437-445. doi:10.1097/JSM.0b013e31815ac44f
100. Stefanyshyn DJ, Stergiou P, Lun VMY, Meeuwisse WH, Worobets JT. Knee angular impulse as a predictor of patellofemoral pain in runners. *Am J Sports Med*. 2006;34(11):1844-1851. doi:10.1177/0363546506288753
101. Doyle E, Doyle TLA, Bonacci J, Fuller JT. The effectiveness of gait retraining on running kinematics, kinetics, performance, pain, and injury in distance runners: a systematic review with meta-analysis. *J Orthop Sports Phys Ther*. 2022;52(4):192-A5. doi:10.2519/jospt.2022.10585
102. Napier C, Cochrane CK, Taunton JE, Hunt MA. Gait modifications to change lower extremity gait biomechanics in runners: a systematic review. *Br J Sports Med*. 2015;49(21):1382-8. doi:10.1136/bjsports-2014-094393
103. Chan ZYS, Zhang JH, Au IPH, et al. Gait retraining for the reduction of injury occurrence in novice distance runners: 1-year follow-up of a randomized controlled trial. *Am J Sports Med*. 2018;46(2):388-395. doi:10.1177/0363546517736277
104. Letafatkar A, Rabiei P, Farivar N, Alamouti G. Long-term efficacy of conditioning training program combined with feedback on kinetics and kinematics in male runners. *Scand J Med Sci Sports*. 2020;30(3):429-441. doi:10.1111/sms.13587
105. Willy R. Innovations and pitfalls in the use of wearable devices in the prevention and rehabilitation of running related injuries. *Phys Ther Sport*. 2018;29:26-33. doi:10.1016/j.ptsp.2017.10.003
106. Li Y, Nie Y, Zhang X, Gu Y. Effects of footwear and foot strike patterns on patellofemoral joint and Achilles tendon loading in novice runners and experienced runners. *Front Sports Act Living.* 2025;7:1610514. doi:10.3389/fspor.2025.1610514

Chapter 2: Is there an association between high-speed running biomechanics and hamstring strain injury? A systematic review

2.1 Outline

This chapter provides a systematic review of the existing evidence into the relationship between running biomechanics and HSI. The review aimed to direct which spatiotemporal, kinematic and/or kinetic aspects of running may be investigated as a risk factor for HSI (i.e. future research within TRIPP Stage 2). It is presented in the style of the journal where it is published:

Wolski, L., Pappas, E., Hiller, C., Halaki, M., & Fong Yan, A. (2021). Is there an association between high-speed running biomechanics and hamstring strain injury? A systematic review. *Sports Biomechanics*, 23(10), 1313-1339. doi: 10.1080/14763141.2021.1960418

This systematic review found limited evidence that athletes with HSIs, whether identified retrospectively or prospectively, run differently from uninjured athletes. A number of recommendations were made within the Systematic Review discussion regarding considerations for future research, including potential variables of interest, study design, use of unaffected side as control, and influence of confounding variables. The Systematic review concluded that further research using validated biomechanical analysis methods is needed to determine any association between running biomechanics and HSI. The next phase of this PhD, therefore, focused on exploring methods to quantify running biomechanics, validating them for high-speed running in order to use these methods to further investigation the relationship between HSI and high-speed running biomechanics.

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Is there an association between high-speed running biomechanics and hamstring strain injury? A systematic review

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ABSTRACT

Despite increased awareness of the multifactorial nature of Hamstring Strain Injury (HSI), the role of running biomechanics remains unclear. The aim of this systematic review was to investigate whether an association exists between running biomechanics and HSI. Five databases were searched from inception to January 2021. Eligibility criteria included epidemiological studies that provide data on running biomechanics in athletes who have sustained a HSI (retrospectively or prospectively) and compared to control data. Searches yielded 4,798 articles. Twelve met the selection criteria. Biomechanical analysis differed considerably across studies, thus meta-analyses was not possible. Studies largely found either no differences or contradicting findings between running biomechanics of athletes who have sustained a HSI (retrospectively or prospectively) and controls, with the exception of lateral trunk kinematics and horizontal propulsive forces. It is important to note some concern regarding the quality of included studies, particularly sample size, increasing the risk of bias associated with results. Further research utilising validated methods of biomechanical analysis, is needed to determine if an association exists between running biomechanics and HSI. Until then, definitive conclusions cannot be drawn as to whether specific biomechanical interventions should be included in injury prevention and/or rehabilitation programmes.

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Introduction

Hamstring strain injury (HSI) poses a significant problem for amateur and professional athletes, particularly due to its high recurrence rate (Green et al., 2020). Despite an increase in HSI prevention and aetiology research, the incidence rate is still particularly high in sports involving high-speed running. It is the most prevalent injury in Australian Rules (Orchard et al., 2013) and Gaelic football (Murphy et al., 2012), as well as the most common muscle injury in soccer (Arnason et al., 2004; Ekstrand et al., 2011) and athletics (Bennell & Crossley, 1996). HSI also frequents cricket (Orchard et al., 2017), Rugby (Brooks et al., 2006), and North American football (Feeley et al., 2008).

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Two types of HSI have been identified based on mechanism of injury; the stretch type and the high-speed running type (Askling & Heiderscheit, 2015). Stretching type injuries occur when the hamstrings elongate with hip flexion and knee extension (Danielsson et al., 2020), occurring during slow or fast end range movements (Askling et al., 2007b). This paper will focus on HSI of the high-speed running type, which is more common in sports involving sprinting (Brooks et al., 2006; Woods et al., 2004) and predominantly affects the biceps femoris muscle (Askling et al., 2007a).

When trying to prevent the enigma of HSI, it is important to acknowledge its complex and multifactorial nature. Older age and previous HSI are the two most evidence-based risk factors in the literature (Green et al., 2020), but various plausible modifiable risk factors have also been identified. A recent systematic review of only prospective studies reported 'factors relating to sports performance and match play, running and hamstring strength were most consistently associated with HSI risk' (Green et al., 2020). Potential running factors included increased high-speed running exposure (Duhig et al., 2016; Ruddy et al., 2018) and variances in trunk and pelvic kinematics (Schuermans, Van Tiggelen, et al., 2017b).

The hamstrings play an important role in high-speed running. With increasing speed (from 80% to 100%), the biceps femoris long head is reported to have the greatest percentage increase in muscle activity of the hamstring group, in the terminal swing phase (Silder et al., 2010). During this phase, the hamstring muscles reach peak force and peak length (Nagano et al., 2014; G. A. Schache et al., 2012), with the biceps femoris exhibiting the greatest peak muscle-tendon strain (G. A. Schache et al., 2012). At this point, the primary function of the hamstring muscles is to eccentrically decelerate hip flexion and knee extension in preparation for initial contact (Yu et al., 2008). From initial contact to early stance the hamstring muscles function to stabilise the knee (Cleather, 2018) and overcome negative horizontal (braking) force by concentrically extending the hip (Stanton & Purdham, 1989). By late stance, horizontal forces turn positive (propulsive) with the hamstrings enduring a smaller, second eccentric peak, as they elongate with rapid knee extension before toe off (Yu et al., 2008). After toe-off, hamstring muscle enters a recovery phase (Howard et al., 2018) before mid to late stance when the hamstring again prepares the limb for contact.

As comprehensively described in recent systematic and literature reviews (Danielsson et al., 2020; Huygaerts et al., 2020), there is much debate about the exact running phase in which a HSI occurs. Muscle actuated forward dynamic simulation (Thelen et al., 2005) and analysis of real-time HSI (Heiderscheit et al., 2005; A. G. Schache et al., 2009) reveal the hamstring to be most susceptive to injury during late swing. Eccentric activity of a lengthened muscle increases muscle damage risk due to increased sarcomere strain (Lieber & Friden, 2002). Thus, it is likely that the mechanism of HSI is one of muscle damage as a result of repetitive eccentric contractions (rather than force), leading to a clinical muscle strain (Lieber & Friden, 1993). To understand how running technique may relate to HSI, running biomechanics should be analysed throughout the entire gait cycle (not just late swing) as the functional task of running requires continuity through phases. For example, late swing performance may be influenced by the mechanics (or technique) of the preceding recovery phase. Therefore, the aim of this systematic review was to determine whether an association exists between running biomechanics throughout the entire gait cycle and HSI of the high-speed running type. It is hypothesised that 1) Running biomechanics will be

different in athletes who go on to sustain a HSI when compared to controls 2) Running biomechanics will be different in athletes that have a history of HSI when compared to controls. The findings of this study will build on the work of Green et al. (2020) and may direct whether biomechanical variables should be investigated in future epidemiological and interventional studies.

Methods

This systematic review was performed according to PRISMA guidelines and registered in. The SR was registered in *PROSPERO (CRD* 42016047765) before commencement.

Search strategy

Five databases (CINAHL, Cochrane, Embase, Medline, SPORTDiscus) were searched from inception until January 2021, with keywords relating to sport, running, hamstring, injury, and biomechanics (see Figure 1 for PRISMA full search strategy). References were imported into Endnote (Version X9), where duplicates were deleted. Articles containing 'ACL' or 'cruciate' in the title/abstract and not containing hamstring in the title/abstract were also removed.

Inclusion and exclusion criteria

Strict inclusion and exclusion criteria were established prior to the database searches. Inclusion criteria were as follows: studies must be cohort, cross-sectional or case-control design, published in peer-reviewed journals, provide data on running biomechanics (spatiotemporal, kinematic, kinetic variables), analyse participants with a history of HSI (retrospectively or prospectively) that are asymptomatic running at time of testing, and have data for a control; either uninjured side or matched, healthy (asymptomatic) controls. Papers were excluded if full-text was not available or contained data from subjects who had undergone hamstring surgery. No language limitations were applied.

Review process

Two reviewers screened the titles and abstracts independently. All potentially applicable articles were obtained for full-text review, by both reviewers. A third reviewer was available for any disagreements. Additional records were sourced through hand searching of reference lists.

Quality analysis

Quality analysis was also conducted independently by two examiners, with a third examiner available for any disagreements. The National Heart, Lung and Blood Institute (NHLBI, 2019) study quality assessment tools and critical appraisal guidelines were utilised for quality assessment and rating ('poor', 'fair' or 'good'). This tool was chosen because it was developed via detailed methodology and accounts for differing study designs (Quality Assessment for Cohort and Cross-Sectional OR Case-Control Studies). Their guidelines for rating were as follows:

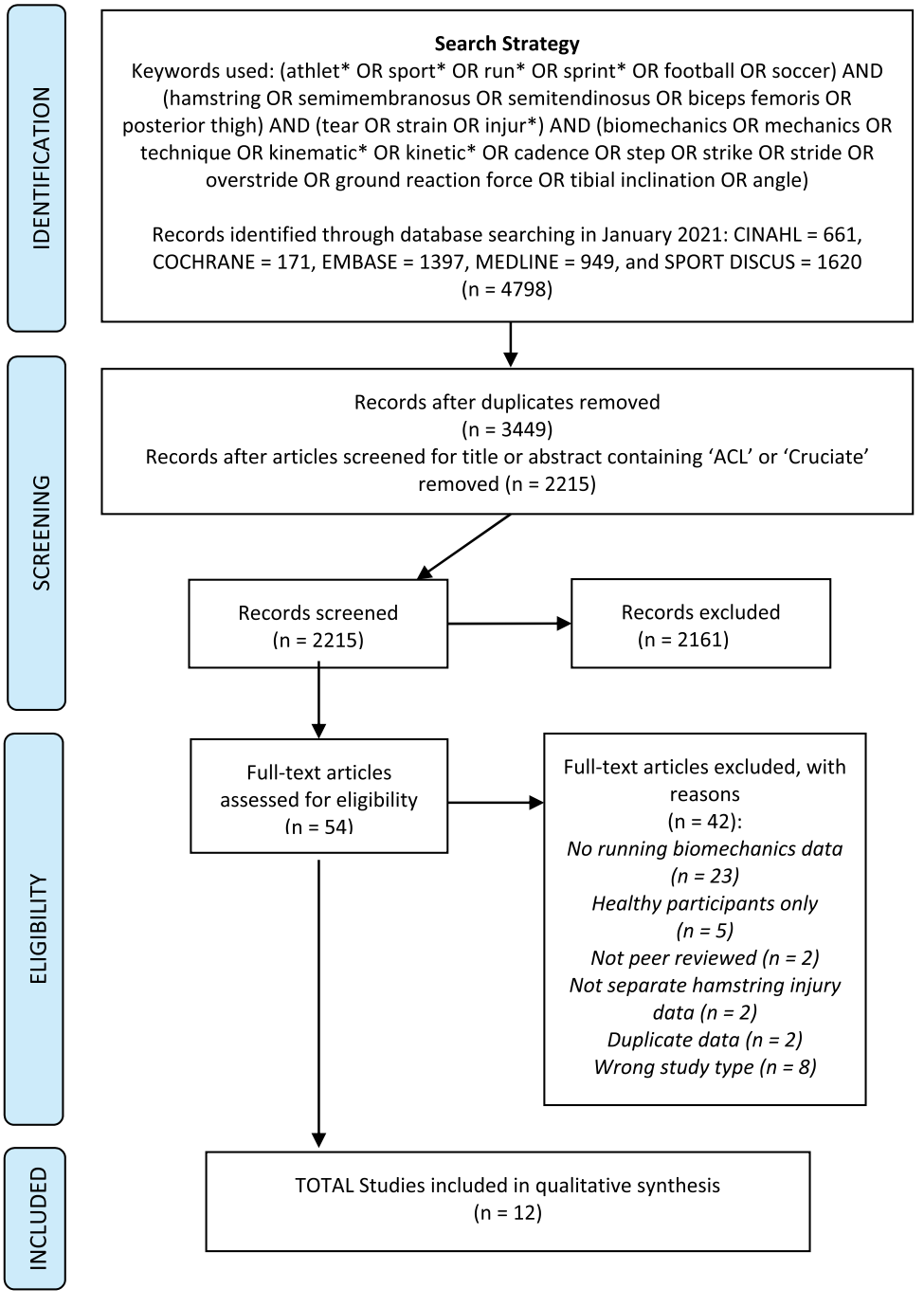

Figure 1. Prisma flow diagram.

'A "good" study has the least risk of bias, and results are considered to be valid. A "fair" study is susceptible to some bias deemed not sufficient to invalidate its results. The fair quality category is likely to be broad, so studies with this rating will vary in their strengths and weaknesses. A "poor" rating indicates significant risk of bias.'

Studies were not excluded based on quality.

Data extraction

Data on demographics, injury definition (anecdotal, professional diagnosis and/or imaging), inclusion/exclusion criteria, biomechanical outcome measures, running protocol, and statistical methods were extracted for each study separately by two investigators. Findings were then compared and any discrepancies resolved via discussion. A third reviewer was available to assist consensus, as required.

If multiple studies reported similar outcome measures, a meta-analysis was planned. Means and standard deviations were to be extracted from the injured leg and compared with the control group and/or uninjured leg. Data was then to be pooled using Comprehensive Meta-Analysis, Version 3, Biostat, Inc. using random effects.

Results

The database search yielded 4798 articles. Fifty-four full-text articles were identified as potentially relevant from title and abstract screening. Of these, 12 met the selection criteria and were included in the synthesis. One study had two designs, thus was analysed as two sub-studies (Schuermans et al., 2017b). Another paper was in Japanese (Kobayashi et al., 2009), consequently was reviewed by two independent Japanese reviewers. For further search details and results, see Figure 1 for PRISMA Flow Diagram.

Study quality

Eight studies were of a case-control (Barreira et al., 2015; Brughelli et al., 2010; Daly et al., 2016; Kobayashi et al., 2009; Lord et al., 2018; Mendiguchia et al., 2016;Schuermans et al., 2017b; Sugimoto et al., 2019)[3], three studies cross-sectional (Ciacci et al., 2013; Higashihara et al., 2019; Lee et al., 2009) and two prospective cohort design (Kenneally-Dabrowski et al., 2019; Schuermans et al., 2017b). Quality analysis revealed three studies rated 'poor' (Barreira et al., 2015; Ciacci et al., 2013; Sugimoto et al., 2019), seven studies 'fair' (Higashihara et al., 2019; Kenneally-Dabrowski et al., 2019; Kobayashi et al., 2009; Lee et al., 2009; Lord et al., 2018; Mendiguchia et al., 2014; Schuermans et al., 2017b) and three studies 'good' (Brughelli et al., 2010; Daly et al., 2016; Schuermans et al., 2017b). See Tables 1 and 2 for full NHBLI quality assessment results. The two most evidence-based risk factors for HSI, age and previous history of HSI were considered the key confounding variables. The main issues affecting overall quality rating were small sample size, lack of validated measure/s of exposure and non-conventional statistical methods.

Study characteristics

Variances in population demographics, sample characteristics, the definition of HSI and running protocol existed between studies (see Table 3). Running was documented as the mechanism of injury in five studies (Daly et al., 2016; Higashihara et al., 2019; Kenneally-Dabrowski et al., 2019; Kobayashi et al., 2009; Mendiguchia et al., 2014). No other studies reported on specific mechanism of injury. Only two studies reported on the exact

Table 1. Quality Analysis Case Control Studies.

	Ciacci et al. (2013)[33]	Higashihara et al. (2019)	Kenneally-Dabrowski et al. (2019)[41]	Lee et al. (2009)[36]	Schuermans et al. (2017b)[39]
Q1: Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes	Yes
Q2: Was the study population clearly specified and defined?	No	Yes	Yes	Yes	Yes
Q3: Was the participation rate of eligible persons at least 50%?	NR	NR	NR	NR	NR
Q4: Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	NR	Yes	Yes	Yes	Yes
Q5: Was a sample size justification, power description, or variance and effect estimates provided?	No	No	No	No	No
Q6: For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	No	No	Yes	No	Yes
Q7: Was the timeframe sufficient so that one could reasonably expect to see an association between the exposure and outcome if it existed?	No	No	Yes	No	Yes
Q8: For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as a continuous variable)?	Yes	Yes	Yes	Yes	Yes
Q9: Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
Q10: Was the exposure(s) assessed more than once over time?	No	No	No	No	No
Q11: Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	No	Yes	Yes	Yes	Yes
Q12: Were the outcome assessors blinded to the exposure status of the participants?	NR	NA	NR	NA	NR
Q13: Was loss to follow-up after baseline 20% or less?	NA	NA	Yes	NA	Yes
Q14: Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	No	No	Yes	No	No
RATING	POOR	FAIR	FAIR	FAIR	FAIR

NR: Not Reported, NA: Not Applicable

hamstring muscle injured (Ciacci et al., 2013; Sugimoto et al., 2019). Both cases of HSI in the Ciacci et al. (2013) study were in the biceps femoris. Twenty three (66%) out of 35 cases of HSI in the Sugimoto et al. (2019) study were in the biceps femoris, the remaining 12 were in the medial muscles (semitendinosus or semimembranosus).

Main findings

Running biomechanical outcome measures and main findings are outlined in Table 4. These have been divided into spatiotemporal, kinematic and kinetic categories. Meta-

Table 2. Quality analysis cross-sectional and Cohort studies.

Study	Population	Sex	Sample Size	Demographics Age (years) (SD) Weight (kg) (SD) Height (cm) (SD) HSI	Controls	Definition of HSI	Running Surface and Testing Equipment	Foot wear	Warm Up	Running Protocol
CASE-CONTROL STUDIES										
Barreira et al. (2015) . [31]	English Premier League Players	Male	HSI: 6 Control: 11	24.5(2.3), 76.3(2.5), 179(3),	21.3(1.2) 82.2(2.8) 183(3)	History of unilateral HSI Occurrence ≤2 years prior to testing Onset during training or competition Prevented participation in normal training and/or competition >48 hours not including the day of injury Identified through club medical records	Non-motorised treadmill, force transducers 200 Hz	NR	5 min cycle	10s acceleration to maximum steady state sprint in final seconds, 1 trial
Brughelli et al. (2010) [32]	Western Australian Football League	NR	HSI: 11 Control: 11	22.4 84.1 183.0	21.9 84.0 183.5	One or more unilateral HSI (to same leg only) Occurrence ≤2 years prior to testing Prevented participation of training ≥1 week	Non-motorised treadmill, horizontal load cell and force transducers 200 Hz	NR	NR	Progress to 80% of maximal speed over a 3s period then maintain velocity for 8s, 1 trial
Daly et al. (2016) [34]	Male elite level hurlers	Male	HSI: 9 Control: 8	28.3(5.2) 81.2(6.6) 179(5.8)	25(5.4) 84.2(7.0) 182(4.9)	Sudden onset of posterior thigh pain occurring during non-contact, high speed running Pain localised to the hamstring region Discomfort with active hamstring contraction and running ≥48 hours Inability to participate in sport ≥48 hours	Treadmill, 3D motion analysis	'Own shoes'	5 min treadmill— Incremental increase to 20 km/hr	Steady state 20 km/h for 10s, 1 trial

(*Continued*)

Table 2. (Continued).

Study	Population	Sex	Sample Size	Demographics Age (years) (SD) Weight (kg) (SD) Height (cm) (SD) HSI	Controls	Definition of HSI	Running Surface and Testing Equipment	Foot wear	Warm Up	Running Protocol
Kobayashi et al. (2009) [35]	University track and field athletes	Male & Female	HSI: 12 Control: 8	21.3(1.2) 60.1(8.3) 166(7.5)	20.1(0.9) 57.8 (8.8) 167.8 (7.0)	History of unilateral hamstring injury Onset caused by running during training or competition Recovered from HSI to the point that they can participate in a game No other lower limb injury	Overground track, electro-goniometer, video analysis	Track spikes	Self-directed	100 m sprint (video analysis set at 50 m from start, recorded at lateral side at least 10 m away), crouch start with starting block, 2 trials, >1.5 h recovery
Lord et al. (2018) [37]	Semi-professional soccer players	NR	HSI: 20 Control: 20	23.8(2.7) 73.9(4.7) NR	20.1(3.2) 71.4(3.6) NR	One or more unilateral HSI (to same leg only) Diagnosed by clinical physiotherapist Caused the athlete to miss at least one week of training Occurrence ≤2 years prior to testing	Non-motorised treadmill, horizontal load cell and force transducers 200 Hz	NR	5 min treadmill, dynamic stretches	6s maximal velocity sprints, 10 trials, 24s jog at (7.2 km/h) recovery

(*Continued*)

Table 2. (Continued).

Study	Population	Sex	Sample Size	Demographics Age (years) (SD) Weight (kg) (SD) Height (cm) (SD) HSI	Demographics Age (years) (SD) Weight (kg) (SD) Height (cm) (SD) Controls	Definition of HSI	Running Surface and Testing Equipment	Foot wear	Warm Up	Running Protocol
Mendiguchia et al. (2014) [38]	Semi-professional soccer players	Male	HSI: 14* Control: 14	21.6(2.5) 72.4(7.1) 173.5 (4.7)	21.9(2.5) 69.3(5.9) 174.6 (4.7)	Sudden onset of posterior thigh pain of non-contact aetiology during a match or training which forced the player to leave that match or training Prevented participation ≥1 official match or week of regular training Tenderness triggered by palpation, stretching and contraction of the hamstring muscles, with or without confirmation by imaging techniques Diagnosed by medical professional An injury that should be assessed within 4 weeks after returning to competition	Overground grass, radar 33.25 Hz	'Usual soccer shoes'	5 min treadmill, stretch, sprint exercises, 3 progressive 6s sprints	50 m maximal sprint, standing start, 2 trials, 6 min recovery[a]
Schuermans et al. (2017b) [39]	Soccer players	NR	HSI: 30 Control: 30	24.7(3.4) 75.2(6.8), 180 (6)	23.7(4.5) 74.4(7.1) 181(5)	Sustained HSI with the last 24 months Prevented participation in ≥1 week of training or competition	Overground track, 3D motion analysis, 10 m step detection system	Indoor soccer shoes	5 min- jog, sprint intervals	40 m sprint (cameras between 15 and 25 m), 12 trials, recovery NR

(*Continued*)

Table 2. (Continued).

Study	Population	Sex	Sample Size	Demographics Age (years) (SD) Weight (kg) (SD) Height (cm) (SD) HSI	Controls	Definition of HSI	Running Surface and Testing Equipment	Foot wear	Warm Up	Running Protocol
Sugimoto et al. (2019)	Participants engaging with running activities	Male & Female	HSI: 35 Control: 35	29.0 (12.4) 64.7 (10.7) 171.2 (9.6)	29.1 (12.5) 60.9 (10.7) 167.1 (9.0)	Medically diagnosed HSI (based on physical examination and MRI) Must be right sided injury (due to camera position for analysis)	Motorised treadmill, video analysis 300 Hz	NR	5 min general stretching, slow-pace treadmill running	10–60 sec 'comfortable' (6.44–8.05 km/h) treadmill run 10–60s
CROSS-SECTIONAL STUDIES										
Ciacci et al. (2013) [33]	Sub-elite male sprinters	Male	HSI: 2 Control: 4	31.5 81.5 182.5	23.25 73.25 180.25	Medically diagnosed HSI	Overground track, 3D motion analysis 100 Hz	Track spikes	'Completed'-details NR	25 m submaximal sprints (30.6 km/h), standing start, 6 trials (only 2 used for analysis), 5–6 min recovery
Higashihara et al. (2019)	College Sprinters	Male	HSI: 10 Control: NA	19(0.3) 65.9(7.1) 172(3.9)	NA NA NA	Acute pain in the hamstring muscle region Sustained during training or competition Prevented participation in ≥1 week of training or competition	Overground track, 3D motion analysis 200 Hz	NR	'Sufficient warm up'	1 trial maximal sprint, start line 40 m from centre of measurement area, total sprint distance NR
Lee et al. (2009) [36]	Variety of Running Related Sports	Male	HSI: 12 Control: NA	23.6(2.8)[b] 86.6 (10.6)[b] 184.4 (4.9)[b]	NA NA NA	Unilateral HSI Diagnosed by medical professional Onset ≤3 years ago No other major lower limb injuries Fully active in chosen sport at time of testing	Overground track, 3D motion analysis 100 Hz	NR	15 min- aerobic and stretching exercises	Submaximal (80%) sprints, distance NR, 6 trials, recovery NR

(*Continued*)

Table 2. (Continued).

Study	Population	Sex	Sample Size	Demographics Age (years) (SD) Weight (kg) (SD) Height (cm) (SD) HSI	Controls	Definition of HSI	Running Surface and Testing Equipment	Foot wear	Warm Up	Running Protocol
COHORT STUDIES										
Kenneally-Dabrowski et al. (2019) [41]	Professional Rugby Players	NR	HSI: 3 Control: 6	27.3(3.2) 100.9 (13.1) 1.9(0.9)	25.3(3.1) 99.7 (13.8) 1.9 (0.9)	Coded as HSI in 'Athlete Management System' Injury Database Sustained during rugby training or game Prevented participation in training or competition No history of hamstring injury in the year prior to baseline testing	Overground track, 3D motion analysis 250 Hz, 8 contiguous force plates 1000 Hz	NR	Self-directed	50 m maximal velocity sprint, data collected 30–50 m, 3 trials, recovery NR
Schuermans et al. (2017b) [39]	Soccer players	NR	HSI: 4 Control: 25	NR[c] NR[d] NR[e]	NR[c] NR[d] NR[e]	Sustained HSI with Prevented participation in ≥1 week of training or competition No history of hamstring injury in the 2 years prior to baseline testing	Overground track, 3D motion analysis, 10 m step detection system	Indoor soccer shoes	5 min- jog, sprint intervals	40 m sprint (3D Motion capture between 15 and 25 m), 12 trials, recovery NR

SD: Standard deviation
HSI: Hamstring strain injury
NA: Not applicable (unaffected side used as control)
NR: Not reported
[a]Two trials completed Test 1 after rehab phase 3.5(1.5) weeks, test 2 at 9.5(1.5) weeks following injury- at this second test only 11 of the 14 cases were followed up (1 recurrent HSI, 1 ankle sprain, 1 personal reason)
[b]Lee et al: takes into consideration additional 14 males recruited for isokinetic strength measures (that didn't undergo biomechanical testing)
[c]Schuermans et al: Only reported all participants mean age 23.7 (4.5) years
[d]Schuermans et al: Only reported all participants mean mass 23.7 (4.5) years
[e]Schuermans et al: Only reported all participants mean age 74.4 (7.1) kg

analyses were not possible given the varying study designs, methodology and outcome measures.

Spatiotemporal findings

Six studies reported on spatiotemporal characteristics. Three studies compared variables of speed between athletes with previous HSI and controls (Barreira et al., 2015; Kenneally-Dabrowski et al., 2019; Mendiguchia et al., 2014). Mendiguchia et al. (2014) reported athletes with previous HSI had a decreased 'theoretical maximal velocity the legs could produce during the same phase under zero load' (calculated via computational methods) than controls at return to sport, but not at follow up approximately two months later. At return to sport, average time since injury in the Mendiguchia et al. (2014) study was 3.5(1.5) weeks. Barreira et al. (2015) reported no significant difference in maximum speed; however, the average time since HSI was not reported; only that the HSI occurred within the last two years. The Kenneally-Dabrowski et al. (2019) exploratory cohort study reported maximum running velocity to be 'similar' between HSI athletes and controls, however, this study had a notably small sample size (three HSI, six controls). All three studies that investigated ground contact time, found no differences between athletes with a history of HSI and controls (Brughelli et al., 2010; Ciacci et al., 2013; Lord et al., 2018). The one study that investigated flight time also reported no significant difference between the injured and the uninjured sides or the control uninjured group (Lord et al., 2018).

Kinematic findings

Four studies investigated trunk kinematics. Both prospective cohort studies reported increased late swing ipsilateral thoracic side bending in athletes who sustained a HSI, when compared to controls (Kenneally-Dabrowski et al., 2019; Schuermans et al., 2017b). Sugimoto et al. (2019) case-control study only analysed trunk flexion, reporting decreased trunk flexion in athletes with a history of HSI, when compared to controls. It is important to note, however, that participants in this study were running at low speeds and assessed by 2D video analysis only. The Schuermans et al. (2017b) case-control study reported no significant difference in three-dimensional trunk kinematics between athletes with a history of HSI and controls.

Pelvic kinematic findings differed between the five studies that investigated it. Increased anterior pelvic tilt was reported in early swing in the Schuermans et al. (2017b) prospective cohort study (between-group analysis), and late swing in the Daly et al. (2016) case control (within-group analysis) study. Higashihara et al. (2019) reported decreased late stance anterior pelvic tilt on the injured side, compared to the uninjured side. The Kenneally-Dabrowski et al. (2019) exploratory prospective cohort study and the case-control arm of the Schuermans et al. (2017b), however, reported nil significant difference between groups.

The seven studies reporting on hip kinematics throughout the gait cycle had conflicting findings. When compared to the uninjured side, Lee et al. (2009) reported significantly decreased hip flexion during late swing in the injured side; whereas, Daly et al. (2016) and Higashihara et al. (2019) reported increased late swing hip flexion.

Table 3. study characteristics.

	Barreira et al. (2015) [31]	Brughelli et al. (2010) [32]	Daly et al. (2016) [34]	Kobayashi et al. (2009) [35]	Lord et al. (2018) [35]	Mendiguchia et al. (2014), p. [38]	Schuermans et al. (2017b) [39]	Sugimoto et al. (2019)
Q1: Was the research questions or objective of the paper clearly stated and appropriate?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Q2: Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Q3: Did the authors provide a sample size justification?	No	No	No	No	No	No	No	No
Q4: Were controls selected or recruited from the same or similar population that gave rise to the cases (including the same timeframe)?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Q5: Were the definitions, inclusion and exclusion criteria, algorithms or processes used to identify or select cases and controls valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Q6: Were the cases clearly defined and differentiated from controls?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Q7: If less than 100% of eligible cases and/or controls were selected for the study, were the cases and/or controls randomly selected from those eligible?	NR	NR	NR	NR	NR	NR	NR	NR
Q8: Was there use of concurrent controls?	NR	NR	NR	NR	NR	NR	NR	NR
Q9: Were the investigators able to confirm that the exposure/risk occurred prior to the development of the condition or event that defined a participant as a case?	No	No	No	No	No	No	No	No
Q10: Were the measures of exposure/risk clearly defined, valid, reliable, and implemented consistently (including the same time period) across all study participants?	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Q11: Were the assessors of exposure/risk blinded to the case or control status of the participants?	NR	NR	NR	NR	NR	NR	NR	Yes
Q12: Were key potential confounding variables measured and adjusted statistically in the analyses? If matching was used, did the investigators account for matching during study analysis?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
RATING	POOR	GOOD	GOOD	FAIR	FAIR	FAIR	GOOD	POOR

NR: Not Reported

Conversely, Kenneally-Dabrowski et al. (2019) reported no tendency for late swing hip flexion-extension angle to discriminate between injured and uninjured groups. Ciacci et al. (2013) reported no differences in hip angle during footstrike, but decreased hip extension at toe off on the injured limb, when compared to the uninjured side (note the particularly small sample size; 2 HSI, 4 controls). Additionally, Higashihara et al. (2019) reported significantly decreased mid-swing hip flexion but no other significant differences in hip flexion-extension during the other running gait phases. Moreover, the Schuermans et al. (2017b) case control and prospective cohort studies both reported no significant differences between groups in hip kinematics in the coronal, sagittal and transverse planes during the swing and stance phases.

The eight studies investigating knee kinematics throughout the gait cycle also had conflicting findings. Lee et al. (2009) reported no significant difference in late swing knee flexion angle between injured and uninjured sides. Equally, Kenneally-Dabrowski et al. (2019) reported no tendency for late swing knee flexion-extension angle to discriminate between injured and uninjured groups. Kobayashi et al. (2009) reported decreased maximum swing-phase knee flexion on the injured side, compared to the uninjured side. Interestingly, Higashihara et al. (2019) (another cross-sectional, within group analysis study), reported significantly increased mid-late swing knee flexion but no other significant differences in knee flexion-extension during the other gait phases. Kobayashi et al. (2009), however, reported increased maximum late swing knee extension on the injured side, compared to the uninjured side. The Ciacci et al. (2013) small cross-sectional study reported no significant differences in foot strike knee angle between injured and uninjured sides. At toe off, Ciacci et al. (2013) reported greater knee flexion in the injured limb while Kobayashi et al. (2009) reported increased knee extension at terminal stance on the injured side, compared to the uninjured side. These two studies also reported differing findings for the maximum stance-phase knee flexion angle; Ciacci et al. (2013) reported no difference between the injured and uninjured sides, whereas Kobayashi et al. (2009) reported maximum stance-phase knee flexion to be decreased on the injured side, compared to the uninjured side. Daly et al. (2016) reported a significant increase in medial knee rotation in injured participants during the early contact phase, but no other significant differences in the sagittal plane, when compared to uninjured participants. The Schuermans et al. (2017b) cohort and case control reported no significant differences in knee kinematics in all phases and planes.

Two studies reported on other kinematic measures (outside of single joint angles). Brughelli et al. (2010) (case-control study) reported no significant differences in vertical centre of mass displacement, vertical stiffness and leg stiffness between athletes with a history of HSI and controls. Another case control, Sugimoto et al. (2019), investigated initial contact overstride angle (measured by tibial inclination), reporting a significant increase in athletes with a history of HSI compared to controls. They also classified participant footstike and noted significantly increased rearfoot strike in athletes with a history of HSI.

Kinetic findings

The seven studies that investigated running kinetics all had varying methodology. Three studies measured force via instrumented, non-motorised treadmill, however the phase of

Table 4. Study outcome measures and results.

	Studies	Outcome Measures	Results: mean (standard deviation)
SPATIO-TEMPORAL	Barreira et al. (2015) [31]	Maximum speed non-motorised treadmill	NS (between groups, p = 0.48)
		Maximum speed outdoor/GPS ($m.s^{-1}$)	NS (between groups, p = 0.39)
	Brughelli et al. (2010) [32]	Contact time (s)	NS (within and between groups, p > 0.05)
	Ciacci et al. (2013) [33]	Average contact time (s)	Within group mean SA% = 1.75*
			HSI injured: 0.096 (0.016), HSI uninjured: 0.1015(0.016)
	Kenneally-Dabrowski et al. (2019) [41]	Maximum running velocity (m/s)	'Similar' between groups
			HSI: 8.97(0.31), Control: 8.52(0.61)
	Lord et al. (2018) [37]	Change in mean contact time (s) from sprint 1 to sprint 10 (%)	NS (within group, p = 0.704)
			NS (between groups, p = 0.862)
		Change in mean flight time (s) from sprint 1 to sprint 10 (%)	NS (within group, p = 0.081
			NS (between groups, p = 0.484)
	Mendiguchia et al. (2014) [38]	Sprint time (s) at 5 m, 10 m, 40 m	Return to Sport 'very likely' slower (between groups)
			HSI: 1.5(0.12), 2.3(0.17), 6.1(0.32), Control: 1.4(0.05), 2.2 (0.07), 5.9(0.18)
			2 month follow up 'unclear' (between groups)
			HSI: 1.4(0.07), 2.2(0.11), 6.0(0.26), Control: 1.4(0.05), 2.2 (0.07), 5.9(0.18)**
		Theoretical maximal velocity the legs could produce at the same phase under zero load (km/h)	Return to Sport 'likely' slower (between groups)
			HSI: 31.4(0.91), Control: 31.9(1.31)
			2 month follow up 'likely' slower (between groups)
			HSI: 31.0(1.45), Control: 31.9(1.31)**
		Top speed (km/hr)	Return to Sport 'likely' slower (between groups)
			HSI: 29.8(0.9), Control: 30.5(1.1)
			2 month follow up 'likely' slower (between groups)
			HSI: 29.8(1.3), Control: 30.5(1.1)**
KINEMATIC	Brughelli et al. (2010) [32]	Vertical stiffness (kN/m)	NS (within and between groups, p > 0.05)
		Leg stiffness (kN/m)	NS (within and between groups, p > 0.05)
		Vertical centre of mass displacement (cm)	NS (within and between groups, p > 0.05)

(*Continued*)

Table 4. (Continued).

Studies	Outcome Measures	Results: mean (standard deviation)
Ciacci et al. (2013) [33]	Foot strike hip flexion angle (deg)	Within group mean SA% = 6.55* HSI injured: 41.95(10.96), HSI uninjured: 33.75(5.89)
	Foot strike knee flexion angle (deg)	Within group mean SA% = 6.8* HSI injured: 28(12.02), HSI uninjured: 23(11.17)
	Toe off hip flexion angle (deg)	Within group mean SA% = 28.45* HSI injured: −8.3(6.36), HSI uninjured: −22.2(2.12)
	Toe off knee flexion angle (deg)	Within group mean SA% = 43.9* HSI injured: 20.5(16.4), HSI uninjured: 6.65(12.8)
	Stance phase max knee flexion (deg)	Within group mean SA% = 6.5* HSI injured: 40.65(18.57), HSI uninjured: 37.95(17.32)
Daly et al. (2016)[34]	Average sagittal, coronal and transverse plane pelvis range of motion (deg)	Increased late swing anterior pelvic tilt within group (p = 0.02) HSI injured > HSI uninjured by 4deg*** All other outcome variables NS (p > 0.05)
	Average sagittal, coronal and transverse plane hip range of motion (deg)	Increased late swing hip flexion within group HSI (p = 0.01) HSI injured > HSI uninjured by 8deg*** All other outcome variables NS within group (p > 0.05)
	Average sagittal, coronal and transverse plane knee range of motion (deg)	Increased medial knee rotation within group HSI (p = 0.03) HSI injured > HSI uninjured by 6deg*** All other outcome variables NS within group (p > 0.05)
	Average sagittal, coronal and transverse plane ankle range of motion (deg)	All outcome variables NS within group (p > 0.05)
Higashihara et al. (2019)	Anterior pelvic tilt throughout entire stride (deg)	Decreased late- stance anterior pelvic tilt within group (=0.039) HSI < HSI uninjured by 5.5deg*** All other phases NS (p > 0.05)
	Joint angles throughout entire stride of the hip (deg)	Decreased mid-swing hip flexion within group (p = 0.002) HSI < HSI uninjured by 4.7deg*** Increased late-swing hip flexion within group (p = 0.049) HSI > HSI uninjured by 3.6deg*** All other phases and outcome variables NS (p > 0.05)
	Joint angles throughout entire stride of the knee (deg)	Increased mid to late-swing hip flexion within group (p = 0.002) HSI > HSI uninjured by 5.8deg*** All other phases and outcome variables NS (p > 0.05)

(*Continued*)

Table 4. (Continued).

Studies	Outcome Measures	Results: mean (standard deviation)
Kenneally-Dabrowski et al. (2019) [41]	Average late swing thoracic lateral flexion (deg)	Tendency to discriminate between groups HSI > Control***
	Average late swing pelvic tilt (deg)	No tendency to discriminate between groups ***
	Average late swing hip flexion-extension (deg)	No tendency to discriminate between groups ***
	Average late swing knee flexion-extension (deg)	No tendency to discriminate between groups ***
Kobayashi et al. (2009) [35]	Maximum stance phase knee flexion- midstance (deg)	Decreased within group HSI injured < HSI uninjured***
	Maximum swing phase knee flexion- early to mid-swing (deg)	Decreased within group HSI injured < HSI uninjured***
	Maximum stance phase knee extension- terminal stance (deg)	Increased within group HSI injured > HSI uninjured***
	Maximum swing phase knee extension—late swing (deg)	Increased within group HSI injured > HSI uninjured***
Lee et al. (2009) [36]	Late swing phase hip flexion angle (deg)	Decreased within group ($p = 0.02$) HSI injured: 88.0(5.7), HSI uninjured: 89.9(4.9)
	Late swing phase knee flexion angle (deg)	NS (within group, $p = 0.61$)
Schuermans et al. (2017b) -case control [39]	Joint angles throughout entire stride ankle, knee, hip, pelvis and thorax (deg)	All outcome variables NS (between group, $p > 0.05$)
Schuermans et al. (2017b)—cohort [39]	Joint angles throughout entire stride of the thorax (deg)	Increased front swing ipsilateral thoracic side bending between groups HSI > Control*** ($p = 0.028$) All other outcome variables NS ($p > 0.05$)
	Joint angles throughout entire stride of the pelvis (deg)	Increased backswing anterior pelvic tilt between groups HSI > Control*** ($p = 0.0445$) All other outcome variables NS between groups ($p > 0.05$)
	Joint angles throughout entire stride of the hip (deg)	All outcome variables NS between groups ($p > 0.05$)
	Joint angles throughout entire stride of the knee (deg)	All outcome variables NS between groups ($p > 0.05$)
	Joint angles throughout entire stride of the ankle (deg)	All outcome variables NS between groups ($p > 0.05$)
Sugimoto et al. (2019)	Initial contact trunk flexion angle (deg)	Decreased between group ($p = 0.43$) HSI: 2.9(2.5), Control 4.5(3.9)
	Initial contract overstride angle—tibial inclination (deg)	Increased between group ($p = 0.001$) HSI: 2.9(3.9), Control: −2.0(5.9)
	Initial contact footstrike classification (n- rear, fore or mid foot strike)	Increased rearfoot strike between group ($p = 0.004$) HSI rearfoot: 26 (74.3%), Control rearfoot: 15 (42.9%)

(*Continued*)

Table 4. (Continued).

	Studies	Outcome Measures	Results: mean (standard deviation)
KINETIC	Barreira et al. (2015) [31]	Acceleration phase max horizontal force (N)	NS (within group, p = 0.75)
		Acceleration phase averaged horizontal force (N)	NS (within group, p = 0.58)
		Acceleration phase max vertical force (N)	NS (within group, p = 0.64)
		Acceleration phase averaged vertical force (N)	NS (within group, p = 0.33)
		Steady state phase max horizontal force (N)	NS (within group, p = 0.81)
		Steady state phase averaged horizontal force (N)	NS (within group, p = 0.92)
		Steady state phase max vertical force (N)	NS (within group, p = 0.11)
		Steady state phase averaged vertical force (N)	NS (within group, p = 0.80)
		Horizontal force peak right (N)	NS (between groups, p = 0.13)
		Horizontal force peak left (N)	NS (between groups, p = 0.42)
		Horizontal force averaged peaks right (N)	NS (between groups, p = 0.25)
		Horizontal force averaged peaks left (N)	NS (between groups, p = 0.23)
		Vertical force peak right (N)	NS (between groups, p = 0.52)
		Vertical force peak left (N)	NS (between groups, p = 0.26)
		Vertical force averaged peaks right (N)	NS (between groups, p = 0.40)
		Vertical force averaged peaks left (N)	NS (between groups, p = 0.49)
	Brughelli et al. (2010) [32]	Average peak horizontal force (N)	Decreased within group ($p < 0.01$) HSI injured: 175(30), HSI uninjured: 326(44) Decreased between groups ($p < 0.05$) HSI: 175(30), Control right: 261(43), Control left: 252(51)
		Average peak vertical force (N)	NS (within and between, $p > 0.05$)
		Impulse (J)	NS (within and between, $p > 0.05$)
		Positive work (J)	NS (within and between, $p > 0.05$)
	Higashihara et al. (2019)	Hip and knee torque during the sprinting gait cycle (N.m)	NS (within group, $p > 0.05$)
	Kenneally-Dabrowski et al. (2019) [41]	Late swing hip angular velocity ($deg.s^{-1}$)	No tendency to discriminate between groups ***
		Late swing hip extensor moment (N.m)	Tendency to discriminate between groups HSI > Control***
		Late swing hip power absorption ($W.kg^{-1}$)	No tendency to discriminate between groups ***
		Late swing knee angular velocity ($deg.s^{-1}$)	No tendency to discriminate between groups ***
		Late swing knee extensor moment (N.m)	No tendency to discriminate between groups ***
		Late swing knee power absorption ($W.kg^{-1}$)	Tendency to discriminate between groups HSI > Control***

(*Continued*)

Table 4. (Continued).

Studies	Outcome Measures	Results: mean (standard deviation)
Lee et al. (2009) [36]	Late swing peak hip flexion angular velocity (deg.s^{-1})	NS (within group, p = 0.49)
	Early swing peak hip flexion angular velocity (deg.s^{-1})	NS (within group, p = 0.94)
	Late swing peak hip extensor moment (N.m)	NS (within group, p = 0.12)
	Early swing peak hip flexor moment (N.m)	NS (within group, p = 0.77)
	Late swing peak hip extension power (W.kg^{-1})	NS (within group, p = 0.91)
	Early swing peak hip flexion power (W.kg^{-1})	NS (within group, p = 0.81)
	Late swing peak knee extension angular velocity (deg.s^{-1})	NS (within group, p = 0.26)
	Late swing peak knee flexor moment (N.m)	NS (within group, p = 0.09)
	Late swing peak knee power absorption (W.kg^{-1})	NS (within group, p = 0.72)
Lord et al. (2018) [37]	Change in mean horizontal propulsive force production (N) from sprint 1 to sprint 10 (%)	Decreased within group (p < 0.05) HSI injured (kicking leg): −13%, HSI uninjured: −3% Decreased between group (kicking legs) p < 0.05 HSI: −13%, Control: −3%
	Change in mean vertical force production from sprint 1 to sprint 10 (%)	NS (within group, p > 0.05) NS (between group, p > 0.642)
Mendiguchia et al. (2014) [38]	Theoretical horizontal force (N/kg)	Return to Sport 'very likely' decreased (between groups) HSI: 6.1(1.04), Control: 6.8(0.56) 2 month follow up 'unclear' (between groups) HSI: 6.9 (0.84), Control: 6.8 (0.56)**
	Theoretical horizontal power (W/kg)	Return to Sport 'very likely' decreased (between groups) HSI: 13.1 (2.39), Control: 15.0 (1.44) 2 month follow up 'unclear' (between groups) HSI: 14.9 (2.15), Control: 15.0 (1.44)**

NS = no significant difference
*Ciacci et al set symmetry angle (SA) threshold for abnormality at 8%
**Control baseline value used
***Exact values not reported

running and speed differed (Barreira et al., 2015; Brughelli et al., 2010; Lord et al., 2018). Four studies reported on overground running; three with motion capture systems (reporting on rotational kinetic energy)(Higashihara et al., 2019; Kenneally-Dabrowski et al., 2019; Lee et al., 2009) and one utilising a validated computational method (force-velocity profiling)(Samozino et al., 2016) using radar to generate horizontal force and power output (Mendiguchia et al., 2014).

Three out of four studies investigating horizontal propulsive force found reduced force in injured participants. Brughelli et al. (2010) reported decreased average peak horizontal force (within and between groups) when sprinting on an instrumented, non-motorised treadmill. Similarly, Lord et al. (2018) found a greater reduction in mean horizontal force production with repeated sprints on the injured side (within and between groups), also when sprinting on an instrumented, non-motorised treadmill. The third study which utilised the same treadmill, reported no significant difference in mean and peak propulsive horizontal force between sides within the injured group for both the acceleration and steady state phases of sprint (Barreira et al., 2015). Mendiguchia et al. (2014) adopted the computational method to determine theoretical horizontal force and horizontal power output. Horizontal force was 'very likely' decreased in injured participants upon return to sport when compared to controls but at follow up approximately 2 months later, the difference between groups was 'unclear'. Horizontal power output was 'very likely' decreased (>5–25% of smallest worthwhile difference) in injured participants upon return to sport when compared to controls but was 'unclear' at follow up (<5% of smallest worthwhile difference).

None of the three studies investigating vertical force variables reported significant differences within or between groups (Barreira et al., 2015; Brughelli et al., 2010; Lord et al., 2018). No within or between group significant differences were reported in impulse and positive work in the one study that investigated these variables (Brughelli et al., 2010).

Three studies investigated lower limb rotational kinetic energy. Kenneally-Dabrowski et al. (2019) reported increased late swing hip extensor moment and knee power absorption in HSI athletes, when compared to controls. Conversely, Lee et al. (2009) and Higashihara et al. (2019) (both cross-sectional studies) reported no significant differences; however, only within-group analysis was performed.

Discussion and implications

This systematic review intended to investigate the relationship between running biomechanics and HSI of the high-speed running type. There is currently very limited high-quality research on this topic that prevents the extraction of firm conclusions, however, we identified preliminary findings that may be useful for directing further research. Overall, the included studies largely found either no differences or contradicting findings between running biomechanics of athletes who retrospectively or prospectively sustained a HSI and controls, with the exception of trunk kinematics and horizontal forces. Future studies are needed to clarify the clinical implication of these findings.

Two prospective cohort studies reported increased trunk lateral trunk flexion during the late swing phase. Both studies were rated 'fair' in terms of quality, primarily due to small sample size. Other research has suggested that gluteus medius weakness may be

present in athletes who sustain a HSI (Franettovich Smith et al., 2017; Schuermans, Danneels, et al., 2017a), thus, the increased lateral trunk flexion may be a compensatory strategy to account for this (Chang et al., 2005).

Athletes who strained their hamstring retrospectively exhibited decreased horizontal propulsive force in three out of four included studies. The hamstrings play a particularly important role in horizontal propulsive force production during acceleration (Morin et al., 2015). Two single case studies in the literature also reported this finding (Mendiguchia et al., 2016; Setuain et al., 2017). Horizontal force deficits may be a result of reduced concentric hip extensor ability (Sugiura et al., 2008), altered muscular activation patterns (Pinniger et al., 2000) and neuromuscular coordination (Higashihara et al., 2010). Morin et al. (2015) identify fast 'pawing' drills as a common training method used to improve horizontal force. 'Pawing' refers to the fast whipping action of the leg from maximum hip flexion to initial contact. The authors duly acknowledge, however, a lack of research investigating the transfer between 'pawing' velocity and horizontal force (Morin et al., 2015).

A kinematic explanation for decreased horizontal propulsive force may be an overstride running technique. An overstriding athlete will land with their foot too far in front of their centre of mass, resulting in increased horizontal braking force (Lieberman et al., 2015). Only one study in this review investigated this variable, reporting increased overstride (as measured by tibial inclination at initial contact) in athletes with a history of HSI, when compared to controls (Sugimoto et al., 2019). They also reported an increased tendency for athletes with a history of HSI to rearfoot strike, even though methodological limitations may have confounded the findings (Sugimoto et al., 2019). Nonetheless, the findings align with Lieberman et al. (2015) who reported an association between rearfoot strikers and overstride.

It is difficult to infer whether the aforementioned potential biomechanical variations are potentially a cause or effect of HSI. A prospective cohort study design is ideal for determining causality (Fuller et al., 2006).[53] Fuller et al. (2006) suggested that 'the study population should normally consist of more than one team of players and the study should last for a minimum period of one season (including preseason), 12 months, or the duration of a tournament'. Only two of the included studies were of prospective cohort design (although both had small sample size), the remaining ten were retrospective case-control or cross-sectional studies in which causation cannot be assumed. Due to sample size and other methodological issues, the observational studies in this field have not been designed to assess causal inference, thus there is currently a lack of high-quality evidence to support running technique training for injury prevention.

A recent Delphi study investigating beliefs and practices of nine AFL physical performance coaches regarding sprinting and HSI highlights the need for additional research in this injury prevention space. All coaches reported that they 'assessed and prescribed training to improve running mechanics to improve running mechanics in order to reduce the risk of HSI'. Overstride and 'abnormal pelvic motion' were reported as potential key contributors to HSI. It was reported that training strategies to improve fatigue tolerance may potentially lessen the effect of these technical contributors, resulting in an indirect injury prevention benefit (Freeman et al., 2021).

There are also a number of limitations within the included studies that should also be acknowledged. No study included power determination or sample size justification.

There was also significant variability between studies in protocol (velocity, phase of sprint etc.), statistical methodology and biomechanical testing equipment used and running surface. Although research has demonstrated differences in sprinting kinematics between conventional treadmill, non-motorised treadmill and overground conditions, there was no consensus between studies investigating treadmill or overground running (McKenna & Riches, 2007). A further limitation was the use of unaffected side as control or within group analysis only, which were methods employed in five of the 12 included studies. Use of the unaffected side as control has been discouraged in the literature, as a consequence of bilateral impairment findings in unilateral injured athletes (Goerger et al., 2015; Wikstrom et al., 2010). Within-group analysis only in the presence of a control group also may be of concern, when biomechanical asymmetry has been displayed in large proportions of uninjured athletes (Exell et al., 2017; Haugen et al., 2018). In order for asymmetry to be relevant, within-side variability must be less than between-side differences (Giakas & Baltzopoulos, 1997). Further research is needed to clarify clinically meaningful asymmetry thresholds for spatiotemporal, kinematic and kinetic variables.

Future observational and interventional biomechanical research should consider the influence of fatigue and high speed running exposure as confounding variables. Various studies in uninjured athletes have reported changes in high-speed running biomechanics with fatigue (Edouard et al., 2016; Pinniger et al., 2000; Small et al., 2009). Biomechanical changes as a result of fatigue may be an explanation for the emerging evidence supporting an association between increased high speed running exposure and HSI (Duhig et al., 2016; Ruddy et al., 2018). For example, Huygaerts et al. (2020) describe a 'Groucho' (decreased knee range of motion) running pattern with fatigue. More research is required to determine whether these changes are maladaptive or protective against HSI. Also recovery after HSI may be incomplete prior to return to sport, with recent evidence displaying supressed running distance in professional footballers (Whiteley et al., 2020). Finally, given the multifactorial nature of HSI, upcoming research may also consider including biomechanical variables of interest within predictive models, as opposed to statistical analysis in isolation.

Conclusions

This systematic review found minimal evidence demonstrating that athletes who strain their hamstring (retrospectively or prospectively) run differently to athletes who don't. The dearth of quality evidence in this area should be highlighted, with only twelve studies meeting the eligibility criteria, all with varying study designs, methodology and outcome measures. Thus, further research utilising validated methods of biomechanical analysis, is needed to determine if an association exists between running biomechanics and HSI. Until then, definitive conclusions cannot be drawn as to whether specific biomechanical interventions should be included in injury prevention and/or rehabilitation programs.

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References

Arnason, A., Sigurdsson, S. B., Gudmundsson, A., Holme, I., Engebretsen, L., & Bahr, R. (2004). Risk factors for injuries in football. *American Journal of Sports Medicine*, *32*(1 Suppl), 5S–16S. https://doi.org/10.1177/0363546503258912

Askling, C. M., & Heiderscheit, B. C. (2015). Acute hamstring muscle injury: Types, rehabilitation, and return to sports. In M. N. Doral & J. Karlsson (Eds.), *Sports Injuries: Prevention, Diagnosis, Treatment and Rehabilitation* (pp. 1–13). Springer Berlin Heidelberg.

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2007a). Acute first-time hamstring strains during high-speed running: A longitudinal study including clinical and magnetic resonance imaging findings. *American Journal of Sports Medicine*, *35*(2), 197–206. https://doi.org/10.1177/0363546506294679

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2007b). Acute first-time hamstring strains during slow-speed stretching: Clinical, magnetic resonance imaging, and recovery characteristics. *American Journal of Sports Medicine*, *35*(10), 1716–1724. https://doi.org/10.1177/0363546507303563

Barreira, P., Drust, B., Robinson, M. A., & Vanrenterghem, J. (2015). Asymmetry after hamstring injury in English premier league: Issue resolved, or perhaps not? *International Journal of Sports Medicine*, *36*(6), 455–459. https://doi.org/10.1055/s-0034-1398493

Bennell, K. L., & Crossley, K. (1996). Musculoskeletal injuries in track and field: Incidence, distribution and risk factors. *Australian Journal of Science and Medicine in Sport*, *28*(3), 69–75.

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American Journal of Sports Medicine*, *34*(8), 1297–1306. https://doi.org/10.1177/0363546505286022

Brughelli, M., Cronin, J., Mendiguchia, J., Kinsella, D., & Nosaka, K. E. N. (2010). Contralateral leg deficits in kinetic and kinematic variables during running in Australian Rules football players with previous hamstring injuries. *Journal of Strength and Conditioning Research*, *24*(9), 2539–2544. https://doi.org/10.1519/JSC.0b013e3181b603ef

Chang, A., Hayes, K., Dunlop, D., Song, J., Hurwitz, D., Cahue, S., & Sharma, L. (2005). Hip abduction moment and protection against medial tibiofemoral osteoarthritis progression. *Arthritis and Rheumatism*, *52*(11), 3515–3519. https://doi.org/10.1002/art.21406

Ciacci, S., Di Michele, R., Fantozzi, S., & Merni, F. (2013). Assessment of kinematic asymmetry for reduction of hamstring injury risk. *International Journal of Athletic Therapy & Training*, *18*(6), 18–23. https://doi.org/10.1123/ijatt.18.6.18

Cleather, D. J. (2018). An important role of the biarticular hamstrings is to exert internal/external rotation moments on the tibia during vertical jumping. *Journal of Theoretical Biology*, *455*, 101–108. https://doi.org/10.1016/j.jtbi.2018.07.013

Daly, C., McCarthy Persson, U., Twycross-Lewis, R., Woledge, R. C., & Morrissey, D. (2016). The biomechanics of running in athletes with previous hamstring injury: A case-control study. *Scandinavian Journal of Medicine & Science in Sports*, *26*(4), 413–420. https://doi.org/10.1111/sms.12464

Danielsson, A., Horvath, A., Senorski, C., Alentorn-Geli, E., Garrett, W. E., Cugat, R., Samuelsson, K., & Hamrin Senorski, E. (2020). The mechanism of hamstring injuries –

A systematic review. *BMC Musculoskeletal Disorders*, *21*(1), 641–642. https://doi.org/10.1186/s12891-020-03658-8

Duhig, S., Shield, A. J., Opar, D., Gabbett, T. J., Ferguson, C., & Williams, M. (2016). Effect of high-speed running on hamstring strain injury risk. *British Journal of Sports Medicine*, *50*(24), 1536–1540. https://doi.org/10.1136/bjsports-2015-095679

Edouard, P., Arnal, P., Gimenez, P., Samozino, P., Jimenez-Reyes, P., Brughelli, M., Mendiguchia, M., & Morin, J. B. (2016). Athletic injury prevention: Determinants of sprint performance. *Annals of Physical and Rehabilitation Medicine*, *59*, e22–e23. https://doi.org/10.1016/j.rehab.2016.07.054

Ekstrand, J., Hagglund, M., & Walden, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *American Journal of Sports Medicine*, *39*(6), 1226–1232. https://doi.org/10.1177/0363546510395879

Exell, T., Irwin, G., Gittoes, M., & Kerwin, D. (2017). Strength and performance asymmetry during maximal velocity sprint running. *Scandinavian Journal of Medicine & Science in Sports*, *27*(11), 1273–1282. https://doi.org/10.1111/sms.12759

Feeley, B. T., Kennelly, S., Barnes, R. P., Muller, M. S., Kelly, B. T., Rodeo, S. A., & Warren, R. F. (2008). Epidemiology of national football league training camp injuries from 1998 to 2007. *American Journal of Sports Medicine*, *36*(8), 1597–1603. https://doi.org/10.1177/0363546508316021

Franettovich Smith, M. M., Bonacci, J., Mendis, M. D., Christie, C., Rotstein, A., & Hides, J. A. (2017). Gluteus medius activation during running is a risk factor for season hamstring injuries in elite footballers. *Journal of Science & Medicine in Sport*, *20*(2), 159–163. https://doi.org/10.1016/j.jsams.2016.07.004

Freeman, B. W., Talpey, S. W., James, L. P., & Young, W. B. (2021). Sprinting and hamstring strain injury: Beliefs and practices of professional physical performance coaches in Australian football. *Physical Therapy in Sport*, *48*, 12–19. https://doi.org/10.1016/j.ptsp.2020.12.007

Fuller, C. W., Ekstrand, J., Junge, A., Andersen, T. E., Bahr, R., Dvorak, J., Hägglund, M., McCrory, P., & Meeuwisse, W. H. (2006). Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *British Journal of Sports Medicine*, *40*(3), 193–201. https://doi.org/10.1136/bjsm.2005.025270

Giakas, G., & Baltzopoulos, V. (1997). Time and frequency domain analysis of ground reaction forces during walking: An investigation of variability and symmetry. *Gait & Posture*, *5*(3), 189–197. https://doi.org/10.1016/S0966-6362(96)01083-1

Goerger, B. M., Marshall, S. W., Beutler, A. I., Blackburn, J. T., Wilckens, J. H., & Padua, D. A. (2015). Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: The JUMP-ACL study. *British Journal of Sports Medicine*, *49*(3), 188. https://doi.org/10.1136/bjsports-2013-092982

Green, B., Bourne, M. N., van Dyk, N., & Pizzari, T. (2020). Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. *British Journal of Sports Medicine*, *54*(18), 1081–1088. https://doi.org/10.1136/bjsports-2019-100983

Haugen, T., Danielsen, J., McGhie, D., Sandbakk, Ø., & Ettema, G. (2018). Kinematic stride cycle asymmetry is not associated with sprint performance and injury prevalence in athletic sprinters. *Scandinavian Journal of Medicine & Science in Sports*, *28*(3), 1001–1008. https://doi.org/10.1111/sms.12953

Heiderscheit, B. C., Hoerth, D. M., Chumanov, E. S., Swanson, S. C., Thelen, B. J., & Thelen, D. G. (2005). Identifying the time of occurrence of a hamstring strain injury during treadmill running: A case study. *Clinical Biomechanics*, *20*(10), 1072–1078. https://doi.org/10.1016/j.clinbiomech.2005.07.005

Higashihara, A., Ono, T., Kubota, J., Okuwaki, T., & Fukubayashi, T. (2010). Functional differences in the activity of the hamstring muscles with increasing running speed. *Journal of Sports Sciences*, *28*(10), 1085–1092. https://doi.org/10.1080/02640414.2010.494308

Higashihara, A., Ono, T., Tokutake, G., Kuramochi, R., Kunita, Y., Nagano, Y., & Hirose, N. (2019). Hamstring muscles' function deficit during overground sprinting in track and field athletes with a history of strain injury. *Journal of Sports Sciences*, *37*(23), 2744–2750. https://doi.org/10.1080/02640414.2019.1664030

Howard, R. M., Conway, R., & Harrison, A. J. (2018). Muscle activity in sprinting: A review. *Sports Biomechanics*, *17*(1), 1–17. https://doi.org/10.1080/14763141.2016.1252790

Huygaerts, S., Cos, F., Cohen, D. D., Calleja-González, J., Guitart, M., Blazevich, A. J., & Alcaraz, P. E. (2020). Mechanisms of hamstring strain injury: Interactions between fatigue, muscle activation and function. *Sports*, *8*(5), 1–15. https://doi.org/10.3390/sports8050065

Kenneally-Dabrowski, C., Brown, N. A. T., Warmenhoven, J., Serpell, B. G., Perriman, D., Lai, A. K. M., & Spratford, W. (2019). Late swing running mechanics influence hamstring injury susceptibility in elite rugby athletes: A prospective exploratory analysis. *Journal of Biomechanics*, *92*, 112–119. https://doi.org/10.1016/j.jbiomech.2019.05.037

Kobayashi, M., Gakuhari, H., Kanehisa, H., Aoyama, T., & Tsunoda, N. (2009). Profiles of activites of thigh muscles during sprint running in track and field athletes experienced hamstrings (muscle) strain injury. *Japanese Journal of Physical Fitness and Sports Medicine*, *58*(1), 81–90. https://doi.org/10.7600/jspfsm.58.81

Lee, M. J., Reid, S. L., Elliott, B. C., & Lloyd, D. G. (2009). Running biomechanics and lower limb strength associated with prior hamstring injury. *Medicine and Science in Sports and Exercise*, *41*(10), 1942–1951. https://doi.org/10.1249/MSS.0b013e3181a55200

Lieber, R. L., & Friden, J. (1993). Muscle damage is not a function of muscle force but active muscle strain. *Journal of Applied Physiology*, *74*(2), 520–526. https://doi.org/10.1152/jappl.1993.74.2.520

Lieber, R. L., & Friden, J. (2002). Mechanisms of muscle injury gleaned from animal models. *American Journal of Physical Medicine & Rehabilitation*, *81*(11 Suppl), S70–79. https://doi.org/10.1097/00002060-200211001-00008

Lieberman, D. E., Warrener, A. G., Wang, J., & Castillo, E. R. (2015). Effects of stride frequency and foot position at landing on braking force, hip torque, impact peak force and the metabolic cost of running in humans. *Journal of Experimental Biology*, *218*(Pt 21), 3406–3414. https://doi.org/10.1242/jeb.125500

Lord, C., Blazevich, A. J., Drinkwater, E. J., & Ma'ayah, F. (2018). Greater loss of horizontal force after a repeated-sprint test in footballers with a previous hamstring injury. *Journal of Science & Medicine in Sport*, *22*(1), 16–21. https://doi.org/10.1016/j.jsams.2018.06.008

McKenna, M., & Riches, P. E. (2007). A comparison of sprinting kinematics on two types of treadmill and over-ground. *Scandinavian Journal of Medicine & Science in Sports*, *17*(6), 649–655. https://doi.org/10.1111/j.1600-0838.2006.00625.x

Mendiguchia, J., Edouard, P., Samozino, P., Brughelli, M., Cross, M., Ross, A., Gill, N., & Morin, J. B. (2016). Field monitoring of sprinting power–force–velocity profile before, during and after hamstring injury: Two case reports. *Journal of Sports Sciences*, *34*(6), 535–541. https://doi.org/10.1080/02640414.2015.1122207

Mendiguchia, J., Samozino, P., Martinez-Ruiz, E., Brughelli, M., Schmikli, S., Morin, J. B., & Mendez-Villanueva, A. (2014). Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *International Journal of Sports Medicine*, *35*(8), 690–695. https://doi.org/10.1055/s-0033-1363192

Morin, J. B., Gimenez, P., Edouard, P., Arnal, P., Jimenez-Reyes, P., Samozino, P., Brughelli, M., & Mendiguchia, J. (2015). Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Frontiers in Physiology*, *6*, 1–14, Article 404. https://doi.org/10.3389/fphys.2015.00404

Murphy, J. C., O'Malley, E., Gissane, C., & Blake, C. (2012). Incidence of injury in Gaelic football: A 4-year prospective study. *American Journal of Sports Medicine*, *40*(9), 2113–2120. https://doi.org/10.1177/0363546512455315

Nagano, Y., Higashihara, A., Takahashi, K., & Fukubayashi, T. (2014). Mechanics of the muscles crossing the hip joint during sprint running. *Journal of Sports Sciences*, *32*(18), 1722–1728. https://doi.org/10.1080/02640414.2014.915423

Orchard, J. W., Kountouris, A., & Sims, K. (2017). Risk factors for hamstring injuries in Australian male professional cricket players. *Journal of Sport and Health Science*, *6*(3), 271–274. https://doi.org/10.1016/j.jshs.2017.05.004

Orchard, J. W., Seward, H., & Orchard, J. J. (2013). Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *American Journal of Sports Medicine*, *41*(4), 734–741. https://doi.org/10.1177/0363546513476270

Pinniger, G. J., Steele, J. R., & Groeller, H. (2000). Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise*, *32*(3), 647–653. https://doi.org/10.1097/00005768-200003000-00015

Ruddy, J. D., Pollard, C. W., Timmins, R. G., Williams, M. D., Shield, A. J., & Opar, D. A. (2018). Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. *British Journal of Sports Medicine*, *52*(14), 919–928. https://doi.org/10.1136/bjsports-2016-096777

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez De Villarreal, E., & Morin, J. B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine & Science in Sports*, *26*(6), 648–658. https://doi.org/10.1111/sms.12490

Schache, A. G., Dorn, W. T., Blanch, D. P., Brown, T. N. A., & Pandy, G. M. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise*, *44*(4), 647–658. https://doi.org/10.1249/MSS.0b013e318236a3d2

Schache, A. G., Wrigley, T. V., Baker, R., & Pandy, M. G. (2009). Biomechanical response to hamstring muscle strain injury. *Gait & Posture*, *29*(2), 332–338. https://doi.org/10.1016/j.gaitpost.2008.10.054

Schuermans, J., Danneels, L., Van Tiggelen, D., Palmans, T., & Witvrouw, E. (2017a). Proximal neuromuscular control protects against hamstring injuries in male soccer players: A prospective study with electromyography time-series analysis during maximal sprinting. *American Journal of Sports Medicine*, *45*(6), 1315–1325. https://doi.org/10.1177/0363546516687750

Schuermans, J., Van Tiggelen, D., Palmans, T., Danneels, L., & Witvrouw, E. (2017b). Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence? *Gait & Posture*, *57*, 270–277. https://doi.org/10.1016/j.gaitpost.2017.06.268

Setuain, I., Lecumberri, P., & Izquierdo, M. (2017). Sprint mechanics return to competition follow-up after hamstring injury on a professional soccer player: A case study with an inertial sensor unit based methodological approach. *Journal of Biomechanics*, *63*, 186–191. https://doi.org/10.1016/j.jbiomech.2017.08.010

Silder, A., Thelen, D. G., & Heiderscheit, B. C. (2010). Effects of prior hamstring strain injury on strength, flexibility, and running mechanics. *Clinical Biomechanics*, *25*(7), 681–686. https://doi.org/10.1016/j.clinbiomech.2010.04.015

Small, K., McNaughton, L. R., Greig, M., Lohkamp, M., & Lovell, R. (2009). Soccer fatigue, sprinting and hamstring injury risk. *International Journal of Sports Medicine*, *30*(8), 573–578. https://doi.org/10.1055/s-0029-1202822

Stanton, P., & Purdham, C. (1989). Hamstring injuries in sprinting - the role of eccentric exercise. *The Journal of Orthopaedic and Sports Physical Therapy*, *10*(9), 343–349. https://doi.org/10.2519/jospt.1989.10.9.343

Sugimoto, D., Kelly, B. D., Mandel, D. L., d'Hemecourt, D. A., Carpenito, S. C., d'Hemecourt, C. A., & d'Hemecourt, P. A. (2019). Running propensities of athletes with hamstring injuries. *Sports*, *7*(9), 12. https://doi.org/10.3390/sports7090210

Sugiura, Y., Saito, T., Sakuraba, K., Sakuma, K., & Suzuki, E. (2008). Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *The Journal of Orthopaedic and Sports Physical Therapy*, *38*(8), 457–464. https://doi.org/10.2519/jospt.2008.2575

The National Heart, Lung and Blood Institute. (2019). *Study quality assessment tools*. Retrieved August 29, 2019, from https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools

Thelen, D. G., Chumanov, E. S., Best, T. M., Swanson, S. C., & Heiderscheit, B. C. (2005). Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting.

Medicine and Science in Sports and Exercise, *37*(11), 1931–1938. https://doi.org/10.1249/01.mss.0000176674.42929.de

Whiteley, R., Massey, A., Gabbett, T., Blanch, P., Cameron, M., Conlan, G., Ford, M. & Williams, M. (2020). Match high-speed running distances are often suppressed after return from hamstring strain injury in professional footballers. *Sports Health*, *13*(3), 290–295. https://doi.org/10.1177/1941738120964456

Wikstrom, E. A., Naik, S., Lodha, N., & Cauraugh, J. H. (2010). Bilateral balance impairments after lateral ankle trauma: A systematic review and meta-analysis. *Gait & Posture*, *31*(4), 407–414. https://doi.org/10.1016/j.gaitpost.2010.02.004

Woods, C., Hawkins, R. D., Maltby, S., Hulse, M., Thomas, A., & Hodson, A. (2004). The football association medical research programme: An audit of injuries in professional football–analysis of hamstring injuries. *British Journal of Sports Medicine*, *38*(1), 36–41. https://doi.org/10.1136/bjsm.2002.002352

Yu, B., Queen, R. M., Abbey, A. N., Liu, Y., Moorman, C. T., & Garrett, W. E. (2008). Hamstring muscle kinematics and activation during overground sprinting. *Journal of Biomechanics*, *41*(15), 3121–3126. https://doi.org/10.1016/j.jbiomech.2008.09.005

Chapter 3: Methodological Considerations for Quantifying High-Speed Running Biomechanics

3.1 Chapter Outline

This chapter outlines the journey to developing a field-based method for quantifying running biomechanics. It will provide a brief history of biomechanical analysis, define the requirements of a field-based system for this research question, review existing field-based biomechanical technology, and describe the process of finding a suitable inertial measurement system for kinematic analysis.

3.2 Past to Present Day Biomechanical Analysis

The history of biomechanical analysis involved contributions of numerous notable figures throughout several time periods. Aristotle (384-322 B.C.) was one of the earliest to describe the movement of animals through an analysis of mechanical systems in his book "De Motu Animalium".[1] Around the same period, Archimedes (287-212 B.C.) developed some foundational biomechanical principles.[1] Skipping to the 15th century, Leonardo da Vinci (1452-1519) laid the groundwork for the fundamental understanding of functional anatomy and joint function.[1] Galilei (1564-1642) further built on this knowledge base by analysing changes in bone integrity with increasing weight.[1] Then, in 1689, Isaac Newton (1642-1726) published the renowned 'Laws of Motion'.[2] This monumental work was expanded on by Giovanni Alfonso Borelli (1609-1697) who determined the human centre of gravity.[1] The 19th and 20th century saw several further advances in biomechanical technology (Figure 3.1); all work of which collectively unpins modern day biomechanical analysis.

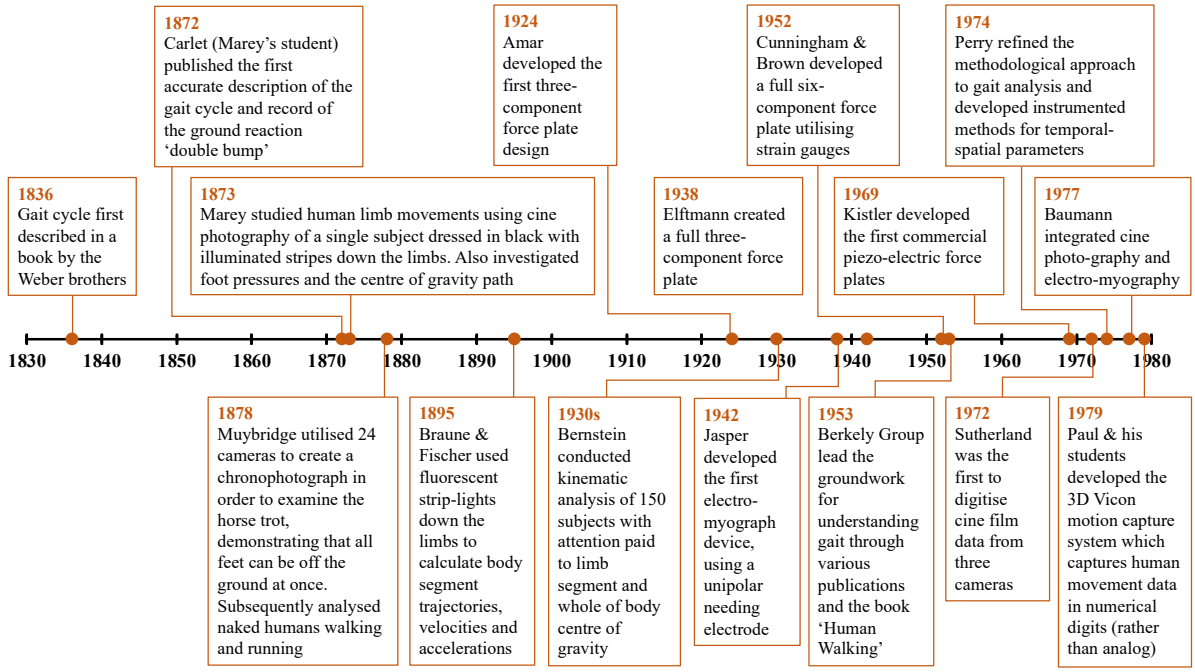


Figure 3.1: Biomechanical technological advances from early 1800s to late 1900s[3-14]

In the late 20th century, vision-based motion analysis progressed from basic 2D image sequences to 3D marker-based motion systems, currently referenced as the 'gold standard' in the literature.[15] From the late 1990s, synchronisation between force plates and the marker-based motion analysis system (MAS) was modernised,[16] enabling complex coordination of spatiotemporal, kinematic and kinetic data to calculate joint forces, and sophisticated mechanical descriptions of movement.[3] Subsequent years saw the advancement in camera technology, including higher resolutions, and increased frame and sampling rates.[17,18] These technical developments resulted in improved system accuracy, greater reliability of equipment, advanced data collection methods, and enhanced clinical translation of findings.[19]

Recent years have seen the development and availability of marker-less systems rapidly advance.[18] Artificial intelligence and vision-based machine learning have facilitated automatic, fast and non-invasive biomechanical analysis.[20] The technology has even been adopted within sporting stadium camera systems for in-game movement recognition and data collection.[18] However, although marker-less systems are comparable to MAS, they are less accurate and valid for kinematic measurements in the transverse and frontal planes.[21] Thus, the MAS remains the current gold standard, but marker-less systems will likely continue to evolve as an efficient, non-invasive option for biomechanical analysis.

The MAS is not without limitations. Externally secured markers are susceptible to soft tissue artefact, despite being secured to bony landmarks.[22] Soft tissue artifact refers to the mobility or 'wobbling' of markers on the skin with movement.[23,24] Particularly with tasks involving high forces (e.g. running), there is a risk of measurement errors associated with soft tissue impact.[25] Marker positioning is also dependent on the clinician's ability to locate landmarks, thus there is also a risk of human error. Nevertheless, when the markers are donned securely and correctly, the MAS captures exceptional detail of spatiotemporal, kinematic and kinetic biomechanical data. The key issues with the MAS for research translation purposes are around practicality. The MAS is expensive and time-consuming as a result of extensive preparation and processing procedures,[17] and the environment is constrained to indoor use as the cameras are infra-red, which limits true representation of movement in functional, field scenarios. [6]

The 21st century has witnessed the introduction of various other technologies for biomechanical analysis such as instrumented treadmills,[26] active (LED) marker systems,[18] action sports cameras,[27] textile-based sensors[28,29] and inertial measurement units (IMUs).[30] Commercially, the imbalance between the 'tech push' and the 'need pull' is becoming apparent. This is highly characteristic of the sports science realm, where coaches and practitioners are regularly approached by commercial entities offering novel biomechanical analysis technologies. The practical utility and validity of these technologies are highly dependent on respective needs (e.g. outcome measures sought, sensitivity and specificity requirements), inhibiting the ability to employ these technologies through a 'one size fits all' approach.[31]

3.3 Biomechanical Analysis Requirements for Current Research Question

As mentioned in Chapter 1, the aim of this research was to investigate the relationship between high-speed running and HSI, and explore whether variations in running biomechanics may contribute

to the development of HSI. The secondary aim was to determine how the use of portable technology may assist in understanding the complex relationship between running biomechanics and HSI. This section details the technical and methodological requirements explored for addressing these research questions.

First and foremost, as detailed in Section 1.5.2, the research should be undertaken in the field, as close as possible to real-world conditions, utilising valid and reliable portable technology.[15] Secondly, since this research focused on the high-speed running type of HSI, the research methodology must encompass analysis of running at various high speeds. Contact or stance time decreases as speed increases, thus the sampling rate of the biomechanical analysis method needs to be sensitive enough to capture this. For brief contact phases, such as those during high-speed running, a sampling rate of 200 Hz or higher is recommended.[18] Lastly, the field-based system must be designed to ensure human interface usability, thereby facilitating the practical translation of research.[32]

In terms of biomechanical variables of interest, the systematic review in Chapter 2 found minimal evidence demonstrating that athletes who strain their hamstrings (retrospectively or prospectively) run differently to athletes who do not. A dearth in the number and quality of evidence in the area was highlighted. Despite this lack of evidence, the systematic review did provide some direction as to which biomechanical variables may be worth investigating in future studies.

From a kinematic perspective, the included studies within the systematic review reported either no differences or contradicting findings between running biomechanics of athletes who retrospectively or prospectively sustained an HSI and controls, except for trunk kinematics. Two prospective cohort studies reported increased trunk lateral flexion during the late swing phase of gait. Both studies were rated 'fair' in terms of quality, primarily due to the small sample size. Other research has suggested that gluteus medius weakness may be present in athletes who sustain an HSI,[33,34] thus, the increased lateral trunk flexion may be a compensatory strategy to account for this.[35] Further clarification is needed to understand better how lumbo-pelvic and lower limb kinematic deviations in running biomechanics may be associated with HSI. Therefore, the field-based running analysis system should preferentially be able to accurately quantify kinematics.

Kinetically, the systematic review found that horizontal force was an important running biomechanical variable to consider in understanding HSI. Three out of four included studies that investigated this variable reported decreased horizontal propulsive force in athletes who have strained their hamstrings retrospectively. No other kinetic variable showed any correlation with HSI. Horizontal propulsive force generation is an integral determinant of sprint performance.[36] Although vertical ground reaction forces typically exceed average positive horizontal ground reaction forces in high-speed running,[37,38] the percentage change in horizontal forces when approaching high speeds is much greater than that of vertically oriented forces.[39-42] During the stance phase, horizontal forces are initially negative (braking force), then transition to positive (propulsive force).[43] As detailed in Chapter 1, the hamstrings play a critical role in both minimising horizontal braking force[44] and subsequent horizontal force propulsion before toe off.[45] As a result of these findings, the field-based running analysis system should quantify horizontal propulsive force.

The systematic review proposed that overstriding running technique may be a kinematic explanation for decreased horizontal propulsive force. At initial contact, an overstriding runner's foot will land too far in front of their centre of gravity.[46] Overstriding is considered undesirable as it results in increased horizontal braking force at initial contact.[47,48] The hamstring muscles are particularly relevant here as they work to eccentrically decelerate hip flexion and knee extension in preparation for initial contact,[45] before overcoming negative horizontal (braking) force by concentrically extending the hip.[44] Hence, if an athlete is overstriding, the hamstring load is greater.[49-51] As such, if the field-based running analysis system could quantify overstride, it is possible to further explore whether overstride is associated with HSI.

Lastly, spatiotemporal requirements should be considered for the field-based running analysis system. In a perfect world, the field-based system would be able to detail all spatiotemporal characteristics but noting biomechanical variables discussed above are largely focused at and around point of contact, point of contact detection is the minimum spatiotemporal requirement for the purposes of this research.

3.4 Existing Field-Based Biomechanical Technology

The existing field-based biomechanical technology alternatives are reviewed in Table 3.1. Unlike other wearable technologies, IMUs minimise disturbance to normal running habits by enabling runners to wear their regular clothes and footwear, allowing unrestricted joint range of motion. Optical fibres are not preferred as they must cross the joint for kinematic analysis,[52] thus are typically embedded into textiles.[29] Insole optical fibres and pressure sensing insoles may also negatively affect runners' normal habits, particularly if they are replacing a preferred orthotic insert. Furthermore, insole optical fibres and pressure-sensing insoles only quantify vertically oriented kinetics.[53-55] Based on the requirements for this thesis, kinetics that are horizontally oriented are of greater interest. Although video-based marker-less systems are emerging as a very promising method for quantifying field-based biomechanics, there is a lack of validated high quality, large-scale data sets to train the high-speed running models.[56-58] This thesis did not have the time or resources to develop them. In the end, it was determined that IMUs and FVP were the most suitable field-based biomechanical technologies for the purposes of our research.

	KINEMATIC DATA	KINETIC DATA	SPATIO-TEMPORAL DATA	ADVANTAGES	LIMITATIONS
INERTIAL MEASUREMENT UNITS (IMU) 	✓	✓	✓	- Relatively low-cost[59] - Capable of tracking several joints simultaneously via configuration of multiple IMUs[29] - Good evidence for use in activity recognition and spatiotemporal parameters[55,59-63]	- Sensor noise[64] - Synchronisation issues[65] - Magnetic disturbances[66] - Environmental interferences[67] - Accelerometer data affected by surface and footwear[68] - Accuracy in ground reaction force prediction variable[69-71] - Further validation required for standardised task and participant specific kinematic outputs[72,73]

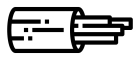
OPTICAL FIBRES 	✓	✓	✓	- Light weight and flexible[29] - Gait phase recognition capable through monitoring muscle activation[74] or insole optical fibres[52] - Immune to electromagnetic interference[29] - Remote sensing capable[75]	- Must be embedded into textile or, affixed using straps or tape[52] - For kinematic analysis, optical fibre must cross the joint/s of interest[29] - Insole optical fibres able to determine only vertically orientated forces[53,54] - Sensitive to environmental factors[29,52]
PRESSURE SENSING INSOLES 	✗	✓	✓	- Valid and reliable for spatiotemporal parameters[55] - Low-cost[76] - Capable of real-time feedback[76,77]	- Athlete comfort variable as pressure sensing insoles replace insoles of athlete's shoes[55] - For analysis over long periods, battery technology insufficient[77] - Accuracy of kinetic measures dependant on system and speed[55], and able to determine only vertically orientated forces[55] - Sensitive to humidity[77]
VIDEO-BASED MARKERLESS SYSTEMS 	✓	✓	✓	- Uses pose estimation (deep learning-based software) algorithms to accurately determine spatiotemporal parameters (even with normal clothing)[57] - Single or multiple camera, depth or standard camera configurations available[57] - Emerging evidence for accurate estimation of ground force reaction data[78,79]	- Use of pose estimation is only as accurate as those data sets used to train them[57] - Lack of large-scale, high-quality data bases[56] - Kinematic outcome measures require further validated for clinical application on an individual basis[57,58] - Multiple cameras enable 3D analysis and improve accuracy of all biomechanical variables[57,80]
SPRINT FORCE-VELOCITY PROFILING (FVP) 	✗	✓	✓	- Validated against gold standard for field-based use to characterise sprint mechanical performance[81] - Details the horizontal force-velocity relationship in achieving horizontal power output[82,83] - Utilises a computational method using only anthropometric and spatiotemporal data[81] - Radar, timing gates and/or video cameras (including smart phone) may be used to collect split times[81,84-87]	- More data sets required to understand profile implication for injury prevention and performance[88] - Limited to acceleration phase of sprinting (computational method does not characterise kinetics during steady state or deceleration)[81] - Spatiotemporal data limited to velocity metrics and total sprint time[81]

Table 3.1: A review of existing field-based technology (icons: Flaticon.com)

IMUs were chosen as they are lightweight, relatively low-cost and demonstrate good accuracy for spatiotemporal parameters. But, for kinematic analysis, they require further refinement and validation against the gold standard MAS.[72,73] This challenge is addressed in Section 3.5 and Chapter 4. Given that the ability for IMUs to quantify kinetics is still developing, [69-71] FVP was determined to currently be the best option for quantification of horizontally oriented forces. FVP technology is already validated and readily available through an iPhone application for split time determination and timing gates.[87] Both of which, should the technology prove useful for injury prevention strategies, can be easily adopted by clinicians and coaching staff in real-world conditions.

3.5 Journey to Finding a Suitable Inertial Measurement System for Kinematic Analysis

The next task was to find a suitable IMU system for kinematic analysis. The challenge was to find one that was valid and reliable for high-speed running in field settings. Thus, the journey began for testing and trialling in order to find a system to validate formally.

3.5.1 Pilot Testing - 'dorsaVi'

The obvious starting point was to pilot the technology that was already held by The University of Sydney; dorsaVi's ViMove IMU system (dorsaVi, Docklands, Victoria, Australia). For running analysis, the system comprised of two IMUs worn anteromedially on each lower leg, using a proprietary template provided by the manufacturer. The position of the IMU was determined based on the participant's height. Disposable application pads (Dorsavi, Melbourne, Australia) were attached to the medial tibia at the designated location, and the IMUs were secured in place. Although the viMove™ has an inbuilt triaxial accelerometer with magnetometer and one triaxial gyroscope, the programmed running set-up only utilises the accelerometer with a sampling rate of 100, 20 and 20Hz for the x, y and z axes respectively.[89] Predetermined running variable outputs were as follows:

- Vertical ground reaction force (N) – right and left (R+L)
- Initial peak acceleration (g) – R+L
- Average ground contact time (ms) – R+L
- Limb asymmetry index (%)
- Cadence (steps per min)
- Total distance (m)
- Total time analysed (min / s)

Since the intent of the IMU was for kinematic analysis (as detailed in Section 3.3), the plan was to work with dorsaVi to utilise the viMove's inbuild gyroscope and access raw data. For squat tasks, the viMove was programmed to quantify tibial angle, which was later investigated in other studies.[90,91] The idea was to amend the running program to include the gyroscope data, in order to provide tibial inclination at POC when running.

Prior to contacting dorsaVi, a trial was conducted to better understand the viMove and its' programmed outputs. In November 2016, the viMove was trialled over a 45 m sprint track, which passes through the university's 3D MAS (including force plates). We had planned to preliminary review how the viMove system spatiotemporal and kinetic data compared to the MAS. Unfortunately, multiple problems were faced before any data comparisons could be made.

Issues were encountered with the MAS and our overground running set-up. Noting the limited capture volume (including force plate area) and larger step length that occurs with sprinting, data from only one or two steps were collected. Thus, limiting the data points for comparison. Furthermore, sunlight from having both roller doors open (one for the acceleration track and other the deceleration zone) as per Figure 3.2 posed issues. When processing the MAS data, large sunlight sections of the capture volume had to be blocked out. Despite this, small sunlight flickers still surfaced, which the MAS system detected as a retroreflective marker, further complicating data collection.

Upon reviewing the sprint data captured via the viMove IMU system, multiple data gaps were present. Over multiple tests, the IMU system consistently failed to register all steps, likely due to the low sampling rate. Missing data and lack of agreement were also reported in subsequent studies.[71,92] Although these overground running studies reported acceptable within-system reliability for dorsaVi IMU tibial acclerometer data, data gaps (signal drop out) led to limited agreement with the reference standard. [71,92] This issue was presented to dorsaVi's software engineer, which included an enquiry about their algorithms to include gyroscope data. In February 2017, dorsavi advised that a research and development algorithm project was underway, but which metrics would be able to be assessed was yet to be confirmed. Upon further enquiry in May 2017, no further update was available.

Figure 3.2: Overground track set up for Pilot testing the dorsaVi's ViMove IMU system (affixed to the lower leg) against the university's 3D Motion Analysis System (Eagle and Cortex 1.1.4.368, Motion Analysis Corporation, Santa Rosa, CA, USA)

3.5.2 The University of Sydney Proof of Concept IMU System Development

In May 2017, a University of Sydney Engineer, advised that he may be able to help us develop our own IMU system. We submitted a 'Software Application Form' and work started on the project.

In August 2017, it was informed that the IMU microprocessor in development could only handle 50 samples per second. Alternative options needed to be investigated as that sampling rate wasn't high enough for high-speed running analysis. It was suggested that we engage Professor Mark Halaki

(who later joined the supervisory team), who was advocating for the Discipline of Exercise and Sport Science to purchase an IMU system with a high sampling rate. The system proposed was for the Noraxon Myomotion but to date the proposal hadn't got up due to lack of staff support.

3.5.3 Noraxon Myomotion Pilot Testing

In September 2017, internal funds were allocated to the Discipline of Exercise and Sport Science for the purchase of the Noraxon Myomotion IMU system (Noraxon USA Inc., Scottsdale, United States, Model 680 receiver, Model 610 sensor, MR 3.16 software). Initially, the school was allocated the Noraxon Myomotion system with one IMU. The initial pilot study evaluated the use of this single IMU for shank inclination (as a representative of overstride). Following the MAS issues with overground running in the dorsaVi trial, a treadmill was used instead for validation.

In November 2017, Pilot testing was conducted comparing the Noraxon Myomotion to the MAS (Eagle and Cortex 1.1.4.368, Motion Analysis Corporation, Santa Rosa, CA, USA). The IMU was secured to the left shank, 3-4 cm above the lateral malleolus (the flattest point of the lateral shank). Over twenty-eight strides, the runner built up from 12 to 18 km/h. MAS data was exported into Visual 3D (Version 4.95, C-Motion Inc., Germantown, MD, USA) to determine body segments and angles as per Appendix 2. Pearson's 'r' statistical testing was used as a preliminary measure of correlation between the IMU and MAS. The results from the initial single runner were encouraging, as per Figures 3.3 and 3.4.

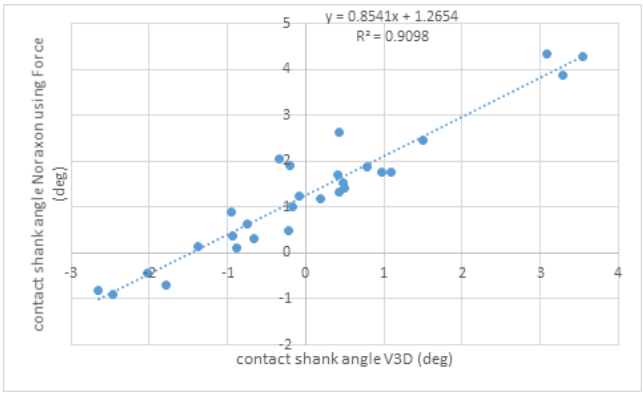


Figure 3.3: The shank angle at ground contact when the force plate was used to identify ground contact were very highly correlated (r=0.95).

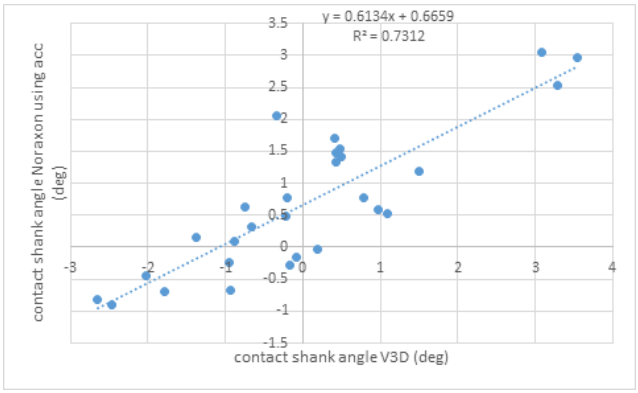


Figure 3.4: When using the accelerometer signal to identify ground contact for the Noraxon system, the correlation was still high (r=0.86).

Following the promising findings from the Noraxon pilot testing, the project was submitted to the university's ethics board for formal investigation. In April 2018, ethics approval was gained (Appendix 4). Two months later, ten single trials were conducted of ten different runners, the results of which raised several concerns. For most of the trials, the synchronisation between the MAS and Noraxon did not function. For those with synchronised data available, one runner had incomplete data, and the rest demonstrated a lack of agreement in shank angle between the MAS and Noraxon systems. Hence, there was low confidence that this single shank IMU would be appropriate for field-based testing. Significant refinement and further validation would be required. Furthermore, from a kinematic perspective, it was disadvantageous to limit our analysis to the shank alone.

Fortunately, shortly after, the university acquired four more IMUs. In December 2018, an ethics modification was submitted to include validation for knee, hip and pelvis angles. After approval in early 2019 (Appendix 4), five further runners were tested. The synchronisation issue was corrected, but the agreement between the MAS and Noraxon systems was variable. It was determined that the inconsistencies were likely a result of the Noraxon sampling rate, which had defaulted back to 100Hz.

Over subsequent months, data collection parameters were further tested and adjusted, increasing the sampling rate to 200Hz and refining the calibration method. This ensured a robust and consistent procedure as detailed in Appendix 2. With these refinements, a validation study was confidently conducted (see Chapter 4).

3.6 References

1. Innocenti B. Biomechanics: a fundamental tool with a long history (and even longer future!). *Muscles Ligaments Tendons J*. 2019;7(4):491. doi:10.32098/mltj.04.2017.02
2. Medved V. History of the Study of Human Locomotion and Elements of Current Research Methodology. In: Medved V, ed. *Measurement and Analysis of Human Locomotion*. Springer International Publishing; 2021:13-37.
3. Whittle MW. *Gait Analysis : An Introduction*. Elsevier Science & Technology; 1991.
4. Marey E-J, Pritchard E. *Movement*. Heinemann's Scientific handbooks. Heinemann; 1895.
5. Carlet M. Essai expérimental sur la locomotion humaine. Etude de la marche. *Ann Sci Nat (Zool)*. 1872;16:1-92.
6. Amar J. Trottoir dynamographique. *Comptes rendus hebdomadaires des séances de l'Académie des Sciences*. 1916;163:130-133.
7. Elftman H. The measurement of the external force in walking. *Science*. 1938;88(2276):152-153.
8. Cunningham DM. Two devices for measuring the forces acting on the human body during walking. *Proc Soc Wxp Stress Anal*. 1952;9:75-90.
9. Baker R. The history of gait analysis before the advent of modern computers. *Gait Posture*. 2007/09/01/ 2007;26(3):331-342. doi:10.1016/j.gaitpost.2006.10.014
10. Sutherland DH, Hagy JL. Measurement of gait movements from motion picture film. *J Bone Joint Surg*. 1972;54(4):787-797.
11. Perry J. Cunical Gait Analyzer. *Bull Prosthet Res*. 1974;22:188.
12. Baumann J, Hanggi A. A method of gait analysis for daily orthopaedic practice. *J Med Eng Technol*. 1977;1(2):86-91.
13. Baumann JU, Baumgartner R. Synchronised photo-optical and EMG gait analysis with radiotelemetry. *Biotelemetry*. Karger Publishers; 1974:94-96.

14. Lu T-W, Chang C-F. Biomechanics of human movement and its clinical applications. *Kaohsiung J Med Sci*. 2012;28(2):S13-S25. doi:10.1016/j.kjms.2011.08.004
15. Willy R. Innovations and pitfalls in the use of wearable devices in the prevention and rehabilitation of running related injuries. *Phys Ther Sport*. 2018;29:26-33. doi:10.1016/j.ptsp.2017.10.003
16. Sutherland DH. The evolution of clinical gait analysis part III – kinetics and energy assessment. *Gait Posture*. 2005;21(4):447-461. doi:10.1016/j.gaitpost.2004.07.008
17. Colyer SL, Evans M, Cosker DP, Salo AIT. A review of the evolution of vision-based motion analysis and the integration of advanced computer vision methods towards developing a markerless system. *Sports Med*. 2018;4(1):1-15. doi:10.1186/s40798-018-0139-y
18. Yeadon MR, Pain MTG. Fifty years of performance-related sports biomechanics research. *J Biomech*. 2023;155:111666. doi:10.1016/j.jbiomech.2023.111666
19. Wren TAL, Tucker CA, Rethlefsen SA, Gorton GE, Õunpuu S. Clinical efficacy of instrumented gait analysis: systematic review 2020 update. *Gait Posture*. 2020;80:274-279. doi:10.1016/j.gaitpost.2020.05.031
20. Roggio F, Ravalli S, Maugeri G, et al. Technological advancements in the analysis of human motion and posture management through digital devices. *World J Orthop*. 2021;12(7):467-484. doi:10.5312/wjo.v12.i7.467
21. Scataglini S, Abts E, Van Bocxlaer C, Van den Bussche M, Meletani S, Truijen S. Accuracy, validity, and reliability of markerless camera-based 3D motion capture systems versus marker-based 3D motion capture systems in gait analysis: a systematic review and meta-analysis. *Sensors*. 2024;24(11):3686. doi:10.3390/s24113686
22. Bergmann JHM, Mayagoitia RE, Smith ICH. A portable system for collecting anatomical joint angles during stair ascent: a comparison with an optical tracking device. *Dyn Med*. 2009;8(1):1-7. doi:10.1186/1476-5918-8-3
23. Camomilla V, Dumas R, Cappozzo A. Human movement analysis: the soft tissue artefact issue. *J Biomech*. 2017;62:1-4. doi:10.1016/j.jbiomech.2017.09.001
24. Bélaise C, Blache Y, Thouzé A, Monnet T, Begon M. Effect of wobbling mass modeling on joint dynamics during human movements with impacts. *Multibody Syst Dyn*. 2016;38(4):345-366. doi:10.1007/s11044-016-9519-6
25. Zeng Z, Liu Y, Li P, Wang L. Validity and reliability of inertial measurement units measurements for running kinematics in different foot strike pattern runners. *Front Bioeng Biotechnol*. 2022;10:1005496. doi:10.3389/fbioe.2022.1005496
26. Encarnación-Martínez A, Pérez-Soriano P, Sanchis-Sanchis R, García-Gallart A, Berenguer-Vidal R. Validity and reliability of an instrumented treadmill with an accelerometry system for assessment of spatio-temporal parameters and impact transmission. *Sensors*. 2021;21(5):1758.
27. Bernardina GRD, Monnet T, Pinto HT, de Barros RML, Cerveri P, Silvatti AP. Are action sport cameras accurate enough for 3D motion analysis? A comparison with a commercial motion capture cystem. *J Appl Biomech*. 2018;35(1):1-17. doi:10.1123/jab.2017-0101
28. Gholami M, Rezaei A, Cuthbert TJ, Napier C, Menon C. Lower body kinematics monitoring in running using fabric-based wearable sensors and deep convolutional neural networks. *Sensors* 2019;19(23):5325. doi:10.3390/s19235325
29. Faisal A, Majumder S, Mondal T, Cowan D, Naseh S, Deen M. Monitoring methods of human body joints: state-of-the-art and research challenges. *Sensors*. 2019;19(11):2629. doi:10.3390/s19112629
30. Liu Q, Mo S, Cheung VC, et al. Classification of runners' performance levels with concurrent prediction of biomechanical parameters using data from inertial measurement units. *J Biomech*. 2020;112:110072. doi:10.1016/j.jbiomech.2020.110072
31. Johnston W, Heiderscheit B. Mobile technology in running science and medicine: Are we ready? *J Orthop Sports Phys*. 2019;49(3):122-125. doi:10.2519/jospt.2019.0604

32. Zhou H, Hu H. Human motion tracking for rehabilitation—A survey. *Biomed Signal Process Control*. 2008;3(1):1-18. doi:10.1016/j.bspc.2007.09.001
33. Franettovich Smith MM, Bonacci J, Mendis MD, Christie C, Rotstein A, Hides JA. Gluteus medius activation during running is a risk factor for season hamstring injuries in elite footballers. *J Sci Med Sport*. 2017;20(2):159-163. doi:10.1016/j.jsams.2016.07.004
34. Schuermans J, Danneels L, Van Tiggelen D, Palmans T, Witvrouw E. Proximal neuromuscular control protects against hamstring injuries in male soccer players: a prospective study with electromyography time-series analysis during maximal sprinting. *Am J Sports Med*. 2017;45(6):1315-1325. doi:10.1177/0363546516687750
35. Chang A, Hayes K, Dunlop D, et al. Hip abduction moment and protection against medial tibiofemoral osteoarthritis progression. *Arthritis Rheum*. 2005;52(11):3515-3519. doi:10.1002/art.21406
36. Edouard P, Samozino P, Slotala R, Mendiguchia J, Morin JB. Hamstring injury prevention: contributions of biomechanics. *Ann Phys Rehabil Med*. 2016;59:e15. doi:10.1016/j.rehab.2016.07.036
37. Kuitunen S, Komi PV, Kyrolainen H. Knee and ankle joint stiffness in sprint running. *Med Sci Sports Exerc*. 2002;34(1):166-173. doi:10.1097/00005768-200201000-00025
38. Weyand PG, Bundle MW, McGowan CP, et al. The fastest runner on artificial legs: different limbs, similar function? *J Appl Physiol*. 2009;107(3):903-11. doi:10.1152/japplphysiol.00174.2009
39. Brughelli M, Cronin J, Chaouachi A. Effects of running velocity on running kinetics and kinematics. *J Strength Cond Res*. 2011;25(4):933-939. doi:10.1519/JSC.0b013e3181c64308
40. Rabita G, Dorel S, Slawinski J, et al. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scand J Med Sci Sports*. 2015;25(5):583-94. doi:10.1111/sms.12389
41. Kyrolainen H, Bellizzi MJ, Komi PV. Biomechanical factors affecting running economy. *Med Sci Sports Exerc*. 2001;33(8):1330-1337. doi:10.1097/00005768-200108000-00014
42. Nummela A, Keranen T, Mikkelsson LO. Factors related to top running speed and economy. *Int J Sports Med*. 2007;28(8):655-61. doi:10.1055/s-2007-964896
43. Mero A, Komi PV, Gregor RJ. Biomechanics of sprint running. *Sports Med*. 1992;13(6):376-392.
44. Stanton P, Purdham C. Hamstring injuries in sprinting - the role of eccentric exercise. *J Orthop Sports Phys Ther*. 1989;10(9):343-349. doi:10.2519/jospt.1989.10.9.343
45. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech*. 2008;41(15):3121-6. doi:10.1016/j.jbiomech.2008.09.005
46. Lieberman DE, Warrener AG, Wang J, Castillo ER. Effects of stride frequency and foot position at landing on braking force, hip torque, impact peak force and the metabolic cost of running in humans. *J Exp Biol*. 2015;218(21):3406-3414. doi:10.1242/jeb.125500
47. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc*. 2011;43(2):296-302. doi:10.1249/MSS.0b013e3181ebedf4
48. Wille CM, Lenhart RL, Wang S, Thelen DG, Heiderscheit BC. Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running. *J Orthop Sports Phys Ther*. Oct 2014;44(10):825-30. doi:10.2519/jospt.2014.5367
49. Gambetta V, Benton D. A systematic approach to hamstring prevention and rehabilitation. *Sports Coach*. 2006;28(4):1-6.
50. Barton CJ, Bonanno DR, Carr J, et al. Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion. *Br J Sports Med*. 2016;50(9):513-526. doi:10.1136/bjsports-2015-095278
51. Orchard J. Biomechanics of muscle strain injury: the Dr Matt Marshall Lecture 2002. *New Zeal J Sports Med*. Summer 2002;30(4):90-96.

52. Zhang X, Wang C, Zheng T, Wu H, Wu Q, Wang Y. Wearable optical fiber sensors in medical monitoring applications: a review. *Sensors*. 2023;23(15):6671. doi:10.3390/s23156671
53. Domingues MF, Tavares C, Leitão C, et al. Insole optical fiber Bragg grating sensors network for dynamic vertical force monitoring. *J Biomed Opt*. 2017;22(9):091507. doi:10.1117/1.JBO.22.9.091507
54. Mahmud S, Khandakar A, Chowdhury MEH, et al. Fiber Bragg Gratings based smart insole to measure plantar pressure and temperature. *Sens Actuators A Phys*. 2023;350:114092. doi:10.1016/j.sna.2022.114092
55. Mason R, Pearson LT, Barry G, et al. Wearables for running gait analysis: a systematic review. *Sports Med*. 2023;53(1):241-268. doi:10.1007/s40279-022-01760-6
56. Mundt M. Bridging the lab-to-field gap using machine learning: a narrative review. *Sports biomech*. 2023:1-20. doi:10.1080/14763141.2023.2200749
57. Wade L, Needham L, McGuigan P, Bilzon J. Applications and limitations of current markerless motion capture methods for clinical gait biomechanics. *PeerJ*. 2022;10:e12995-e12995. doi:10.7717/peerj.12995
58. Van Hooren B, Pecasse N, Meijer K, Essers JMN. The accuracy of markerless motion capture combined with computer vision techniques for measuring running kinematics. *Scand J Med Sci Sports*. 2023;33(6):966-978. doi:10.1111/sms.14319
59. Camomilla V, Bergamini E, Fantozzi S, Vannozzi G. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: a systematic review. *Sensors*. 2018;18(3):873. doi:10.3390/s18030873
60. García-Pinillos F, Latorre-Román P, Soto-Hermoso V, et al. Agreement between the spatiotemporal gait parameters from two different wearable devices and high-speed video analysis. *PLoS One*. 2019;14(9):e0222872. doi:10.1371/journal.pone.0222872
61. Brahms CM, Zhao Y, Gerhard D, Barden JM. Stride length determination during overground running using a single foot-mounted inertial measurement unit. *J Biomech*. 2018;71:302-305. doi:10.1016/j.jbiomech.2018.02.003
62. Dideriksen OM, Soegaard OC, Nielsen OR. Validity of self-reported running distance. *J Strength Cond Res*. 2016;30(6):1592-1596. doi:10.1519/JSC.0000000000001244
63. Schmidt M, Rheinländer C, Nolte KF, Wille S, Wehn N, Jaitner T. IMU-based determination of stance duration during sprinting. *Procedia Eng*. 2016;147:747-752. doi:10.1016/j.proeng.2016.06.330
64. Akbari A, Thomas X, Jafari R. Automatic noise estimation and context-enhanced data fusion of IMU and Kinect for human motion measurement. presented at: IEEE 14th International Conference on Wearable and Implantable Body Sensor Networks (BSN); 09-12 May 2017 2017; Eindhoven, Netherlands.
65. Verdel N, Mohorcic M, Drobnic M, Supej M, Depolli M. Time synchronization in wireless IMU sensors for accurate gait analysis during running. presented at: IEEE International Workshop on Sport, Technology and Research (STAR) 14-16 Sept 2023 2023; Cavalese - Trento, Italy.
66. Robert-Lachaine X, Mecheri H, Larue C, Plamondon A. Effect of local magnetic field disturbances on inertial measurement units accuracy. *Appl Ergon*. 2017;63:123-132. doi:10.1016/j.apergo.2017.04.011
67. Benson LC, Räisänen AM, Clermont CA, Ferber R. Is this the real life, or is this just laboratory? A scoping review of IMU-based running gait analysis. *Sensors*. 2022;22(5):1722. doi:10.3390/s22051722
68. Sheerin KR, Reid D, Besier TF. The measurement of tibial acceleration in runners—a review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. *Gait Posture*. 2019/01/01/ 2019;67:12-24. doi:10.1016/j.gaitpost.2018.09.017
69. Kenneally-Dabrowski CJ, Serpell BG, Spratford W. Are accelerometers a valid tool for measuring overground sprinting symmetry? *Int J Sports Sci Coach*. 2018;13(2):270-277. doi:10.1177/1747954117716790

70. Gurchiek RD, McGinnis RS, Needle AR, McBride JM, van Werkhoven H. The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *J Biomech*. 2017;61:263-268. doi:10.1016/j.jbiomech.2017.07.035
71. Raper D, Witchalls J, Phillips E, Knight E, Drew M, Waddington G. Use of a tibial accelerometer to measure ground reaction force in running: a reliability and validity comparison with force plates. *J Sci Med Sport*. 2017;21(1):84-88. doi:10.1016/j.jsams.2017.06.010
72. Weygers I, Kok M, Konings M, Hallez H, De Vroey H, Claeys K. Inertial sensor-based lower limb joint kinematics: a methodological systematic review. *Sensors*. 2020;20(3):673. doi:10.3390/s20030673
73. Zeng Z, Liu Y, Hu X, Tang M, Wang L. Validity and reliability of inertial measurement units on lower extremity kinematics during running: a systematic review and meta-analysis. *Sports Med* 2022;8(1):86. doi:10.1186/s40798-022-00477-0
74. Zhang W, Ju L, Jia H, Ding X, Feng Y. Semiring-optic-fiber (SROF) sensor-based abnormal gait recognition via monitoring muscle activation. *IEEE Sens J*. 2023;23(17):19307-19317. doi:10.1109/JSEN.2023.3292923
75. Khonina SN, Kazanskiy NL, Butt MA. Optical fibre-based sensors—an assessment of current innovations. *Biosensors*. 2023;13(9):835. doi:10.3390/bios13090835
76. Ciniglio A, Guiotto A, Spolaor F, Sawacha Z. The design and simulation of a 16-sensors plantar pressure insole layout for different applications: from sports to clinics, a pilot study. *Sensors*. 2021;21(4):1450. doi:10.3390/s21041450
77. Zhang Z, Dai Y, Xu Z, et al. Insole systems for disease diagnosis and rehabilitation: a review. *Biosens J*. 2023;13(8):833. doi:10.3390/bios13080833
78. Mundt M, Born Z, Goldacre M, Alderson J. Estimating ground reaction forces from two-dimensional pose data: a biomechanics-based comparison of AlphaPose, BlazePose, and OpenPose. *Sensors*. 2022;23(1):78. doi:10.3390/s23010078
79. Peng Y, Wang W, Wang L, et al. Smartphone videos-driven musculoskeletal multibody dynamics modelling workflow to estimate the lower limb joint contact forces and ground reaction forces. *Med Biol Eng Comput*. 2024;62(12):3841-3853. doi:10.1007/s11517-024-03171-3
80. Clark RA, Mentiplay BF, Hough E, Pua YH. Three-dimensional cameras and skeleton pose tracking for physical function assessment: A review of uses, validity, current developments and Kinect alternatives. *Gait Posture*. 2019;68:193-200. doi:10.1016/j.gaitpost.2018.11.029
81. Samozino P, Rabita G, Dorel S, et al. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand J Med Sci Sports*. 2016;26(6):648-658. doi:10.1111/sms.12490
82. Jaskólska A, Goossens P, Veenstra B, Jaskólskp A, Skinner JS. Treadmill measurement of the force-velocity relationship and power output in subjects with different maximal running velocities. *Sports Med Train Rehabil*. 1998;8(4):347-358. doi:10.1080/15438629909512537
83. Morin J-B, Edouard P, Samozino P. Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc*. 2011;43(9):1680-1688. doi:10.1249/mss.0b013e318216ea37
84. Mendiguchia J, Samozino P, Martinez-Ruiz E, et al. Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *Int J Sports Med*. 2014;35(8):690-695 6p. doi:10.1055/s-0033-1363192
85. Haugen AT, Breitschädel AF, Samozino AP. Power-force-velocity profiling of sprinting athletes: methodological and practical considerations when using timing gates. *J Strength Cond Res*. 2018;34(6):1769-1773. doi:10.1519/JSC.0000000000002890
86. Cross MR, Brughelli M, Samozino P, Morin J-B. Methods of power-force-velocity profiling during sprint running: a narrative review. *Sports Med*. 2017;47(7):1255-1269. doi:10.1007/s40279-016-0653-3

87. Romero-Franco N, Jiménez-Reyes P, Castaño-Zambudio A, et al. Sprint performance and mechanical outputs computed with an iPhone app: comparison with existing reference methods. *Eur J Sport Sci*. 2017;17(4):386-392. doi:10.1080/17461391.2016.1249031
88. Hicks DS, Drummond C, Williams KJ, Pickering C, van den Tillaar R. Individualization of training based on sprint force-velocity profiles: a conceptual framework for biomechanical and technical training recommendations. *Strength Cond J*. 2023;45(6):711-725. doi:10.1519/SSC.0000000000000790
89. Charry E, Hu W, Umer M, Ronchi A, Taylor S. Study on estimation of peak ground reaction forces using tibial accelerations in running. presented at: 2013 IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing; 02-05 Apr 2013 2013; Melbourne, Australia.
90. Hughes T, Jones RK, Starbuck C, Picot J, Sergeant JC, Callaghan MJ. Are tibial angles measured with inertial sensors useful surrogates for frontal plane projection angles measured using 2-dimensional video analysis during single leg squat tasks? A reliability and agreement study in elite football (soccer) players. *J Electromyogr Kinesiol*. 2019;44:21-30. doi:10.1016/j.jelekin.2018.11.005
91. Drapeaux A, Carlson K. A comparison of inertial motion capture systems: DorsaVi and Xsens. *IJKSS*. 2020;8(3):24. doi:10.7575/aiac.ijkss.v.8n.3p.24
92. Hughes T, Jones RK, Starbuck C, Sergeant JC, Callaghan MJ. The value of tibial mounted inertial measurement units to quantify running kinetics in elite football (soccer) players. A reliability and agreement study using a research orientated and a clinically orientated system. *J Electromyogr Kinesiol*. 2019;44:156-164. doi:10.1016/j.jelekin.2019.01.001

Chapter 4: Validity of an Inertial Measurement Unit System to Measure Lower Limb Kinematics at Point of Contact during Incremental High-Speed Running

4.1 Outline

The exploration of technology for field-based high-speed, biomechanical running analysis, as well as the extensive pilot testing in the preceding chapter, led to the validation study presented in this chapter. The primary aim of this study was to validate the use of a multi-sensor IMU system for biomechanical lower limb kinematic analysis at point of contact (POC) during incremental high-speed running. It is presented in the style of the journal where it is published:

Wolski, L., Halaki, M., Hiller, C. E., Pappas, E., & Fong Yan, A. (2024). Validity of an Inertial Measurement Unit System to Measure Lower Limb Kinematics at Point of Contact during Incremental High-Speed Running. *Sensors (Basel, Switzerland),* 24(17), 5718. doi: 10.3390/s24175718

This validation study reported the IMU system to reliably identify POC, and accurately measure stride time, anterior pelvic tilt and hip flexion angle across all speeds tested. However, it was inaccurate and inconsistent in estimating knee flexion and shank angles. The discussion section of this publication acknowledges study limitations, including the generalizability of findings given the single case study design. It's important to note that although a runner's biomechanics may vary with extrinsic (e.g. footwear, surface) and intrinsic differences (e.g. foot strike pattern), the purpose of the study was not about quantifying running technique, rather whether the two systems are in agreement across incremental high-speeds. Ultimately, the findings of this study provided valuable insights on the IMU system (both in terms of strengths and weaknesses) to shift to field-based research.

ADDITIONAL NOTE: *Additional methodological detail on validation study data collection procedures is contained in 'Appendix 2: Manual of Procedures'.*

sensors

MDPI

Article

Validity of an Inertial Measurement Unit System to Measure Lower Limb Kinematics at Point of Contact during Incremental High-Speed Running

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Abstract: There is limited validation for portable methods in evaluating high-speed running biomechanics, with inertial measurement unit (IMU) systems commonly used as wearables for this purpose. This study aimed to evaluate the validity of an IMU system in high-speed running compared to a 3D motion analysis system (MAS). One runner performed incremental treadmill running, from 12 to 18 km/h, on two separate days. Sagittal angles for the shank, knee, hip and pelvis were measured simultaneously with three IMUs and the MAS at the point of contact (POC), the timing when the foot initially hits the ground, as identified by IMU system acceleration, and compared to the POC identified via force plate. Agreement between the systems was evaluated using intra-class correlation coefficients, Pearson's *r*, Bland–Altman limits of agreements, root mean square error and paired *t*-tests. The IMU system reliably determined POC (which subsequently was used to calculate stride time) and measured hip flexion angle and anterior pelvic tilt accurately and consistently at POC. However, it displayed inaccuracy and inconsistency in measuring knee flexion and shank angles at POC. This information provides confidence that a portable IMU system can aid in establishing baseline running biomechanics for performance optimisation, and/or inform injury prevention programs.

Keywords: sensor; measurement; accelerometer; gait; biomechanics

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1. Introduction

Biomechanical analyses of running are frequently utilised by skilled practitioners in the sports science and medicine realm. Running forms the fundamental basis of numerous sports, and assessment may enable technical coaching to optimise performance and/or inform injury prevention programs [1–3]. Running analysis often relies on technology, as certain gait cycle characteristics are difficult to see with the naked eye. This becomes particularly relevant as running speed increases, when the stance phase duration of running approaches 0.1 s [4]. The ongoing challenge for practitioners and coaches is finding a field-based method of running analysis that is valid and reliable [5], noting the gold standard for high-speed running analysis is the lab-based motion analysis system (MAS). Although the MAS provides accurate measures of spatiotemporal, kinematic and kinetic parameters, its ability for use in the field or outdoors is limited. Furthermore, the MAS is expensive and time consuming as a result of extensive processing procedures [6].

Inertial measurement units (IMUs) are an emerging portable, inexpensive method for analysing running biomechanics [7]. IMUs are portable sensors made up of three components: an accelerometer, gyroscope and magnetometer which, respectively, provide three-dimensional linear acceleration, angular velocity and orientation outputs. Computational methods enable various spatiotemporal and kinetic outputs, and two or more

calibrated IMUs are capable of tracking joint angles, permitting functional activity kinematic analysis [8,9].

For IMU use in running, there is not a 'one size fits all' algorithm; precision is determined by user requirement, and accuracy will fluctuate depending on design and calibration [10,11]. The ability of IMUs to predict running kinetics is variable [12,13], and despite emerging evidence demonstrating merit in using IMUs for kinematic analysis [14–19], the majority of studies to date have utilised IMUs for activity recognition and spatiotemporal parameters [7,20–24]. Furthermore, it is recognised that running biomechanics change with increasing speed [4,25–27]; but as velocity increases, the precision of IMU outputs may change [28–30]. Thus, in order to confidently utilise IMUs in the field, it is necessary to validate relevant biomechanical variables at speeds pertinent to the activity of interest.

The primary aim of this study was to validate the use of a multisensor IMU system for biomechanical lower limb kinematic analysis at point of contact (POC) during incremental high-speed running. Sagittal plane angles of the shank, knee, hip and pelvis were evaluated. The secondary aim of this study was to determine whether the existing IMU system was able to accurately measure stride time during incremental running.

2. Materials and Methods

The academic institution's Human Research Ethics Board approved this protocol (project number 2018/133). One female sprinter (Age: 29 years, height: 1.65 m, weight: 58 kg) was recruited and provided informed consent to participate in two trials involving incremental running on a conventional treadmill, two weeks apart. She fulfilled the following approved inclusion criteria: aged between 18–50 years old, regularly participated (at least 1x/week) in a sport or exercise that requires high-speed running over the last 6 weeks, no musculoskeletal injury within the last 3 months, no neurological conditions, no lower extremity surgery within the last year and a body mass index less than 30.

The IMU system trialled in this study was the Noraxon 'MyoMOTION' sensor and software (Noraxon USA Inc., Scottsdale, AZ, USA, Model 680 receiver, Model 610 sensor, MR 3.16 software). The IMUs used for this research had >8 h operating time (3 h to recharge), were 37.6 mm × 52 mm × 18.1 mm in size, weighed 34 g, and could sample at rates up to 200 Hz and had a Gyro speed of 2000 deg/s with an acceleration range of 16G.

A 14 camera MAS (Eagle and Cortex 1.1.4.368, Motion Analysis Corporation, Santa Rosa, CA, USA) was utilised as the gold standard comparison for capturing 3D motion of the shank, thigh and pelvis segments at a sampling rate of 200 Hz. Positioned in the centre of the 4 m × 3 m × 3 m capture volume was a conventional treadmill (Model FQTM250, Fitquip, Scarborough, Australia). The reference gold standard comparison for POC timing was determined via a force plate (Model 9287BA, Kistler, Winterthur, Switzerland) sampling at a rate of 200 Hz mounted directly below the left rear base of the treadmill. Once the treadmill was in position, the force plate was zeroed. The IMU system and MAS force platform were time synchronised via the Noraxon MyoSync device (Noraxon USA Inc.). This device generates a pulse to synchronise signals across multiple systems.

IMUs were secured unilaterally to the runner's left shank (Sensor 1) and left thigh (Sensor 2) with double-sided tape (Logemas Pty Ltd., Albion, Australia) and elastic adhesive bandage (Elastoplast, Beiersdorf Australia Pty Ltd., North Ryde, Australia). Sensor 1 was positioned approximately 3–4 cm above the lateral malleolus and Sensor 2 on the mid lateral thigh. The final IMU was worn centrally on the sacrum via a Noraxon myoMOTION pelvic strap (Sensor 3) and reinforced with rigid tape (Elastoplast, Beiersdorf Australia Pty Ltd., North Ryde, Australia). Vertical IMU alignment when standing was checked and ensured.

Twenty-two 12 mm retroreflective markers were adhered via double-sided tape to the pelvis and left leg (posterior superior iliac spines, anterior superior iliac spines, greater trochanter, lateral femoral epicondyle, medial femoral condyle, tibial tuberosity, head of fibula, lateral malleoli and medial malleoli, head of the first and fifth metatarsals, and the distal end of the hallux), including two 4 marker clusters on their lateral shank and

lateral thigh for more accurate tracking direction relative to joint centres [31]. Foot markers were also adhered via double-sided tape to standard running shoes in the corresponding position to palpated bony landmarks.

Once the retroreflective markers and IMUs were donned (as seen in Figure 1), calibration of both systems was conducted. Static reference data were collected simultaneously by the two systems with the runner standing on the centre of a conventional treadmill in order to determine the anatomical reference (zero) position for the lower limb kinematic data (Figure 2). A positive shank angle denoted inclination relative to the standing position.

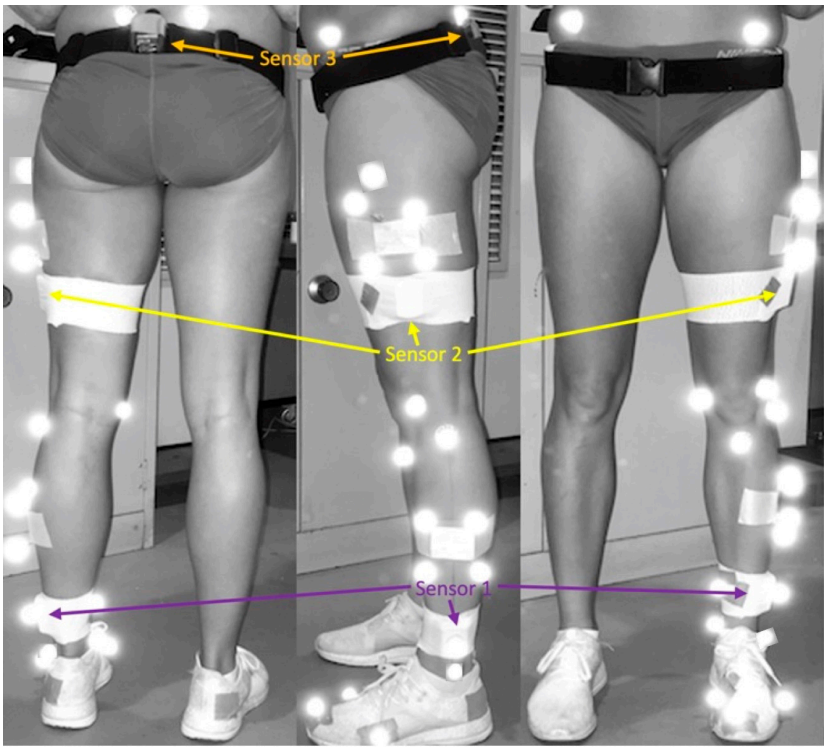

Figure 1. IMU and retroreflective marker set up.

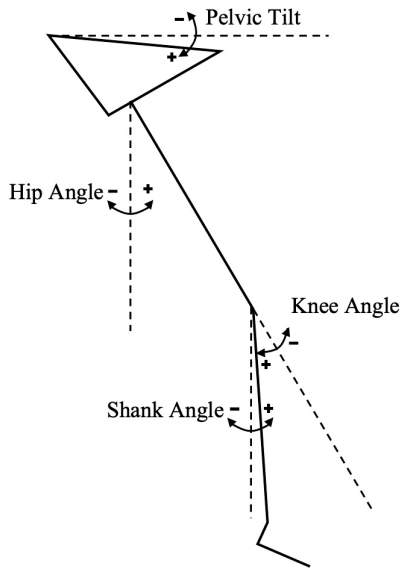

Figure 2. Kinematic data collected.

The runner conducted her own warm up consisting of graduated running and dynamic stretches before practicing the trial protocol. The runner was given five minutes to rest

between the practice and the trial. The runner was then instructed to perform incremental running at speeds of 12, 14, 16 and 18 km/h. The runner controlled the increase in speed, and once the target speed was achieved, she was instructed to remain in a steady state (neither accelerating nor decelerating) at each speed for at least 5 s.

Following the trial, MAS markers were reviewed and force plate POC checked for noise. Any marker switches were rectified and unidentified markers were named. The MAS trial capture of approximately 40 s (6–10 stride cycles per speed) was next exported into Visual 3D (Version 4.95, C-Motion Inc., Germantown, MD, USA) for segment definition and joint angle computation. A biomechanical model was created to develop virtual markers (based on bony landmark markers) for the pelvis, left hip joint centre, left knee joint centre, left tibial tuberosity centre and left malleolar centre. Thigh and shank clusters were utilised as target tracking markers. X, Y and Z axes in Visual 3D correspond to the medio-lateral, antero-posterior and axial anatomical axes. This biomechanical model enabled sagittal plane kinematics for the pelvis, hip, knee (Carden sequence X, Y, Z) and shank to be extracted (Carden sequence Y, Z, X). For joint calculation of the IMU data, the same segments were used.

Matlab (9.13.0 (R2022B), The MathWorks Inc., Natick, MA, USA) software was utilised for POC determination for MAS and IMU system trial data. For the MAS force plate data, POC was determined by a threshold selection of the summed vertical ground reaction force (Figure 3) and the first data point above the baseline force level. For the IMU system, POC was identified using the shank IMU's vertical, earth-based accelerometer data (axial axes). Shank accelerometer data were chosen to minimise impact transmission time lag from the collision point/feet to pelvis [32]. The first negative minima in acceleration trace after maximal hip flexion was manually identified for each stride cycle (Figure 3).

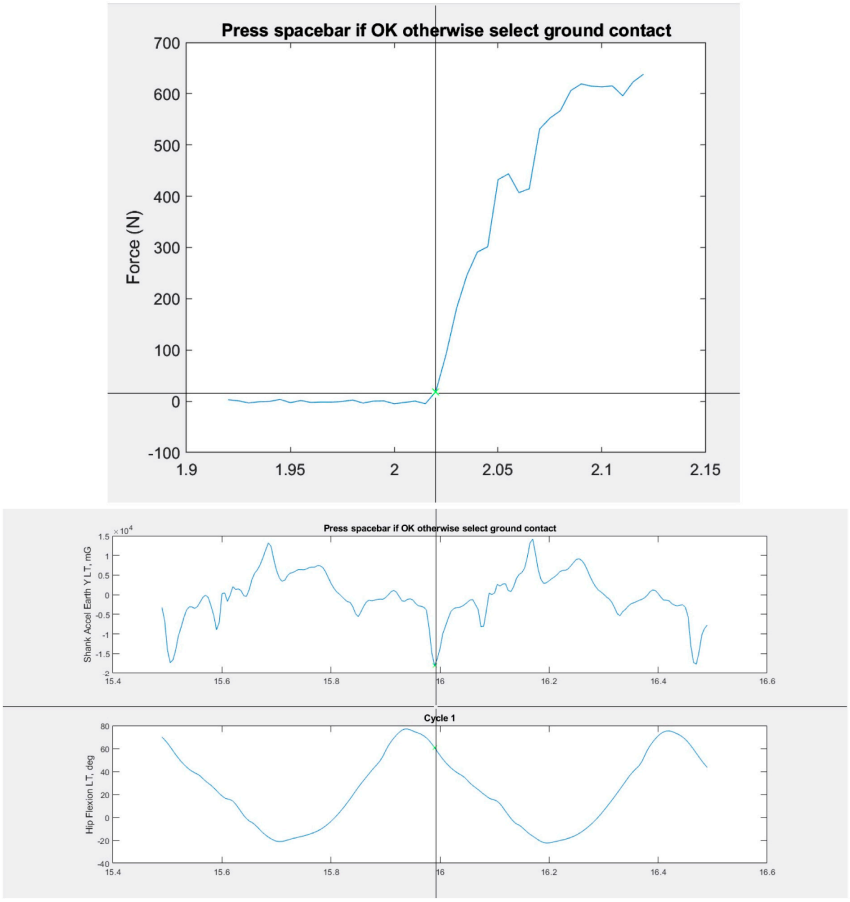

Figure 3. Matlab screenshots displaying Motion Analysis System point of contact identification (**top**) and Inertial Measurement System POC detection method (**bottom**).

Biomechanical data from both systems was then exported into Excel (Microsoft Corporation, Redmond, WA, USA, 2019) for visualisation and calculation of stride time (time between respective POCs). Review of a trial video on the IMU system enabled time stamp identification of each speed. Running data during transition between speeds were removed before statistical analysis. This entire trial protocol was repeated with the same participant on a second day, 2 weeks later. Noting one stride cycle was considered one sample, and at least six strides were collected for each of the four speeds over two occasions, the sample size was deemed appropriate for at least 80% power [33,34].

Statistical analysis was conducted via SPSS Statistics (IBM SPSS Software, version 15.0). Agreement in kinematics (sagittal plane pelvic, hip, knee and shank angle), stride time and POC between the systems were evaluated using single measures 2-way mixed effects, intra-class coefficients (ICCs) for absolute agreement, Pearson's *r* correlation (with 2-tailed significance value), root mean square error (RMSE) and paired *t*-tests. Bland–Altman Plots were used to evaluate potential directional bias for kinematic variables.

ICC values were a priori categorised as excellent (0.90 to 1.00), good (0.75 to 0.89), moderate (0.50 to 0.75) or poor (0.00 to 0.49) [35]. The magnitude of Pearson's *r* correlation coefficients were classified as very high (0.90 to 1.00), high (0.70 to 0.89), moderate (0.50 to 0.69), low (0.30 to 0.49) or negligible (0.00 to 0.30) [36]. We determined that a kinematic error (RMSE) between 2 and 5 degrees was considered an acceptable level based on common clinical situations [37]. We also calculated IMU system RMSE as a percentage of MAS mean in order to appreciate the clinical relevance for joint angles of varying size.

3. Results

Over 5 s at each speed (12, 14, 16 and 18 km/h), a total of 38 strides per trial, were collected. An example of kinematic data obtained through the entire stride cycle as identified by respective MAS and IMU system methods (before extraction of POC kinematic data) is displayed in Figure 4. Descriptive statistics for POC identification; sagittal plane pelvis, hip, knee and shank angle; and stride time are shown in Table 1 and Bland–Altman plots (Figure 5). Additional data provided in Appendix A include individual plots for each variable across speed.

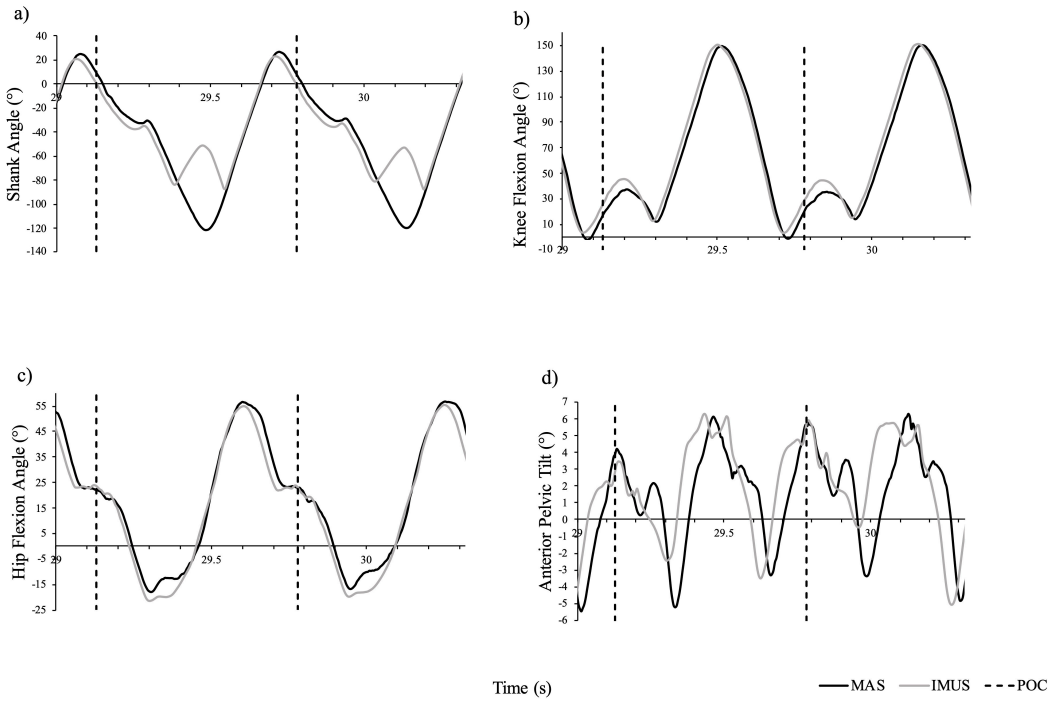

Figure 4. Sample sagittal angles for (**a**) shank, (**b**) knee, (**c**) hip and (**d**) pelvis as measured by the MAS (black) and the IMU system (grey) while running at 16 km/h.

Table 1. ICC, Pearson correlation coefficient, RMSE and *t*-test results for the IMUS and MAS at POC.

	Trial 1				Trial 2			
	ICC (95% CI), *p* Value	**Pearson's *r*, *p* Value**	**IMU System RMSE (% MAS Mean)**	**Paired *t*-Test MAS $\bar{x}$ (SD), IMU System $\bar{x}$ (SD), *p* Value**	**ICC (95% CI), *p* Value**	**Pearson's *r*, *p* Value**	**IMU System RMSE (% MAS Mean)**	**Paired *t*-Test MAS $\bar{x}$ (SD), IMU System $\bar{x}$ (SD), *p* Value**
POC Detection								
12 km/h	1.00 (1.00,1.00), <0.001 *	1.00, <0.001 *	0.005 s ^	5.44 (2.12), 5.44 (2.13), 0.003 *	1.00 (1.00,1.00), <0.001 *	1.00, <0.001 *	0.0052 s ^	6.15 (2.75), 6.15 (2.75), <0.001 *
14 km/h	1.00 (1.00,1.00), <0.001 *	1.00, <0.001 *	0.0043 s ^	18.98 (2.23), 18.98 (2.24), <0.001 *	1.00 (1.00,1.00), <0.001 *	1.00, <0.001 *	0.0052 s ^	22.33 (2.29), 22.33 (2.29), <0.001 *
16 km/h	1.00 (1.00,1.00), <0.001 *	1.00, <0.001 *	0.0155 s ^	31.40 (1.97), 31.40 (1.97), <0.001 *	1.00 (0.99,1.00), <0.001 *	1.00, <0.001 *	0.0047 s ^	34.94 (1.63), 34.94 (1.63), <0.001 *
18 km/h	1.00 (1.00,1.00), <0.001 *	1.00, <0.001 *	0.0038 s ^	41.94 (1.32), 41.94 (1.32), 0.030 *	1.00 (0.99,1.00), <0.001 *	1.00, <0.001 *	0.0076 s ^	44.70 (1.19), 44.70 (1.19), 0.010 *
POC Shank Angle								
12 km/h	0.04 (−0.01,0.26), 0.024 *	0.61, 0.060	6.84° (94.34%)	7.25 (1.44), 0.51 (1.28), <0.001*	0.11 (−0.01,0.44), <0.001 *	0.89, <0.001 *	5.81° (76.56%)	7.59 (1.57), 1.81 (1.46), <0.001 *
14 km/h	0.03 (−0.01,0.18), 0.037 *	0.55, 0.08	8.20° (88.28%)	9.29 (1.55), 1.19 (1.21), <0.001*	0.02 (−0.01,0.14), 0.012 *	0.71, 0.015 *	7.83° (91.96%)	8.51 (1.27), 0.73 (0.81), <0.001 *
16 km/h	0.01 (−0.00,0.06), 0.680	0.48, 0.155	10.09° (88.44%)	11.41 (1.03), 1.36 (0.87), <0.001*	0.05 (−0.01,0.30), 0.004 *	0.82, 0.012 *	8.50° (80.97%)	10.50 (1.64), 2.05 (1.38), <0.001 *
18 km/h	0.01 (−0.01,0.12), 0.202	0.42, 0.35	10.13° (88.71%)	11.42 (0.89), 1.39 (1.70), <0.001*	−0.00 (−0.01,0.07), 0.580	−0.09, 0.858	10.08° (83.36%)	12.09 (1.12), 2.12 (1.22), <0.001 *
POC Knee Angle								
12 km/h	0.08 (−0.03,0.40), 0.030 *	0.60, 0.067	7.30° (43.17%)	16.90 (2.27), 23.98 (1.78), <0.001 *	0.06 (−0.01,0.31), <0.001 *	0.81, <0.001 *	9.03° (56.98%)	15.85 (1.96), 24.81 (1.73), <0.001 *
14 km/h	0.08 (−0.01,0.39), <0.001 *	0.81, 0.003 *	8.20° (50.37%)	16.28 (2.10), 24.39 (1.80), <0.001 *	0.00 (−0.00,0.04), 0.204	0.27, 0.429	10.89° (68.21%)	15.97 (1.10), 26.80 (0.94), <0.001 *
16 km/h	0.01 (−0.01,0.06), 0.158	0.35, 0.324	10.83° (68.59%)	15.79 (0.99), 26.55 (1.32), <0.001 *	0.00 (−0.00,0.04), 0.338	0.17, 0.68	12.11° (79.94%)	15.15 (1.29), 27.18 (0.89), <0.001 *
18 km/h	0.07 (−0.01,0.42), 0.014 *	0.81, 0.029 *	10.07° (61.74%)	16.31 (1.88), 26.26 (2.65), <0.001 *	−0.01 (−0.01,0.04), 0.915	−0.61, 0.195	12.66° (82.23%)	15.40 (1.30), 27.92 (0.94), <0.001 *
POC Hip Angle								
12 km/h	0.87 (0.36,0.97), <0.001 *	0.92, <0.001 *	0.86° (3.97%)	21.61 (1.63), 22.19 (1.62), 0.021 *	0.88 (0.64,0.96), <0.001 *	0.88, <0.001 *	0.52° (2.38%)	21.61 (0.94), 21.69 (1.12), 0.579
14 km/h	0.86 (0.49,0.96), <0.001 *	0.90, <0.001 *	0.68° (2.93%)	23.17 (1.26), 23.58 (1.29), 0.041 *	0.53 (−0.09,0.87), <0.001 *	0.84, <0.001 *	1.20° (5.22%)	22.95 (0.94), 24.02 (1.02), <0.001 *
16 km/h	0.69 (0.04,0.92), 0.002 *	0.84, 0.003 *	1.34° (5.66%)	23.66 (1.32), 24.59 (1.81), 0.017 *	0.70 (−0.09,0.94), <0.001 *	0.88, 0.004 *	1.39° (5.82%)	23.95 (1.60), 25.12 (1.65), 0.005 *
18 km/h	0.54 (−0.13,0.90), 0.065	0.74, 0.055	1.31° (5.80%)	22.61 (0.82), 21.93 (1.69), 0.186	0.65 (−0.09,0.94), 0.020 *	0.78, 0.066	1.02° (4.14%)	24.72 (1.17), 25.49 (1.06), 0.052

Table 1. *Cont.*

	Trial 1				Trial 2			
	ICC (95% CI), *p* Value	**Pearson's *r*, *p* Value**	**IMU System RMSE (% MAS Mean)**	**Paired *t*-Test MAS $\bar{x}$ (SD), IMU System $\bar{x}$ (SD), *p* Value**	**ICC (95% CI), *p* Value**	**Pearson's *r*, *p* Value**	**IMU System RMSE (% MAS Mean)**	**Paired *t*-Test MAS $\bar{x}$ (SD), IMU System $\bar{x}$ (SD), *p* Value**
POC Pelvis Angle								
12 km/h	0.96 (0.43,0.99), <0.001 *	0.99, <0.001 *	0.47° (17.11%)	2.77 (1.74), 2.38 (1.77), 0.002 *	0.42 (−0.05,0.81), <0.001 *	0.88, <0.001 *	1.24° (43.04%)	2.89 (0.88), 4.06 (0.72), <0.001 *
14 km/h	0.95 (0.48,0.99), <0.001 *	0.98, <0.001 *	0.46° (17.55%)	2.61 (1.43), 2.26 (1.52), 0.003 *	0.68 (−0.04,0.93), <0.001 *	0.96, <0.001 *	1.04° (39.92%)	2.61 (1.08), 3.60 (1.11), <0.001 *
16 km/h	0.82 (0.13,0.96), <0.001 *	0.91, 0.011 *	0.86° (22.84%)	3.77 (1.30), 3.12 (1.46), 0.008 *	0.84 (0.07,0.97), <0.001 *	0.92, 0.001 *	0.89° (25.99%)	3.44 (1.46), 4.14 (1.54), 0.012 *
18 km/h	0.72 (0.11,0.94), 0.018 *	0.82, 0.023 *	0.73° (13.62%)	5.33 (0.71), 4.97 (1.14), 0.216	0.88 (0.17,0.98), 0.001 *	0.93, 0.006	0.43° (9.58%)	4.51 (0.85), 4.18 (0.85), 0.048 *
Stride Time								
12 km/h	0.78 (0.32,0.94), 0.003 *	0.76, 0.01 *	0.0047 s (0.68%)	0.70 (0.01), 0.07 (0.01), 0.758	0.94 (0.80,0.98), <0.001 *	0.94, <0.001 *	0.0039 s (0.56%)	0.71 (0.01), 0.71 (0.01), 1.0
14 km/h	0.88 (0.60,0.96), <0.001 *	0.87, <0.001 *	0.0040 s (0.59%)	0.67 (0.01), 0.67 (0.01), 0.724	0.87 (0.59,0.96), <0.001 *	0.88, <0.001 *	0.0034 s (0.49%)	0.69 (0.01), 0.69 (0.01), 0.676
16 km/h	0.72 (0.19,0.92), 0.008 *	0.76, 0.011 *	0.0042 s (0.64%)	0.65 (0.01), 0.65 (0.00), 0.726	0.99 (0.96,0.99), <0.001 *	0.99, <0.001 *	0.0018 s (0.26%)	0.67 (0.01), 0.67 (0.01), 0.351
18 km/h	0.89 (0.46, 0.98), 0.002 *	0.90, 0.006 *	0.0038 s (0.62%)	0.61 (0.01), 0.61 (0.01), 1.00	0.21 (−0.88,0.85), 0.346	0.19, 0.725	0.0061 s (0.96%)	0.64 (0.01), 0.64 (0.00), 0.771

^ No %MAS mean recorded as data reflects a time stamp; * *p* value < 0.05; ICC—Intraclass Correlation Coefficient; RMSE—Root Mean Square Error; $\bar{x}$—Mean; SD—Standard Deviation.

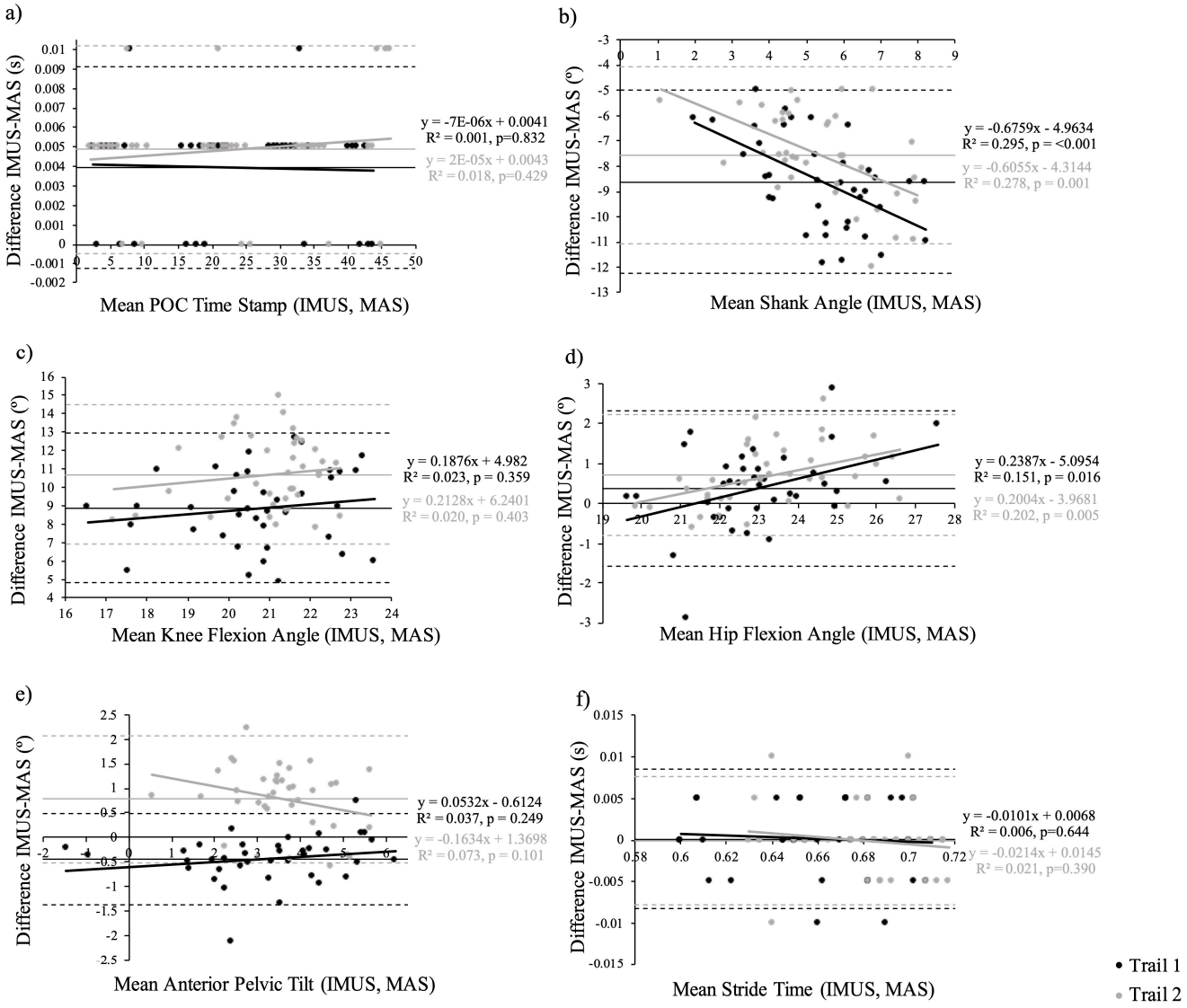

Figure 5. Bland–Altman Plots (mean difference plotted against the average of each measurement pair) for (**a**) point of contact (POC), (**b**) shank angle, (**c**) knee flexion angle, (**d**) hip flexion angle, (**e**) anterior pelvic tilt and (**f**) stride time for Trial 1 (black) and Trial 2 (grey).

POC was consistently determined by the IMU system (ICC 1.0 for all speeds across both trials) and had a perfect linear correlation with the MAS (Pearson's *r* values of 1.0 for all speeds across both trials). RMSE revealed a high level of accuracy (0.0038–0.0155 s across both trials); however, the paired *t*-test revealed a significant difference for both trials ($p < 0.030$ for all speeds). This may be explained within the Bland–Altman plot, which displayed a minor offset error (0–0.01 s).

The IMU system was inconsistent in measuring shank inclination (ICC 'poor' at all speeds over both trials). Pearson's *r* values were variable and tended to decrease to 'negligible' as speed increased to 18 km/h. Accuracy of shank inclination was also poor, with RMSE reported as 80–94% of MAS mean and significant differences in paired *t*-tests over all speeds in both trials. Both systematic and offset errors were evident on the Bland–Altman plot.

The IMU system also performed inconsistently in measuring knee flexion (ICC 'poor' across all speeds in both trials). Pearson's *r* values were inconsistent and varied from 'poor' to 'high' across speeds and trials. Accuracy was likewise poor and decreased with speed (RMSE ranged from 7 to 12° or 43–82% MAS mean). The paired *t*-test also revealed a

significant difference between variables over all speeds in both trials. The Bland–Altman plot displayed offset error but no consistent systematic error.

Hip flexion was measured more consistently by the IMU system (ICC 'high' to 'moderate' with increasing speed for both trials). A strong linear correlation with the reference MAS was evident (Pearson's *r* values were 'very high' or 'high' across speeds for both trials). The majority of paired *t*-tests were significant; however, accuracy was very good, with an RMSE of <1.4° (<6% of MAS mean) across all speeds in both trials. The Bland–Altman plot revealed minor offset error.

Sagittal plane pelvic tilt was also measured with reasonable consistency by the IMU system (ICC T1 speed 12 and 14 km/h 'very high', speed 16 km/h 'high', speed 18 km/h 'moderate; T2 speed 12 km/h 'poor', speed 14 km/h 'moderate, speed 16 and 18 km/h 'high'). Pearson's *r* analysis demonstrated a 'very high' linear correlation between the systems across both trials, with the exception of T1 speed 18 km/h and T2 speed 12 km/h, which were reported as 'high'. Accuracy was fair, with an RMSE of <0.9° in T1 (13–22% of MAS mean) and <1.3° in T2 (9–40% of MAS mean). Paired *t*-tests revealed a significant difference across all speeds except speed 18 km/h for both trials. Minimal offset error was evident on the Bland–Altman plot.

The IMU system measured stride time with reasonable consistency as well (ICC varied between 'moderate' to 'very high' except for being 'poor' for Trail 2 at 18 km/h). A linear correlation was evident in all speeds across both trials (Pearson's *r* values of 'very high' or 'high') except T2 speed 18 (Pearson's *r* 'negligible'). Accuracy was excellent (RMSE 0.00–0.01 s across all trials, <1% of MAS mean).

4. Discussion

This study assessed the validity in the use of a multisensor IMU system for biomechanical lower limb kinematic analysis at POC and stride time during incremental high-speed running. The IMU system accurately and consistently determined POC, which subsequently was used to calculate stride time. The IMU system demonstrated an acceptable degree of error and was consistent in measuring hip flexion angle and anterior pelvic tilt, but was inaccurate and inconsistent for knee flexion and shank angle.

Although our 200 Hz IMU system detected POC with excellent consistency and a very high level of accuracy, a negligible offset error of approximately one sample (0.005 s) was evident. Sinclair et al. described similar findings when validating 1000 Hz shank-mounted accelerometers for POC detection during conventional treadmill running at approximately 14 km/h. They reported very good correspondence between the reference standard force place and accelerometer methods, but noted an equivalent level of absolute error [38]. Other studies may have attempted to correct this time lag by using sensors closer to the collision point, i.e., the foot [32], though accuracy of spatiotemporal parameters with foot mounted sensors is variable and dependant on sensor position on the foot [39,40]. For this protocol, it would not be worthwhile including an additional foot sensor as, statistically, the shank sensor detected POC with a high level of accuracy. Nevertheless, algorithmic adjustment may be an option should a consistent offset (subject, speed or system specific) be considered pertinent in future trials, particularly if the IMU system has a lower sampling rate. Sampling rates of 200 Hz or greater are associated with improved agreement levels when compared to reference systems [41].

From a kinematic perspective, the ability to definitively compare our findings with other studies is challenging. A limited number of comparable studies exist within the literature [42], utilising varying IMU systems with differing technical specifications and methodologies. Nuesch et al. compared outputs from a 400 Hz IMU system against an optoelectronic MAS during conventional running. Running kinematic data were collected at a participant-selected average speed of 10.5 km/h [43]. They reported that their IMU system underestimated both hip and knee flexion angle at POC, with RMSEs of 19.3 and 36.1 degrees, respectively. Conversely, the IMU system in the current study overestimated knee flexion and demonstrated only a trivial overestimation of hip flexion at POC, but

with RMSEs at 12 km/h of only 9.03 and 0.52 degrees, respectfully. Lin et al. reported that their IMU system was effective at estimating hip and knee flexion angles throughout the gait cycle on a nonmotorised treadmill, but reported poor accuracy for anterior pelvic tilt (when compared to an optical MAS). However, their participants were running faster (approximately 19 to 25 km/h), while their IMU system collected data at 100 Hz [44]. Similarly, the 500 Hz IMU system evaluated against the optoelectronic MAS in Ruiz-Malagon et al.'s validation study tested poorly for pelvic kinematic measurements during treadmill running at up to 15 km/h [45].

Our results indicate that the IMU system in this study is not recommended for sagittal plane knee and shank measurements at POC. Noting the shank IMU is a critical determinant of knee position, it is no surprise that, following poor results for shank angle, knee flexion also tested poorly. The IMU system significantly overestimated knee flexion and shank angle at POC by >7°. Particularly at the shank, this offset worsened with increased speed. Higher levels of validity seem to be associated with how close the sensor was to the area of interest [41]. This may be an explanation as to why the pelvic sensor alone accurately measured anterior pelvic tilt; the pelvic and thigh sensors accurately measured hip flexion, but the thigh and shank sensors inaccurately measured knee and shank angle. It is plausible that the shank sensor was positioned too distal on the lower leg. More research is needed to understand the effect of placement and its impact on data collection.

An interesting point to note on the example kinematic data obtained through the entire stride cycle (Figure 4) is a flip in the shank pitch angle between POCs. Although this issue was not pertinent for this study (as we were only interested in POC data), upon discussing this with the manufacturer (Noraxon USA Inc.), it appears that the matter could be related to sensor saturation and quaternions. Noraxon has stated that their newer model 'Ultium' has been configured to address this issue.

When interpreting the results of the present study, we must acknowledge the methodological limitations. Firstly, the single case design may affect the generalisability of findings. The results may vary with gender, age, and extrinsic (footwear, running surface) and intrinsic differences (e.g., foot strike pattern, velocity) [46]. Peak impact force will vary depending on foot strike pattern type (e.g., rearfoot, midfoot or forefoot). At slower speeds, distance runners tend to rear foot strike, whereas sprinters adopt a forefoot strike [47]. At speeds greater than 18 km/h, most runners who rearfoot strike at slower speeds transition to a mid or forefoot strike pattern [48]. Strike type tends to also be associated with footwear. Habitually shod runners mostly have a rearfoot strike, whereas runners who are habitually barefoot or wear minimalistic shoes mostly strike at the fore or midfoot [49].

Running surface is another factor to consider when interpreting the findings. This study was conducted on a conventional treadmill. When compared to overground, runners on conventional treadmills elicit biomechanical differences including extended step (contact) times and increased knee extension at POC. These findings can be attributed to the hypothesis that a conventional treadmill contributes to hip extension, as the belt moves the lower extremity backwards [50]. Although overground running would have been preferred, the conventional treadmill enabled greater control of running velocity in order to differentiate between speeds for the purposes of incremental validation. Additionally, environmental constraints of the current MAS laboratory disallowed the collection of multiple strides at different overground speeds.

Another important point to note is the use of externally secured markers and wearable sensors and the resultant soft tissue artifact risk. Soft tissue artifact refers to the mobility or 'wobbling' of markers on the skin with movement [51,52]. IMUs and clusters secured in the middle of body segments are particularly susceptible to this due to changes in muscle contour. Despite optimisation of MAS single marker position on bony landmarks, these too are subject to motion artifact with impact [53]. Thus, with increasing running speed and subsequent impacts, both systems are suspectable to measurement errors associated with soft tissue impact [54]. This issue is obviously not unique to this study alone and

is a limitation that should be considered in all studies utilising wearable markers and technology.

Overall, the results of this single female participant study suggest that the IMU system described (Noraxon 'MyoMOTION') demonstrated appropriate agreement with the gold standard MAS for sagittal plane pelvic and hip kinematics at POC and stride time determination during high-speed running. At the same time, this study found that the IMU system described is not recommended for knee flexion or shank angle at POC. Further testing of other IMU systems and additional subjects is required to enable generalisation of findings. Nonetheless, these preliminary findings suggest that that the IMU system described enables sophisticated analysis of the validated running variables of interest out-field, which in turn can be used to optimise performance and/or inform injury prevention programs.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Committee of THE UNIVERSITY OF SYDNEY (protocol code 2018/133).

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

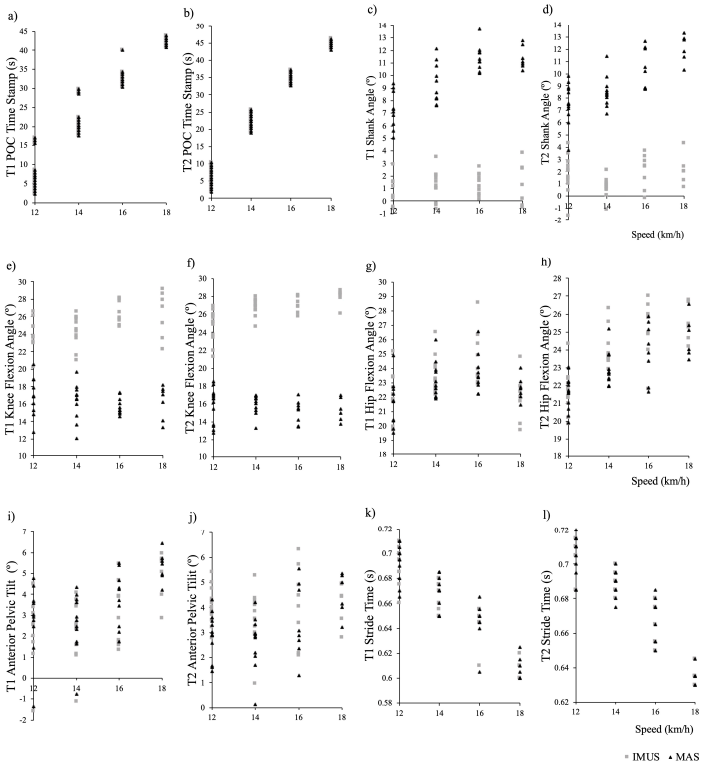

Figure A1. (**a**–**l**): Plots of individual study variables across speed for each trial (T1, T2). Point of contact (POC) is denoted in figures (**a**,**b**), shank angle (°) in (**c**,**d**), knee flexion angle (°) in (**e**,**f**), hip flexion angle (°) in (**g**,**h**), anterior pelvic tilt in Figures (**i**,**j**) and, stride time (s) in (**k**,**l**).

References

1. Mendiguchia, J.; Castaño-Zambudio, A.; Jiménez-Reyes, P.; Morin, J.B.; Edouard, P.; Conceição, F.; Tawiah-Dodoo, J.; Colyer, S.L. Can we modify maximal speed running posture? Implications for performance and hamstring injury management. *Int. J. Sports Physiol. Perform.* **2021**, *17*, 374–383. [CrossRef] [PubMed]
2. Barton, C.J.; Bonanno, D.R.; Carr, J.; Neal, B.S.; Malliaras, P.; Franklyn-Miller, A.; Menz, H.B. Running retraining to treat lower limb injuries: A mixed-methods study of current evidence synthesised with expert opinion. *Br. J. Sports Med.* **2016**, *50*, 513–526. [CrossRef] [PubMed]
3. Ceyssens, L.; Vanelderen, R.; Barton, C.; Malliaras, P.; Dingenen, B. Biomechanical risk factors associated with running-related injuries: A systematic review. *Sports Med.* **2019**, *49*, 1095–1115. [CrossRef] [PubMed]
4. Weyand, P.G.; Sternlight, D.B.; Bellizzi, M.J.; Wright, S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J. Appl. Physiol.* **2000**, *89*, 1991–1999. [CrossRef]
5. Willy, R. Innovations and pitfalls in the use of wearable devices in the prevention and rehabilitation of running related injuries. *Phys. Ther. Sport* **2018**, *29*, 26–33. [CrossRef]
6. Colyer, S.L.; Evans, M.; Cosker, D.P.; Salo, A.I.T. A review of the evolution of vision-based motion analysis and the integration of advanced computer vision methods towards developing a markerless system. *Sports Med.* **2018**, *4*, 24. [CrossRef]
7. Camomilla, V.; Bergamini, E.; Fantozzi, S.; Vannozzi, G. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: A systematic review. *Sensors* **2018**, *18*, 873. [CrossRef]
8. Faisal, A.; Majumder, S.; Mondal, T.; Cowan, D.; Naseh, S.; Deen, M. Monitoring methods of human body joints: State-of-the-art and research challenges. *Sensors* **2019**, *19*, 2629. [CrossRef]
9. Luinge, H.J.; Veltink, P.H. Measuring orientation of human body segments using miniature gyroscopes and accelerometers. *Med. Biol. Eng. Comput.* **2005**, *43*, 273–282. [CrossRef]
10. Potter, M.; Ojeda, L.; Perkins, N.; Cain, S. Effect of IMU Design on IMU-derived stride metrics for running. *Sensors* **2019**, *19*, 2601. [CrossRef]
11. Pacini Panebianco, G.; Bisi, M.C.; Stagni, R.; Fantozzi, S. Analysis of the performance of 17 algorithms from a systematic review: Influence of sensor position, analysed variable and computational approach in gait timing estimation from IMU measurements. *Gait Posture* **2018**, *66*, 76–82. [CrossRef]
12. Kenneally-Dabrowski, C.J.; Serpell, B.G.; Spratford, W. Are accelerometers a valid tool for measuring overground sprinting symmetry? *Int. J. Sports Sci. Coach.* **2018**, *13*, 270–277. [CrossRef]
13. Gurchiek, R.D.; McGinnis, R.S.; Needle, A.R.; McBride, J.M.; van Werkhoven, H. The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *J. Biomech.* **2017**, *61*, 263–268. [CrossRef] [PubMed]
14. Nagahara, R.; Kameda, M.; Neville, J.; Morin, J.-B. Inertial measurement unit-based hip flexion test as an indicator of sprint performance. *J. Sports Sci.* **2020**, *38*, 53–61. [CrossRef]
15. Milner, C.E.; Ferber, R.; Pollard, C.D.; Hamill, J.; Davis, I. Biomechanical factors associated with tibial stress fracture in female runners. *Med. Sci. Sports Exerc.* **2006**, *38*, 323–328. [CrossRef]
16. Struzik, A.; Konieczny, G.; Stawarz, M.; Grzesik, K.; Winiarski, S.; Rokita, A. Relationship between lower limb angular kinematic variables and the effectiveness of sprinting during the acceleration phase. *Appl. Bionics Biomech.* **2016**, *2016*, 7480709. [CrossRef] [PubMed]
17. Toyoshima, R.; Sakurai, S. Kinematic characteristics of high step frequency sprinters and long step length sprinters at top speed phase. *Int. J. Sport Health Sci.* **2016**, *14*, 41–50. [CrossRef]
18. Bergamini, E.; Guillon, P.; Camomilla, V.; Pillet, H.; Skalli, W.; Cappozzo, A. Trunk inclination estimate during the sprint start using an inertial measurement unit: A validation study. *J. Appl. Biomech.* **2013**, *29*, 622–627. [CrossRef]
19. Raper, D.P.; Witchalls, J.; Philips, E.J.; Knight, E.; Drew, M.K.; Waddington, G. Use of a tibial accelerometer to measure ground reaction force in running: A reliability and validity comparison with force plates. *J. Sci. Med. Sport* **2018**, *21*, 84–88. [CrossRef]
20. Mason, R.; Pearson, L.T.; Barry, G.; Young, F.; Lennon, O.; Godfrey, A.; Stuart, S. Wearables for running gait analysis: A systematic review. *Sports Med.* **2023**, *53*, 241–268. [CrossRef]
21. García-Pinillos, F.; Latorre-Román, P.; Soto-Hermoso, V.; Párraga-Montilla, J.; Pantoja-Vallejo, A.; Ramírez-Campillo, R.; Roche-Seruendo, L. Agreement between the spatiotemporal gait parameters from two different wearable devices and high-speed video analysis. *PLoS ONE* **2019**, *14*, e0222872. [CrossRef] [PubMed]
22. Brahms, C.M.; Zhao, Y.; Gerhard, D.; Barden, J.M. Stride length determination during overground running using a single foot-mounted inertial measurement unit. *J. Biomech.* **2018**, *71*, 302–305. [CrossRef] [PubMed]
23. Dideriksen, O.M.; Soegaard, O.C.; Nielsen, O.R. Validity of self-reported running distance. *J. Strength Cond. Res.* **2016**, *30*, 1592–1596. [CrossRef] [PubMed]
24. Schmidt, M.; Rheinländer, C.; Nolte, K.F.; Wille, S.; Wehn, N.; Jaitner, T. IMU- based determination of stance duration during sprinting. *Procedia Eng.* **2016**, *147*, 747–752. [CrossRef]
25. Agresta, C.E.; Peacock, J.; Housner, J.; Zernicke, R.F.; Zendler, J.D. Experience does not influence injury-related joint kinematics and kinetics in distance runners. *Gait Posture* **2018**, *61*, 13–18. [CrossRef]
26. Brughelli, M.; Cronin, J.; Chaouachi, A. Effects of running velocity on running kinetics and kinematics. *J. Strength Cond. Res.* **2011**, *25*, 933–939. [CrossRef]

27. Fukuchi, R.; Fukuchi, C.; Duarte, M. A public dataset of running biomechanics and the effects of running speed on lower extremity kinematics and kinetics. *PeerJ PrePrints* **2017**, *5*, e3298. [CrossRef]
28. Lebel, K.; Boissy, P.; Hamel, M.; Duval, C. Inertial measures of motion for clinical biomechanics: Comparative assessment of accuracy under controlled conditions—Effect of velocity. *PLoS ONE* **2013**, *8*, e79945. [CrossRef]
29. Provot, T.; Chiementin, X.; Oudin, E.; Bolaers, F.; Murer, S. Validation of a high sampling rate inertial measurement unit for acceleration during running. *Sensors* **2017**, *17*, 1958. [CrossRef]
30. Falbriard, M.; Meyer, F.; Mariani, B.; Millet, G.P.; Aminian, K. Accurate estimation of running temporal parameters using foot-worn inertial sensors. *Front. Physiol.* **2018**, *9*, 610. [CrossRef]
31. Buczek, F.L.; Rainbow, M.J.; Cooney, K.M.; Walker, M.R.; Sanders, J.O. Implications of using hierarchical and six degree-of-freedom models for normal gait analyses. *Gait Posture* **2010**, *31*, 57–63. [CrossRef] [PubMed]
32. Mo, S.; Chow, D.H.K. Accuracy of three methods in gait event detection during overground running. *Gait Posture* **2018**, *59*, 93–98. [CrossRef] [PubMed]
33. Donner, A.; Eliasziw, M. Sample size requirements for reliability studies. *Stat. Med.* **1987**, *6*, 441–448. [CrossRef] [PubMed]
34. Shoukri, M.M.; Asyali, M.H.; Donner, A. Sample size requirements for the design of reliability study: Review and new results. *Stat. Methods Med. Res.* **2004**, *13*, 251–271. [CrossRef]
35. Koo, T.K.; Li, M.Y. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J. Chiropr. Med.* **2016**, *15*, 155–163. [CrossRef] [PubMed]
36. Mukaka, M. Statistics corner: A guide to appropriate use of correlation in medical research. *Malawi Med. J.* **2012**, *24*, 69–71.
37. Cuesta-Vargas, A.I.; Galán-Mercant, A.; Williams, J.M. The use of inertial sensors system for human motion analysis. *Phys. Ther. Rev.* **2010**, *15*, 462–473. [CrossRef]
38. Sinclair, J.; Hobbs, S.J.; Protheroe, L.; Edmundson, C.J.; Greenhalgh, A. Determination of gait events using an externally mounted shank accelerometer. *J. Appl. Biomech.* **2013**, *29*, 118–122. [CrossRef]
39. Zrenner, M.; Küderle, A.; Roth, N.; Jensen, U.; Dümler, B.; Eskofier, B.M. Does the position of foot-mounted IMU sensors influence the accuracy of spatio-temporal parameters in endurance running? *Sensors* **2020**, *20*, 5705. [CrossRef]
40. Küderle, A.; Roth, N.; Zlatanovic, J.; Zrenner, M.; Eskofier, B.; Kluge, F. The placement of foot-mounted IMU sensors does affect the accuracy of spatial parameters during regular walking. *PLoS ONE* **2022**, *17*, e0269567. [CrossRef]
41. Macadam, P.; Cronin, J.; Neville, J.; Diewald, S. Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: A systematic review. *Gait Posture* **2019**, *73*, 26–38. [CrossRef]
42. Zeng, Z.; Liu, Y.; Hu, X.; Tang, M.; Wang, L. Validity and reliability of inertial measurement units on lower extremity kinematics during running: A systematic review and meta-analysis. *Sports Med.* **2022**, *8*, 86. [CrossRef]
43. Nüesch, C.; Roos, E.; Pagenstert, G.; Mündermann, A. Measuring joint kinematics of treadmill walking and running: Comparison between an inertial sensor based system and a camera-based system. *J. Biomech.* **2017**, *57*, 32–38. [CrossRef] [PubMed]
44. Lin, Y.-C.; Price, K.; Carmichael, D.S.; Maniar, N.; Hickey, J.T.; Timmins, R.G.; Heiderscheit, B.C.; Blemker, S.S.; Opar, D.A. Validity of inertial measurement units to measure lower-limb kinematics and pelvic orientation at submaximal and maximal effort running speeds. *Sensors* **2023**, *23*, 9599. [CrossRef]
45. Ruiz-Malagón, E.J.; García-Pinillos, F.; Molina-Molina, A.; Soto-Hermoso, V.M.; Ruiz-Alias, S.A. RunScribe Sacral Gait Lab™ validation for measuring pelvic kinematics during human locomotion at different speeds. *Sensors* **2023**, *23*, 2604. [CrossRef]
46. Lai, Y.-J.; Chou, W.; Chu, I.H.; Wang, Y.-L.; Lin, Y.-J.; Tu, S.J.; Guo, L.-Y. Will the foot strike pattern change at different running speeds with or without wearing shoes? *Int. J. Environ. Res. Public Health* **2020**, *17*, 6044. [CrossRef] [PubMed]
47. Dicharry, J.M.P.T. Kinematics and kinetics of gait: From lab to clinic. *Clin. Sports Med.* **2010**, *29*, 347–364. [CrossRef] [PubMed]
48. Forrester, S.E.; Townend, J. The effect of running velocity on footstrike angle—A curve-clustering approach. *Gait Posture* **2015**, *41*, 26–32. [CrossRef]
49. Lieberman, D.E.; Venkadesan, M.; Werbel, W.A.; Daoud, A.I.; Mang'Eni, R.O.; D'Andrea, S.; Davis, I.S.; Pitsiladis, Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* **2010**, *463*, 531–535. [CrossRef]
50. McKenna, M.; Riches, P.E. A comparison of sprinting kinematics on two types of treadmill and over-ground. *Scand. J. Med. Sci. Sports* **2007**, *17*, 649–655. [CrossRef]
51. Camomilla, V.; Dumas, R.; Cappozzo, A. Human movement analysis: The soft tissue artefact issue. *J. Biomech.* **2017**, *62*, 1–4. [CrossRef] [PubMed]
52. Bélaise, C.; Blache, Y.; Thouzé, A.; Monnet, T.; Begon, M. Effect of wobbling mass modeling on joint dynamics during human movements with impacts. *Multibody Syst. Dyn.* **2016**, *38*, 345–366. [CrossRef]
53. Bergmann, J.H.M.; Mayagoitia, R.E.; Smith, I.C.H. A portable system for collecting anatomical joint angles during stair ascent: A comparison with an optical tracking device. *Dyn. Med.* **2009**, *8*, 3. [CrossRef] [PubMed]
54. Zeng, Z.; Liu, Y.; Li, P.; Wang, L. Validity and reliability of inertial measurement units measurements for running kinematics in different foot strike pattern runners. *Front. Bioeng. Biotechnol.* **2022**, *10*, 1005496. [CrossRef] [PubMed]

Chapter 5: Utilising Inertial Measurement Units and Force–Velocity Profiling to Explore the Relationship Between Hamstring Strain Injury and Running Biomechanics

5.1 Outline

This chapter presents the culminating field-based observational research which investigated running biomechanics as a risk factor for HSI. In one combined study, cross sectional comparison of athletes with history of HSI compared to healthy controls is presented, followed by a one-year injury surveillance period and prospective analysis of the entire cohort. The IMU variables validated in the previous chapter, as well as force velocity profiling (previously validated by a separate research group) were used as portable methods for evaluating variances in running biomechanics. This research nests within Stage 2 of the TRIPP framework (exploring risk factors) and is presented in the style of the journal where it is published:

Wolski, L., Halaki, M., Hiller, C. E., Pappas, E., & Fong Yan, A. (2025). Utilising Inertial Measurement Units and Force–Velocity Profiling to Explore the Relationship Between Hamstring Strain Injury and Running Biomechanics. Sensors, 25(5), 1518. doi: 10.3390/s25051518

This observational study reported, at a cross-sectional level, a potential relationship between increased anterior pelvic tilt at POC and HSI and prospectively, an emerging relationship between a velocity-orientated profile and HSI. This study was the first of its kind to conduct both FVP and IMU kinematic analysis in a field-based settings. However, restrictions imposed with COVID-19 resulted in a significantly smaller than planned sample size. Nonetheless, the study was considered a valuable feasibility trial, offering several lessons learnt in the practical implementation of field-based technologies.

ADDITIONAL NOTES:

- *Supplementary methodological detail on cross-sectional and cohort study data collection procedures, including calculation of clinically meaning differences are contained in 'Appendix 2: Manual of Procedures'*
- *Respective ethics documentation including approval evidence, and template copies of the relevant recruitment letter, participant information and consent forms can be found in 'Appendix 4: Ethics Documentation'*
- *The two HSIs prospectively sustained in the study were reported by assessing physiotherapists as 1x 'long head biceps grade 1' and 1x 'Medial HS strain high gd 1/low gd 2'.*

sensors

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Article

Utilising Inertial Measurement Units and Force–Velocity Profiling to Explore the Relationship Between Hamstring Strain Injury and Running Biomechanics

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Abstract: The purpose of this study was to retrospectively and prospectively explore associations between running biomechanics and hamstring strain injury (HSI) using field-based technology. Twenty-three amateur sprinters performed 40 m maximum-effort sprints and then underwent a one-year injury surveillance period. For the first 30 m of acceleration, sprint mechanics were quantified through force–velocity profiling. In the upright phase of the sprint, an inertial measurement unit (IMU) system measured sagittal plane pelvic and hip kinematics at the point of contact (POC), as well as step and stride time. Cross-sectional analysis revealed no differences between participants with a history of HSI and controls except for anterior pelvic tilt (increased pelvic tilt on the injured side compared to controls). Prospectively, two participants sustained HSIs in the surveillance period; thus, the small sample size limited formal statistical analysis. A review of cohort percentiles, however, revealed both participants scored in the higher percentiles for variables associated with a velocity-oriented profile. Overall, this study may be considered a feasibility trial of novel technology, and the preliminary findings present a case for further investigation. Several practical insights are offered to direct future research to ultimately inform HSI prevention strategies.

Keywords: sensor; measurement; accelerometer; gait; biomechanics; sprint; kinematic; kinetic; spatiotemporal

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1. Introduction

Hamstring strain injury (HSI) is of considerable concern in high-speed running sports. With a particularly high incidence [1–6] and recurrence rate [1,2], HSI presents a significant challenge for clinicians and coaching staff. Age and previous history of HSI are well-established risk factors for HSI [3], but several other factors are considered to play a role, including high-speed running exposure [4], reduced flexibility [5], and decreased hamstring strength metrics [3]. While the role of the hamstrings in high-speed running is well researched and understood [6], the connection between running biomechanics and HSI remains less clear. This connection has been studied in two reviews [7,8], with both concluding emerging evidence suggests an association between running biomechanics and HSI, but more research is needed.

Kinematic experimental studies suggest lumbopelvic control, anterior pelvic tilt, forward trunk lean, trunk lateral flexion, and maximal hip flexion angle may be linked to

HSI [9]. From a kinetic perspective, decreased horizontal propulsive force is suggested to be associated with HSI [7]. The hamstrings play a major role in horizontal force production during high-speed running [10], making a compelling case for reduced horizontal force as a cause and/or consequence of HSI [11–14]. Further field-based evaluation of these variables is required to define thresholds for injury screening out of the lab environment, and subsequently inform prevention strategies.

The gold standard for biomechanical analysis is the Motion Analysis System (MAS). Although the MAS provides exceptional detail on spatiotemporal, kinematic, and kinetic biomechanical metrics, environmental constraints hinder its ability to accurately replicate movement in real-world contexts [6]. The 21st century has seen the introduction and development of various innovative field-based technologies, such as vision-based measurement systems [15–18], inertial measurement units (IMUs) [19–21], optical fibre technology [22,23], pressure sensing insoles [24,25], and force–velocity profiling (FVP) [26,27]. To investigate the aforementioned kinematic and kinetic variables of interest in a field-based setting, portable technology that is validated for use in high-speed running is required. Additionally, the technology should be relatively low-cost to enable adoption by sporting organisations for potential injury prevention initiatives. For the purposes of this study, IMU and FVP systems were considered the most appropriate field-based technologies.

Inertial measurement units (IMUs) are a growing, low-cost, portable technology for quantifying running biomechanics [28]. IMUs include three components: an accelerometer, a gyroscope, and a magnetometer, which provide measurements of three-dimensional linear acceleration, angular velocity, and orientation. Multiple calibrated IMUs can track joint angles, enabling kinematics analysis during functional activities [29,30]. Although IMUs can produce kinetic outputs through computational methods, their accuracy in predicting ground reaction forces is variable [31,32]. A recently published study validated an IMU system against the MAS for use in high-speed running [33]. The IMU system correctly identified the point of contact (POC), which was subsequently used to calculate stride time, and accurately measured the sagittal plane pelvic tilt and hip angle at the POC [33]. Unfortunately, the validation study found the IMU system to be inaccurate and inconsistent in measuring knee flexion and shank angles at the POC, making it unsuitable for such measurements [33]. The current study aimed to use the same IMU system in the field in order to retrospectively and prospectively analyse the relationship between validated outcomes; namely sagittal plane pelvis and hip kinematics at the POC, and HSI.

Sprint force–velocity profiling (FVP) is an innovative approach to characterising the kinetics of acceleration and sprint mechanical performance. The relationship between running velocity and the ability to generate horizontal force on the ground is described by the linear force–velocity model. Given that power results from force multiplied by velocity, the slope of the force–velocity relationship displays the contributions of force and velocity in achieving maximum horizontal power output [26,27]. Although the time over a given sprint distance may be the same between two athletes, their FVPs may be different, e.g., higher force or velocity orientation [34]. In the last decade, a simple computational method for determining FVP using only anthropometric and spatiotemporal data was validated against a track embedded with force plates [35]. Initially, high-speed digital cameras, radar technology, and timing gates were used to calculate times and velocity [35–38]. Shortly after, a simple iPhone application calculating split times for FVP modelling was also validated [39]. A secondary aim of our study was to utilise the iPhone application method in the field to retrospectively and prospectively analyse the relationship between FVP (as a representation of horizontal force production) and HSI.

The overall purpose of this study was to explore associations between running biomechanics and hamstring strain injury (HSI) using field-based technology. We hypothesised

that running biomechanics, namely spatiotemporal and kinematic variables as measured by an IMU system and FVP through an iPhone application, may significantly differ between participants with a history of HSI and controls. Retrospective and prospective analysis via a one-year injury surveillance will further inform which biomechanics variables may be a cause or consequence of HSI. Additionally, we aimed to offer 'lessons learnt' in using these novel technologies to direct future research.

2. Materials and Methods

2.1. Testing Protocol

The academic institution's Human Research Ethics Board approved this protocol (project number 2018/674). Athletes aged 17–50 years who actively participated in a sport involving sprinting and did not have a current medical condition or injury that affected their ability to sprint pain-free were invited to participate in the study. Twenty-three amateur sprinters were recruited to perform a single maximum-effort 40 m sprint (mean age 25.7 ± 10.6 years; height 1.76 ± 0.08 m; weight 72.1 ± 10.1 kg; 10 females, 13 males). A significantly larger sample size was originally planned (planned: G-power output based on power = 0.8, n = 109), including various professional rugby, football, and soccer clubs. Unfortunately, the occurrence of the COVID-19 pandemic drastically limited the ability to test and recruit. Therefore, the study reported here is a feasibility study aimed at providing practical insights and directing future research to ultimately inform HSI prevention strategies.

Testing was conducted individually over a two-week period (based on participant availability). Following trial familiarisation (both verbally and through written participant information), participants provided informed consent and baseline details (age, sex, height, weight, HSI history).

A 40 m track was set up on grass with a line of tape measure and large blue markers denoting start and finish. The FVP protocol was conducted in accordance with 'MySprint' iPhone application instructions (Version 1.10 installed on iPhone XR running iOS 13). Tall yellow agility poles were used to denote 5 m intervals for the first 30 m. Poles were offset to account for parallax error (as per Figure 1). Sprint trials were filmed with the iPhone's built-in camera on 'Slo-mo' for 1080 p at 240 fps, mounted on a tripod 10 m from the track enabling smooth rotational movement.

Five Noraxon 'MyoMOTION' IMUs and software (Noraxon USA Inc., Scottsdale, AZ, United States, Model 680 receiver, Model 610 sensor, MR 3.16 software) were used in this study for kinematic data capture during the steady-state phase of the 40 m sprint. The IMUs had >8 h operating time (3 h to recharge), were 37.6 mm × 52 mm × 18.1 mm in size, weighed 34 g, had a sampling rate of 200 Hz, a gyroscope speed of 2000 deg/s and an acceleration range of 16G, with ±1 degree in the sagittal and frontal plane and ±2 degrees in the transverse plane. The IMU system was previously validated against the gold standard MAS. The current setup replicated that of the validation [33].

IMUs were secured bilaterally to participants' shanks and thighs with double-sided tape (Logemas Pty Ltd., Albion, Australia) and an elastic adhesive bandage (Elastoplast, Beiersdorf Australia Pty Ltd., North Ryde, Australia). The shank sensors were positioned laterally approximately 3–4 cm above the lateral malleolus and thigh sensors on the mid-lateral thigh. The final IMU was secured centrally on the sacrum via a Noraxon myoMOTION pelvic strap and reinforced with rigid tape (Elastoplast, Beiersdorf Australia Pty Ltd., North Ryde, Australia). The serial numbers of each IMU were input into the Noraxon software against the relevant body part where the sensor was placed. Then, body-to-sensor calibration of the IMUs was performed in the participants' neutral standing posture.

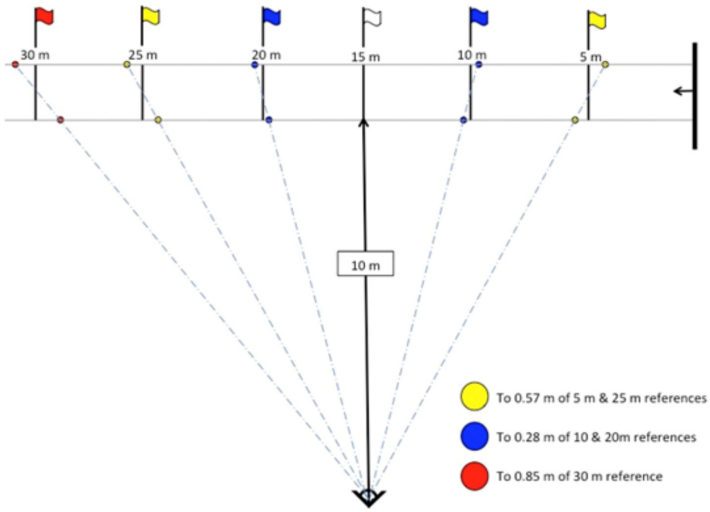

Figure 1. Force–velocity profiling setup taken from 'MySprint' iPhone application instructions (Version 1.10 installed on iPhone XR running iOS 13). Distances of 5, 10, 15, 20 and 30 metres are marked by flags.

Following the FVP and IMU setup, each participant was instructed to complete a self-directed warm-up which generally consisted of graduated running, dynamic stretches, drills, and trial practice. The 40 m sprint trial (encompassing both IMU and FVP capture) was subsequently conducted on grass from a crouch start (see Figure 2). Air pressure (hPa) and temperature (°C) were recorded at the time of testing with iPhone XR running iOS 13 (Apple Weather application).

Figure 2. Photographic example of single maximum-effort 40 m sprint.

2.2. Surveillance Procedure

After the sprint trial, participants were followed for a one-year injury surveillance period, involving weekly mobile phone text message reporting through a survey administration platform (Qualtrics 2019–2020, Provo, UT, USA). Participants were asked the following: 'In the last week, have you had pain in the hamstring region (back of thigh) that has affected your ability to train or compete?' The text message required a 'yes' or 'no' response. If participants did not respond to the weekly text, they were sent a reminder text message. If after two reminder text messages, participants still did not respond, they were contacted by one of the study investigators to confirm ongoing study participation.

If the participant answered 'yes', a physiotherapist was notified to contact the participant to arrange an appropriate time/day/location to assess the injury free of charge. This physiotherapist conducted an initial assessment only and did not provide treatment. Further physiotherapy treatment was at the discretion of the participant. If the participant sustained an HSI and wanted to report it sooner than when the weekly text message was due, participants were provided details of the chief investigator for referral to a physiotherapist for assessment. Physiotherapists conducting injury assessments were not involved in baseline sprint testing, data processing, or statistical analysis.

2.3. HSI Reporting

Reporting HSI for cross-sectional analysis was based on self-report only. Although participants who reported a previous HSI largely had confirmation through medical professional diagnosis and/or imaging, this evidence was not individually sought. For cohort analysis, as mentioned above, a physiotherapist confirmed the HSI diagnosis. To be included in the study analysis, the HSI must have occurred while training or in competition during non-contact, high-speed running.

2.4. Data Processing

2.4.1. IMU Data

IMU sprint trial data were exported into Matlab (The MathWorks Inc., Version R2020b, Natick, MA, USA) software for POC detection, which was performed using the vertical, earth-referenced accelerometer data (axial axis) from the shank IMU. The first negative minimum in the acceleration trace following maximal hip flexion was manually determined for each stride cycle. Anterior pelvic tilt and hip flexion angular data at the POC, as well as stride and step time, were subsequently exported into Excel (Microsoft Excel 2019, Microsoft Corporation, Washington, DC, USA). The shank sensor was only used for POC determination, as it was not accurate enough for use based on previous validation [33].

Six consecutive steps were selected to represent steady-state running for analysis of kinematic data in the latter part of the 40 m sprint. The root mean square error (RMSE) of the hip flexion data at the POC of every 6 consecutive steps was calculated, and the 6 steps with the lowest RMSE were selected (i.e., 3 steps on each side).

2.4.2. FVP Data

Five-meter split times from the first 30 m of the sprint were calculated using the 'MySprint' iPhone application (Version 1.10 installed on iPhone XR running iOS 13). The start of the sprint was the first frame in which the participant's thumb left the ground. Split times were determined by scrolling through the captured video using the application, aligning the participant's hip with respective agility poles. Each split time was recorded in milliseconds.

Participant split times, height, and weight, as well as temperature and air pressure at the time of testing, were inputted into a preformatted, free-access Excel spreadsheet [40] (Microsoft Excel 2019, Microsoft Corporation, Washington, USA) using the 'Solver' add-in macro to implement validated FVP equations. The following FVP variables were automatically generated for each participant:

- 30 m time (s);
- Vmax: Maximum velocity (m/s);
- F0: Theoretical maximum horizontal force at null velocity (N);
- V0: Theoretical maximum velocity under zero load (m/s);
- Pmax: Maximal mechanical power output (W/kg);
- FV Slope: Linear F-V relationship slope, negative indicates more force-oriented, positive indicates more velocity-oriented ($-1 \geq 1$);
- RFmax: Ratio of horizontal component of ground reaction force (RF) maximum value (%);
- Drf: Rate of decrease in RF (%);
- Vopt: Speed at maximal power output (m/s).

2.5. Statistical Analysis

2.5.1. Cross-Sectional Analysis

Cross-sectional data were analysed using SPSS Statistics (IBM SPSS Software, Version 15.0). Mixed Model Analysis was used to compare kinematic differences between groups

in each of the IMU variables listed above. A covariance structure of autoregressive AR1 was used with the fixed factor of HSI either coded by side (i.e., coding each side as either with or without a history of HSI) or by participant (i.e., coding the participant as with or without a history of HSI), with the step number as repeated measures and participant ID as the subject identifier. Given the evidence of age and sex differences in sprinting performance [41], differences in FVP data between groups were analysed through Analysis of Covariance (ANCOVA), while controlling for age and sex.

2.5.2. Cohort Analysis

The small sample size (as a result of restrictions imposed with COVID-19) precluded formal prospective statistical analysis. For those who sustained an HSI in the surveillance period, percentile evaluation was used to compare those who sustained an HSI in the surveillance period to controls for FVP variables and to compare injured sides to uninjured sides for IMU variables across the full cohort.

3. Results

3.1. Cross-Sectional Results

3.1.1. IMU Data Findings

Five participants were removed because of unusable IMU data. Thus, 18 participants in total were included in the cross-sectional IMU data analysis. Eleven had a history of HSI (mean age 33.1 ± 11.8 years; height 1.73 ± 0.1 m; weight 70.2 ± 13.0 kg; eight females, three males); seven did not (mean age 19 ± 3.3 years; height 1.76 ± 0.1 cm; weight 72.8 ± 5.8 kg; two females, five males). Table 1 details the cross-sectional statistical analysis results for IMU data.

Table 1. Cross-sectional analysis of IMU data by HSI side and by subject, using Mixed Model Analysis (Type III Fixed Effects).

IMU Variable	HSI History by Side μ (95% CI)	Control by Side μ (95% CI)	Sig. by Side (*p* Value)	HSI History by Participant μ (95% CI)	Control by Participant μ (95% CI)	Sig. by Participant (*p* Value)
Anterior Pelvic Tilt at POC (°)	3.1 (−0.2, 6.4)	1.7 (−1.6, 5.0)	<0.001 *	2.3 (−1.4, 7.1)	1.0 (−4.3, 6.3)	0.573
Hip Flexion at POC (°)	56.7 (52.4, 61.1)	55.2 (51.0, 59.3)	0.121	53.8 (48.6, 59.0)	58.7 (52.2, 65.2)	0.231
Step time (s)	0.238 (0.231, 0.244)	0.237 (0.232, 0.242)	0.796	0.24 (0.235, 0.246)	0.232 (0.225, 0.239)	0.053
Stride time (s)	0.473 (0.461, 0.485)	0.474 (0.462, 0.486)	0.478	0.48 (0.464, 0.495)	0.465 (0.445, 0.484)	0.216

IMU: inertial measurement unit, HSI: hamstring strain injury, μ: mean, CI: confidence interval, POC: point of contact, * significant difference between groups.

3.1.2. FVP Data Findings

All participants (n = 23) were included in cross-sectional FVP data analysis. Thirteen had a history of HSI (mean age 31 ± 11.9 years; height 1.73 ± 0.1 m; weight 70 ± 12.7 kg; eight females, five males); ten did not (mean age 19 ± 2.7 years; height 1.78 ± 0.1 m; weight 74 ± 5.9 kg; two females, eight males). Baseline cross-sectional analysis revealed no significant differences in FVP between participants with and without a history of HSI. Age and sex covariates, however, influenced the FVP data as indicated in Table 2. Increasing age was associated with a slower 30 m time and reductions in Pmax and RFmax. For sex, males had faster 30 m times, as well as increased Vmax, F0, V0, Pmax, and RFmax.

Table 2. Cross-sectional analysis of FVP data by subject, using Analysis of Covariance, controlling for age and sex.

FVP Variable	HSI History by Side μ (SD)	Control by Side μ (SD)	*p* Value
30 m Time (s)	4.87 (0.36)	4.60 (0.24)	0.463 *^
Vmax (m/s)	7.48 (0.81)	8.01 (0.59)	0.660 ^
F0 (N/kg)	8.98 (1.28)	8.90 (0.48)	0.493 ^
V0 (m/s)	7.77 (0.93)	8.45 (0.70)	0.663 ^
Pmax (W/kg)	17.39 (2.97)	18.80 (1.63)	0.312 *^
FV Slope	−1.75 (0.24)	−1.06 (0.12)	0.753
RFmax (%)	44.55 (2.98)	46.56 (1.75)	0.582 *^
Drf (%)	−10.8 (0.9)	−10.5 (0.6)	0.782
Vopt (m/s)	4.01 (0.10)	3.92 (0.14)	0.664

FVP: force–velocity profile, HSI: hamstring strain injury, μ: mean, SD: standard deviation, Vmax: maximum velocity, F0: theoretical maximum horizontal force at null velocity, V0: theoretical maximum velocity under zero load, Pmax: maximal mechanical power output, FV Slope: linear F-V relationship slope (negative indicates more force-oriented, positive indicates more velocity-oriented), RFmax: ratio of horizontal component of ground reaction force (RF) maximum value, Drf: rate of decrease in RF, Vopt: speed at maximal power output, * significant difference in age covariant between groups, ^ significant difference in sex covariant between groups.

3.2. Cohort Results

All participants completed the full surveillance period. Two male participants sustained an HSI of the high-speed running type during the one-year surveillance period (HSI#1, age: 24 years, height: 1.78 m, weight: 83 kg; HSI#2, age: 18 years, height: 1.75 m, weight: 77 kg). Both injuries were classified recurrent (not index), affecting the same side documented at baseline. No HSIs of the stretch type were sustained within the cohort. Percentile evaluation revealed the two participants who sustained an HSI were in the higher percentiles for maximum velocity (m/s) for both the entire cohort (HSI#1: 90th percentile, HSI#2: 85th percentile) and the group with a previous history of HSI (HSI#1: 91st percentile, HSI#2: 82nd percentile). There were IMU variables that seemed to be single outliers (e.g., reduced anterior pelvic tilt, step time, and stride time), but none that were consistent across both injured participants. All variable percentiles are detailed in Table 3.

Table 3. Cohort baseline variable percentiles for the two participants who sustained an injury during the one-year surveillance period.

	Variable	HSI Cohort Participant #1 Percentile of Cohort	HSI Cohort Participant #2 Percentile of Cohort
IMU Data	Mean Anterior Pelvic Tilt at POC—Injured Side	14.9%	17.4%
	Mean Anterior Pelvic Tilt at POC—Uninjured Side	0.9%	32.9%
	Mean Hip Flexion at POC —Injured Side	81.3%	14.3%
	Mean Hip Flexion at POC —Uninjured Side	67.9%	61.6%
	Step Time—Injured Side	0.0%	19.7%
	Step Time—Uninjured Side	77.5%	4.2%
	Stride time—Injured Side	16.2%	2.1%
	Stride time—Uninjured Side	22.5%	2.8%

Table 3. *Cont.*

	Variable	HSI Cohort Participant #1 Percentile of Cohort	HSI Cohort Participant #2 Percentile of Cohort
FVP Data	30 m Time	20.0%	5.0%
	Vmax	90.0%	85.0%
	F0	25.0%	85.0%
	V0	90.0%	85.0%
	Pmax	55.0%	100.0%
	FV Slope	90.0%	50.0%
	RFmax	65.0%	100.0%
	Drf	90.0%	55.0%
	Vopt	90.0%	85.0%

IMU: inertial measurement unit, FVP: force–velocity profile, HSI: hamstring strain injury, μ: mean, SD: standard deviation, Vmax: maximum velocity, F0: theoretical maximum horizontal force at null velocity, V0: theoretical maximum velocity under zero load, Pmax: maximal mechanical power output, FV Slope: linear F-V relationship slope (negative indicates more force-oriented, positive indicates more velocity-oriented), RFmax: ratio of horizontal component of ground reaction force (RF) maximum value, Drf: rate of decrease in RF, Vopt: speed at maximal power output.

4. Discussion

This study retrospectively and prospectively investigated the relationship between running biomechanics and HSI and reported preliminary findings that anterior pelvic tilt and FVP may be associated with HSI. Unfortunately, COVID-19 restrictions resulted in a small sample size, limiting the power and subsequent generalisability of the findings. Nevertheless, the protocol may be considered a feasibility trial of novel technology (IMUs and FVP using iPhone app), and the preliminary findings present a case for further investigation. In this section, we will discuss the main findings, as well as offer valuable lessons learnt to direct future observational research.

4.1. Anterior Pelvic Tilt and HSI

In our study, increased anterior pelvic tilt at the POC (on previously injured side) during sprinting was associated with HSI. This finding was at the cross-sectional level; thus, it cannot be determined whether this finding may be a cause or consequence of HSI. It is important to also acknowledge that for the cross-sectional arm of the study, HSI was based on retrospective self-report only. Our prospective cohort analysis of two participants who sustained an HSI did not support increased anterior tilt as a cause of HSI. Rather, one of these two participants actually scored in the lower percentiles for anterior pelvic tilt at the POC.

A compelling argument exists for how anterior pelvic tilt may play a role in HSI. The hamstring muscles (except the short head of the biceps femoris) originate from the ischial tuberosity within the pelvis; hence, theoretically, any level of pelvic tilt will affect hamstring length and subsequent tension loads [42]. Moreover, a time series analysis using video raster stereography demonstrated an inverse relationship between anterior pelvic tilt and hip and knee flexion in the late swing phase of high-speed running [43]. The authors proposed that increased anterior pelvic tilt would limit hip flexion, prompting the athlete to extend the knee further as a compensatory mechanism [43]. Although decreased hip flexion could be interpreted as protective [44,45], increased knee extension places a significant load on the hamstrings [46], as they must generate large eccentric forces to decelerate the knee joint and prepare the limb for contact [47]. Excessive muscle strain associated with this

late-swing eccentric contraction is what is believed to be the primary mechanism behind HSIs of the 'high-speed running' type [6].

Our findings are comparable to other studies that have also investigated pelvic kinematics and HSI. On a retrospective level, Daly et al. (2016) found increased late-swing anterior pelvic tilt in participants with a history of HSI, when compared to controls [48]. Higashihara et al. (2019) reported decreased late stance anterior pelvic tilt on the injured side (compared to the uninjured side) [49], and Schuermans et al. (2017) found no difference in anterior pelvic tilt throughout the gait cycle between participants with and without a history of HSI [50]. Prospectively, Schuermans et al. (2017) reported increased anterior pelvic tilt in early swing in participants who sustained an HSI in their cohort study [50], while Kenneally-Dabrowski et al. (2019) found no difference in late-swing anterior pelvic tilt between cohort groups [51].

An important consideration when interpreting anterior pelvic tilt findings within and between studies is calibration protocol. Some studies (including the present study) calibrate in neutral standing posture, while others calibrate from true vertical. A recent study measured standing anterior pelvic tilt (relative to vertical) at baseline before a five-year HSI surveillance period in football players. They reported increased neutral standing anterior pelvic tilt in those who sustained an HSI during the surveillance period [52]. The current study calibrated zero in neutral standing posture, so running measurements reflected only the angular deviation from standing.

Owing to variations in running protocols and discrepancies in the running phases analysed and calibration protocol, the ability to draw definitive conclusions across these studies is limited. Nevertheless, there is a case for further investigation into the association between anterior pelvic tilt and HSI. Future studies should consider reporting on anterior pelvic tilt in neutral standing posture and then documenting the relative change in running in order to direct the development of relevant preventative strategies, e.g., target static lumbopelvic control and/or dynamic lumbopelvic control.

4.2. FVP and HSI

Another preliminary finding from our study, warranting further investigation, is the difference in FVP between participants who prospectively sustained an HSI and the controls. While our retrospective analysis revealed no difference in FVP between participants with and without a history of HSI, prospective analysis of two participants revealed both participants scored in the higher percentiles for variables associated with velocity (Vmax, V0, and Vopt). One of these participants also rated in high percentiles for horizontal force propulsion (F0: 85%), power output (Pmax: 100%), and mechanical effectiveness measured by the rate of decline in reaction force with increasing speed (Drf: 100%). Our findings bear similarities to a cross-sectional study that also utilised the 'MySprint' iPhone application, reporting higher V0 and Drf in sub-elite male football players who had a history of HSI, when compared to controls [53].

Other studies found no significant differences in velocity-related variables but reported an association between low F0 and HSI. A large prospective cohort study used radar or laser technology for sprint velocity data to compute FVP over two 30 m sprints in university and professional football players at different time points during the season. They reported that lower F0 values were significantly associated with HSI risk in the weeks following the sprint measurement [12]. A case–control study utilising radar technology for FVP also found reduced F0 (as well as Pmax) in semi-professional football players compared to controls. Testing was undertaken immediately after clearance of return to play following HSI, and nil difference between groups was reported upon testing 2 months after [36]. The same research group later published a paper of two HSI case reports: one soccer player

with FVP data immediately before and during the injury, and one rugby player with FVP data seven days before HSI and after return to sport. They found that the horizontal force was reduced before and after the respective HSIs [11]. Finally, a prospective cohort study recorded only F0 using radar technology for FVP over two 30 m sprints. They reported an association between lower F0 and HSI occurring between pre- and mid-season in premier division male Finnish football players [14]. The absence of velocity-related data limits the comparability of findings. Nevertheless, the findings of our study and those aforementioned above present emerging evidence for a relationship between sprint mechanical output and HSI. Ultimately, more research is needed to better understand normative data and clarify which FVP variables are of relevance to HSI for varying sports (or field positions), demographics, and stages of injury (e.g., for primary, secondary, or tertiary prevention).

For better research translation, future studies may consider adopting the FVP classification method presented by Hicks and colleagues [54]. Their classification system explains the interaction between velocity and force-orientated profiles by categorising FVP into four quadrants: 1: high F0 and V0, 2: high F0 and low V0, 3: low relative F0 and V0, 4: low F0 and high V0. Thresholds should be determined relative to the specific cohort. For each quadrant, they propose the effect on sprint performance (initial steps versus upright maximal velocity), including technical characteristics (e.g., level of forward lean) and suggested training recommendations to enhance performance [54]. If future epidemiological studies determine these FVP quadrants are relevant in the context of HSI, Hicks et al.'s training recommendations may be a good starting point for interventional studies [54].

4.3. Direction for Future Studies

4.3.1. Use of IMUs

Several lessons learnt from this study regarding the use of IMUs can be shared. Although our IMU data were validated [33], and in agreement with other studies involving overground sprinting [55–59], there were data gaps in five participants resulting in exclusion from analysis. Noraxon's newer version 'Ultium' provides in-sensor data storage which may mitigate this issue by filling gaps where live transmission is interrupted [60]. Nonetheless, several factors may have contributed to the incompleteness of these data sets, particularly those related to field-based usage.

The IMU system was validated in a laboratory environment against a gold standard motion analysis system [33]. In this setting, a variety of common IMU issues can be controlled. Using IMUs in the field presents various concerns, including power supply problems [29], sensor noise [61], synchronisation issues [62], magnetic disturbances [63], and environmental interferences [19], all of which may contribute to the intermittent cessation of recording leading to missing data. Furthermore, the validation was conducted on a motorised treadmill with a controlled speed, slope, and surface, all of which are variables that cannot be controlled in field-based, overground conditions.

For future studies using IMUs for running, we recommend several mitigation strategies to address these issues. Firstly, data should be validated in environments that closely replicate real-world conditions, e.g., in overground conditions or outside the laboratory (where feasible). Guidelines and a standardised measurement process for IMUs are needed to enhance the accuracy of running measurements and improve comparability across studies [21]. Although high sampling rates are advised for a greater accuracy of high-speed speeding analysis [64], they can result in data overload. Thus, it is advisable to minimise the number of sensors used [65]. On testing day, check for local magnetic disturbance and delay/move tests accordingly [55], or consider developing a magnetometer-free method [20]. As for calibration, the procedure for overground running should incorporate assumptions

to simplify the global reference frame of the IMU to minimise drift errors [65]. Finally, a full battery charge should always be ensured.

4.3.2. Protocol Considerations

Upon completion and reflection of this study, key takeaways can be offered in terms of study design and methodology to enhance data reliability and generalisability. On top of having a prospective cohort design and large sample size, future studies should test over several time periods, quantify exposure, and extend running data capture distance.

In real-life conditions, the assessment of running biomechanics may be considered as part of musculoskeletal screening for both injury risk reduction and performance [66]. Time and costing constraints can limit musculoskeletal screening to only one occasion at baseline, but in reality, screening should be conducted regularly as results can fluctuate throughout the season [67]. Variables such as isometric hamstring strength have been used as an in-season monitoring secondary prevention tool for HSI, with testing after every match informing training volume for the subsequent week [68]. Indeed, this level of testing frequency is currently not feasible for running biomechanical analysis due to longer setup and processing time. However, future technological advances may permit simultaneous running analysis within competition and training, e.g., through validation of vision machine learning methods [17,69]. In the meantime, it is recommended to test throughout the surveillance period as often as practicable.

The collection of exposure data may also help us understand potential fluctuations in results throughout the season and other confounding factors for injury. In sports performance, the term "exposure" commonly refers to the intensity and duration of physical activity, which together contribute to an athlete's overall workload. It encompasses the time spent in training or competition and can include a detailed breakdown of specific tasks performed [70]. Sudden increases in high-speed running can increase HSI risk [3], and equally, not enough high-speed conditioning can increase HSI risk [4]. An explanation for this disparity in findings is likely related to fatigue, and that a certain level of high-speed running load may be protective in nature [71,72].

Finally, it may be worth extending the running data capture distance. Our testing distance was 30 m for FVP, with an additional 10 m for kinematic data capture (40 m in total). This may be sufficient for many multi-directional team sports, where the average sprint effort is less than 30 m [73], but may be insufficient for track sprinters who compete over distances of 100 m or greater. Furthermore, as a result of IMU validation constraints, we only captured sagittal plane pelvis and hip kinematic data at the point of contact in upright running. Future studies may look to investigate whether there is a link between kinematics in the early phases of acceleration [74], force–velocity profile, and HSI.

5. Conclusions

This combined cross-sectional and prospective cohort study demonstrated preliminary findings that present a case for further research investigating running biomechanics and HSI. Cross-sectional analysis revealed participants with a history of HSI exhibited increased anterior pelvic tilt at the point of contact (on the injured side) during upright sprinting when compared to controls. Prospectively, participants who sustained an HSI scored in the higher percentiles for variables associated with a velocity-oriented profile (Vmax, V0, and Vopt). The sample size was limited; thus, the findings should be interpreted for feasibility purposes only. Therefore, several practical insights were suggested for the use of novel technology (IMU and FVP) to quantify running biomechanics for future observational research, which ultimately aims to inform HSI prevention strategies.

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References

1. Ekstrand, J.; Bengtsson, H.; Waldén, M.; Davison, M.; Khan, K.M.; Hägglund, M. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: The UEFA Elite Club Injury Study from 2001/02 to 2021/22. *Br. J. Sports Med.* **2022**, *57*, 292–298. [CrossRef] [PubMed]
2. Diemer, W.M.; Winters, M.; Tol, J.L.; Pas, H.I.M.F.L.; Moen, M.H. Incidence of acute hamstring injuries in soccer: A systematic review of 13 studies involving more than 3800 athletes with 2 million sport exposure hours. *J. Orthop. Sports Phys. Ther.* **2021**, *51*, 27–36. [CrossRef] [PubMed]
3. Green, B.; Bourne, M.N.; van Dyk, N.; Pizzari, T. Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. *Am. J. Sports Med.* **2020**, *54*, 1081–1088. [CrossRef]
4. Moreno-Pérez, V.; Del Coso, J.; López-Del Campo, R.; Resta, R.; Romero-Sangüesa, J.; Courel-Ibáñez, J.; Méndez-Villanueva, A. Reduced Match Exposure in the Previous 2 Matches Accounts for Hamstring Muscle Injury Incidence in Professional Football Players. *Sports Health* **2024**, *16*, 109–114. [CrossRef] [PubMed]
5. De Vos, R.-J.; Reurink, G.; Goudswaard, G.-J.; Moen, M.H.; Weir, A.; Tol, J.L. Clinical findings just after return to play predict hamstring re-injury, but baseline MRI findings do not. *Br. J. Sports Med.* **2014**, *48*, 1377–1384. [CrossRef]
6. Danielsson, A.; Horvath, A.; Senorski, C.; Alentorn-Geli, E.; Garrett, W.E.; Cugat, R.; Samuelsson, K.; Hamrin Senorski, E. The mechanism of hamstring injuries–A systematic review. *BMC Musculoskelet. Disord.* **2020**, *21*, 641. [CrossRef]
7. Wolski, L.; Pappas, E.; Hiller, C.; Halaki, M.; Fong Yan, A. Is there an association between high-speed running biomechanics and hamstring strain injury? A systematic review. *Sports Biomech.* **2024**, *23*, 1313–1339. [CrossRef]
8. Kalema, R.N.; Schache, A.G.; Williams, M.D.; Heiderscheit, B.; Siqueira Trajano, G.; Shield, A.J. Sprinting biomechanics and hamstring injuries: Is there a link? A literature review. *Sports* **2021**, *9*, 141. [CrossRef]
9. Bramah, C.; Mendiguchia, J.; Dos'Santos, T.; Morin, J.-B. Exploring the role of sprint biomechanics in hamstring strain injuries: A current opinion on existing concepts and evidence. *Sports Med.* **2024**, *54*, 783–793. [CrossRef]
10. Morin, J.B.; Gimenez, P.; Edouard, P.; Arnal, P.; Jimenez-Reyes, P.; Samozino, P.; Brughelli, M.; Mendiguchia, J. Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Front. Physiol.* **2015**, *6*, 404. [CrossRef]
11. Mendiguchia, J.; Edouard, P.; Samozino, P.; Brughelli, M.; Cross, M.; Ross, A.; Gill, N.; Morin, J.B. Field monitoring of sprinting power-force-velocity profile before, during and after hamstring injury: Two case reports. *J. Sports Sci.* **2016**, *34*, 535–541. [CrossRef] [PubMed]
12. Edouard, P.; Lahti, J.; Nagahara, R.; Samozino, P.; Navarro, L.; Guex, K.; Rossi, J.; Brughelli, M.; Mendiguchia, J.; Morin, J.-B. Low horizontal force production capacity during sprinting as a potential risk factor of hamstring injury in football. *Int. J. Environ. Res. Public. Health* **2021**, *18*, 7827. [CrossRef] [PubMed]
13. Lord, C.; Blazevich, A.J.; Drinkwater, E.J.; Ma'ayah, F. Greater loss of horizontal force after a repeated-sprint test in footballers with a previous hamstring injury. *J. Sci. Med. Sport.* **2019**, *22*, 16–21. [CrossRef] [PubMed]
14. Lahti, J.; Mendiguchia, J.; Edouard, P.; Morin, J.-B. A novel multifactorial hamstring screening protocol: Association with hamstring muscle injuries in professional football (soccer)—A prospective cohort study. *Biol. Sport.* **2022**, *39*, 1021–1031. [CrossRef]
15. Mundt, M. Bridging the lab-to-field gap using machine learning: A narrative review. *Sports Biomech.* **2023**, *18*, 1–20. [CrossRef]

16. Wade, L.; Needham, L.; McGuigan, P.; Bilzon, J. Applications and limitations of current markerless motion capture methods for clinical gait biomechanics. *PeerJ* **2022**, *10*, e12995. [CrossRef]
17. Van Hooren, B.; Pecasse, N.; Meijer, K.; Essers, J.M.N. The accuracy of markerless motion capture combined with computer vision techniques for measuring running kinematics. *Scand. J. Med. Sci. Sports* **2023**, *33*, 966–978. [CrossRef]
18. Ceriola, L.; Taborri, J.; Donati, M.; Rossi, S.; Patane, F.; Mileti, I. Comparative Analysis of Markerless Motion Capture Systems for Measuring Human Kinematics. *IEEE Sens. J.* **2024**, *24*, 28135–28144. [CrossRef]
19. Benson, L.C.; Räisänen, A.M.; Clermont, C.A.; Ferber, R. Is This the Real Life, or Is This Just Laboratory? A Scoping Review of IMU-Based Running Gait Analysis. *Sensors* **2022**, *22*, 1722. [CrossRef]
20. Weygers, I.; Kok, M.; Konings, M.; Hallez, H.; De Vroey, H.; Claeys, K. Inertial Sensor-Based Lower Limb Joint Kinematics: A Methodological Systematic Review. *Sensors* **2020**, *20*, 673. [CrossRef]
21. Zeng, Z.; Liu, Y.; Hu, X.; Tang, M.; Wang, L. Validity and reliability of inertial measurement units on lower extremity kinematics during running: A systematic review and meta-analysis. *Sports Med.* **2022**, *8*, 86. [CrossRef] [PubMed]
22. Zhang, X.; Wang, C.; Zheng, T.; Wu, H.; Wu, Q.; Wang, Y. Wearable Optical Fiber Sensors in Medical Monitoring Applications: A Review. *Sensors* **2023**, *23*, 6671. [CrossRef] [PubMed]
23. Khonina, S.N.; Kazanskiy, N.L.; Butt, M.A. Optical Fibre-Based Sensors—An Assessment of Current Innovations. *Biosensors* **2023**, *13*, 835. [CrossRef] [PubMed]
24. Ciniglio, A.; Guiotto, A.; Spolaor, F.; Sawacha, Z. The Design and Simulation of a 16-Sensors Plantar Pressure Insole Layout for Different Applications: From Sports to Clinics, a Pilot Study. *Sensors* **2021**, *21*, 1450. [CrossRef]
25. Zhang, Z.; Dai, Y.; Xu, Z.; Grimaldi, N.; Wang, J.; Zhao, M.; Pang, R.; Sun, Y.; Gao, S.; Boyi, H. Insole Systems for Disease Diagnosis and Rehabilitation: A Review. *Biosensors* **2023**, *13*, 833. [CrossRef]
26. Morin, J.-B.; Edouard, P.; Samozino, P. Technical ability of force application as a determinant factor of sprint performance. *Med. Sci. Sports Exerc.* **2011**, *43*, 1680–1688. [CrossRef]
27. Morin, J.-B.; Samozino, P. Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *Int. J. Sports Physiol. Perform.* **2016**, *11*, 267–272. [CrossRef]
28. Camomilla, V.; Bergamini, E.; Fantozzi, S.; Vannozzi, G. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: A systematic review. *Sensors* **2018**, *18*, 873. [CrossRef]
29. Faisal, A.; Majumder, S.; Mondal, T.; Cowan, D.; Naseh, S.; Deen, M. Monitoring methods of human body joints: State-of-the-art and research challenges. *Sensors* **2019**, *19*, 2629. [CrossRef]
30. Luinge, H.J.; Veltink, P.H. Measuring orientation of human body segments using miniature gyroscopes and accelerometers. *Med. Biol. Eng. Comput.* **2005**, *43*, 273–282. [CrossRef]
31. Kenneally-Dabrowski, C.J.; Serpell, B.G.; Spratford, W. Are accelerometers a valid tool for measuring overground sprinting symmetry? *Int. J. Sports Sci. Coach.* **2018**, *13*, 270–277. [CrossRef]
32. Gurchiek, R.D.; McGinnis, R.S.; Needle, A.R.; McBride, J.M.; van Werkhoven, H. The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *J. Biomech.* **2017**, *61*, 263–268. [CrossRef] [PubMed]
33. Wolski, L.; Halaki, M.; Hiller, C.E.; Pappas, E.; Yan, A.F. Validity of an inertial measurement unit system to measure lower limb kinematics at point of contact during incremental high-speed running. *Sensors* **2024**, *24*, 5718. [CrossRef]
34. Jaskólska, A.; Goossens, P.; Veenstra, B.; Jaskólskp, A.; Skinner, J.S. Treadmill measurement of the force-velocity relationship and power output in subjects with different maximal running velocities. *Sports Med. Train. Rehabil.* **1998**, *8*, 347–358. [CrossRef]
35. Samozino, P.; Rabita, G.; Dorel, S.; Slawinski, J.; Peyrot, N.; Saez De Villarreal, E.; Morin, J.B. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand. J. Med. Sci. Sports* **2016**, *26*, 648–658. [CrossRef]
36. Mendiguchia, J.; Samozino, P.; Martinez-Ruiz, E.; Brughelli, M.; Schmikli, S.; Morin, J.B.; Mendez-Villanueva, A. Progression of Mechanical Properties during On-field Sprint Running after Returning to Sports from a Hamstring Muscle Injury in Soccer Players. *Int. J. Sports Med.* **2014**, *35*, 690–695, 696p. [CrossRef]
37. Haugen, A.T.; Breitschädel, A.F.; Samozino, A.P. Power-force-velocity profiling of sprinting athletes: Methodological and practical considerations when using timing gates. *J. Strength. Cond. Res.* **2018**, *34*, 1769–1773. [CrossRef]
38. Cross, M.R.; Brughelli, M.; Samozino, P.; Morin, J.-B. Methods of Power-Force-Velocity Profiling During Sprint Running: A Narrative Review. *Sports Med.* **2017**, *47*, 1255–1269. [CrossRef]
39. Romero-Franco, N.; Jiménez-Reyes, P.; Castaño-Zambudio, A.; Capelo-Ramírez, F.; Rodríguez-Juan, J.J.; González-Hernández, J.; Toscano-Bendala, F.J.; Cuadrado-Peñafiel, V.; Balsalobre-Fernández, C. Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. *Eur. J. Sport. Sci.* **2017**, *17*, 386–392. [CrossRef]
40. Morin, J.-B.; Samozino, P. Spreadsheet for Sprint Acceleration Force-Velocity-Power Profiling. Available online: https://jbmorin.net/downloads (accessed on 1 February 2020).
41. Korhonen, M.T.; Mero, A.; Suominen, H. Age-related differences in 100-m sprint Performance in male and female master runners. *Med. Sci. Sports Exerc.* **2003**, *35*, 1419–1428. [CrossRef]
42. Drake, R.; Vogl, A.W.; Mitchell, A.W.M. Lower Limb. In *Gray's Anatomy for Students*, 3rd ed.; Elsevier: Saint Louis, MO, USA, 2014.

43. Alizadeh, S.; Mattes, K. How anterior pelvic tilt affects the lower extremity kinematics during the late swing phase in soccer players while running: A time series analysis. *Hum. Mov. Sci.* **2019**, *66*, 459–466. [CrossRef] [PubMed]
44. Small, K.; McNaughton, L.R.; Greig, M.; Lohkamp, M.; Lovell, R. Soccer fatigue, sprinting and hamstring injury risk. *Int. J. Sports Med.* **2009**, *30*, 573–578. [CrossRef] [PubMed]
45. Pinniger, G.J.; Steele, J.R.; Groeller, H. Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Med. Sci. Sports Exerc.* **2000**, *32*, 647–653. [CrossRef]
46. Huygaerts, S.; Cos, F.; Cohen, D.D.; Calleja-Gonzalez, J.; Guitart, M.; Blazevich, A.J.; Alcaraz, P.E. Mechanisms of hamstring strain injury: Interactions between fatigue, muscle activation and function. *Sports* **2020**, *8*, 18. [CrossRef]
47. Yu, B.; Queen, R.M.; Abbey, A.N.; Liu, Y.; Moorman, C.T.; Garrett, W.E. Hamstring muscle kinematics and activation during overground sprinting. *J. Biomech.* **2008**, *41*, 3121–3126. [CrossRef]
48. Daly, C.; McCarthy Persson, U.; Twycross-Lewis, R.; Woledge, R.C.; Morrissey, D. The biomechanics of running in athletes with previous hamstring injury: A case-control study. *Scand. J. Med. Sci. Sports.* **2016**, *26*, 413–420. [CrossRef]
49. Higashihara, A.; Ono, T.; Tokutake, G. Hamstring muscles' function deficit during overground sprinting in track and field athletes with a history of strain injury. *J. Sports Sci.* **2019**, *37*, 2744–2750. [CrossRef]
50. Schuermans, J.; Van Tiggelen, D.; Palmans, T.; Danneels, L.; Witvrouw, E. Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence? *Gait Posture* **2017**, *57*, 270–277. [CrossRef]
51. Kenneally-Dabrowski, C.; Brown, N.A.T.; Warmenhoven, J.; Serpell, B.G.; Perriman, D.; Lai, A.K.; Spratford, W. Late swing running mechanics influence hamstring injury susceptibility in elite rugby athletes: A prospective exploratory analysis. *J. Biomech.* **2019**, *92*, 112–119. [CrossRef]
52. Bayrak, A.; Patlar, S. Increased anterior pelvic tilt angle elevates the risk of hamstring injuries in soccer player. *Res. Sports Med.* **2024**, *33*, 129–145. [CrossRef]
53. Ishøi, L.; Thorborg, K.; Hölmich, P.; Krommes, K. Sprint performance in football (soccer) players with and without a previous hamstring strain injury: An explorative cross-sectional study. *Int. J. Physiother.* **2020**, *15*, 947–957. [CrossRef] [PubMed]
54. Hicks, D.S.; Drummond, C.; Williams, K.J.; Pickering, C.; van den Tillaar, R. Individualization of training based on sprint force-velocity profiles: A conceptual framework for biomechanical and technical training recommendations. *Strength. Cond. J.* **2023**, *45*, 711–725. [CrossRef]
55. Wada, T.; Nagahara, R.; Gleadhill, S.; Ishizuka, T.; Ohnuma, H.; Ohgi, Y. Measurement of pelvic orientation angles during sprinting using a single inertial sensor. *Proceedings* **2020**, *49*, 10. [CrossRef]
56. de Ruiter, C.J.; Wilmes, E.; Brouwers, S.A.J.; Jagers, E.C.; van Dieën, J.H. Concurrent validity of an easy-to-use inertial measurement unit-system to evaluate sagittal plane segment kinematics during overground sprinting at different speeds. *Sports Biomech.* **2022**, *23*, 2757–2770. [CrossRef] [PubMed]
57. Bastiaansen, B.J.; Wilmes, E.; Brink, M.S.; de Ruiter, C.J.; Savelsbergh, G.J.; Steijlen, A.; Jansen, K.M.; van der Helm, F.C.; Goedhart, E.A.; van der Laan, D. An inertial measurement unit based method to estimate hip and knee joint kinematics in team sport athletes on the field. *J. Vis. Exp.* **2020**, *2020*, e60857. [CrossRef]
58. Miranda-Oliveira, P.; Branco, M.; Fernandes, O. Accuracy and Interpretation of the Acceleration from an Inertial Measurement Unit When Applied to the Sprint Performance of Track and Field Athletes. *Sensors* **2023**, *23*, 1761. [CrossRef]
59. Purcell, B.; Channells, J.; James, D.; Barrett, R. Use of accelerometers for detecting foot-ground contact time during running. *Bio-MEMS Nanotechnol.* **2005**, *6036*, 292–299. [CrossRef]
60. Ultium Motion Hardware User Manual. NUSA, Inc.: Scottsdale, AZ, USA, 2024.
61. Akbari, A.; Thomas, X.; Jafari, R. Automatic noise estimation and context-enhanced data fusion of IMU and Kinect for human motion measurement. In Proceedings of the IEEE 14th International Conference on Wearable and Implantable Body Sensor Networks (BSN), Eindhoven, The Netherlands, 9–12 May 2017; pp. 178–182. [CrossRef]
62. Verdel, N.; Mohorcic, M.; Drobnic, M.; Supej, M.; Depolli, M. Time synchronization in wireless IMU sensors for accurate gait analysis during running. In Proceedings of the IEEE International Workshop on Sport, Technology and Research (STAR), Trento, Italy, 14–16 September 2023; pp. 126–129. [CrossRef]
63. Robert-Lachaine, X.; Mecheri, H.; Larue, C.; Plamondon, A. Effect of local magnetic field disturbances on inertial measurement units accuracy. *Appl. Ergon.* **2017**, *63*, 123–132. [CrossRef]
64. Macadam, P.; Cronin, J.; Neville, J.; Diewald, S. Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: A systematic review. *Gait Posture* **2019**, *73*, 26–38. [CrossRef]
65. Baker, L.M.; Yawar, A.; Lieberman, D.E.; Walsh, C.J. Predicting overstriding with wearable IMUs during treadmill and overground running. *Sci. Rep.* **2024**, *14*, 6347. [CrossRef]
66. Lahti, J.; Mendiguchia, J.; Ahtiainen, J.; Anula, L.; Kononen, T.; Kujala, M.; Matinlauri, A.; Peltonen, V.; Thibault, M.; Toivonen, R.-M.; et al. Multifactorial individualised programme for hamstring muscle injury risk reduction in professional football: Protocol for a prospective cohort study. *BMJ Open Sport. Exerc.* **2020**, *6*, e000758. [CrossRef]

67. Jiménez-Reyes, P.; Garcia-Ramos, A.; Párraga-Montilla, J.A.; Morcillo-Losa, J.A.; Cuadrado-Peñafiel, V.; Castaño-Zambudio, A.; Samozino, P.; Morin, J.-B. Seasonal changes in the sprint acceleration force-velocity profile of elite male soccer players. *J. Strength. Cond. Res.* **2022**, *36*, 70–74. [CrossRef] [PubMed]
68. Wollin, M.; Thorborg, K.; Drew, M.; Pizzari, T. A novel hamstring strain injury prevention system: Post-match strength testing for secondary prevention in football. *Br. J. Sports Med.* **2020**, *54*, 498–499. [CrossRef]
69. Morin, J.-B.; Le Mat, Y.; Osgnach, C.; Barnabó, A.; Pilati, A.; Samozino, P.; Prampero, P.E. Individual acceleration-speed profile in-situ: A proof of concept in professional football players. *J. Biomech.* **2021**, *123*, 110524. [CrossRef]
70. Soligard, T.; Schwellnus, M.; Alonso, J.-M.; Bahr, R.; Clarsen, B.; Dijkstra, H.P.; Gabbett, T.; Gleeson, M.; Hägglund, M.; Hutchinson, M.R.; et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br. J. Sports Med.* **2016**, *50*, 1030–1041. [CrossRef]
71. Silva, J.R.; Magalhães, J.F.; Ascensão, A.A.; Oliveira, E.M.; Seabra, A.F.; Rebelo, A.N. Individual match playing time during the season affects fitness-related parameters of male professional soccer players. *J. Strength. Cond. Res.* **2011**, *25*, 2729–2739. [CrossRef]
72. Gómez-Piqueras, P.; Alcaraz, P.E. If you want to prevent hamstring injuries in soccer, run fast: A narrative review about practical considerations of sprint training. *Sports* **2024**, *12*, 134. [CrossRef]
73. Taylor, J.B.; Wright, A.A.; Dischiavi, S.L.; Townsend, M.A.; Marmon, A.R. Activity demands during multi-directional team sports: A systematic review. *Sports Med.* **2017**, *47*, 2533–2551. [CrossRef] [PubMed]
74. Nagahara, R.; Matsubayashi, T.; Matsuo, A.; Zushi, K. Kinematics of transition during human accelerated sprinting. *Biol. Open* **2014**, *3*, 689–699. [CrossRef]

Chapter 6: Research Summary, Discussion and Conclusion

6.1 Summary of Research Findings

This thesis aimed to bridge the gap between performance and clinical perspectives and address the divergence in beliefs between sprint coaches and sports physiotherapists, investigating the relationship between running biomechanics and HSI.

After framing the problem (Chapter 1), the existing evidence and literature were reviewed (Chapter 2). The systematic review revealed emerging evidence that there was an association between running biomechanics and HSI, but there was concern regarding the quality of included studies (particularly in regards to sample size). Additionally, significant variability was noted between the 12 studies in terms of protocol and methodology. As such, the ability to compare or develop a synopsis across studies was limited. Furthermore, only two of the studies were prospective cohort studies, thus we were unable to infer whether the preliminary findings may be a cause and/or consequence of HSI. In the end, it was recommended that further studies, adopting validated measures of biomechanical analysis, were needed to clarify if a relationship exists between running biomechanics and HSI – which was the driver behind the subsequent studies in this thesis.

With the aim of obtaining accurate data in real-world, field-based settings, the methodological considerations for quantifying high-speed running biomechanics were examined (Chapter 3). The history of human biomechanical analysis was explored, and existing field-based technologies were reviewed. It was determined that sprint FVP would be most suitable for quantifying kinetic variables of interest and an inertial measurement unit (IMU) system for quantifying kinematic variables of interest. Both methods also provided spatiotemporal information. Unlike sprint FVP which was previously validated and ready for use in observational research, an IMU system required trial and testing. The arduous journey to finding suitable IMU system to validate was subsequently described. The key challenge was identifying an IMU system with a sampling rate high enough to capture the kinematics of high-speed running.

Next, a validation study of the selected IMU system was conducted (Chapter 4). It was compared against the gold standard MAS for determination of point of contact (POC), sagittal plane lower limb kinematics at POC, as well as stride time during incremental high-speed running. The IMU system reliably identified POC, and accurately measured stride time, anterior pelvic tilt and hip flexion angle. But it was inaccurate and inconsistent in estimating knee flexion and shank angles. Nevertheless, the validated variables could be confidently quantified by the portable IMU system for subsequent field-based observational research (Chapter 5).

The culminating research study was a combined cross-sectional and prospective cohort trial investigating the association between running biomechanics and HSI. Twenty-three sprinters' running biomechanics were quantified during a 40m sprint effort, before a one-year HSI surveillance period. The first 30m of the sprint were used to calculate FVP and, in the latter, more steady-state of the sprint, pelvic tilt and hip flexion angle at POC was measured together with step and stride time.

In summary, anterior pelvic tilt was demonstrated as a variable of interest at a cross-sectional level, and prospectively, the two participants who sustained an HSI exhibited a velocity-oriented profile when compared to controls. Since the sample size was limited (as a result of restrictions associated with COVID-19), the study itself was considered more of a feasibility trial of novel technology rather than a properly powered observational study (as per the original plan). As some of the most valuable lessons come from setbacks, a key advantage of this research was that not only did it contribute to the literature on the association between running biomechanics and HSI, it also offered several practical insights into the implementation of novel technology to inform HSI prevention strategies.

6.2 Discussion

6.2.1 Practical Implications

Clinicians and coaches should make informed decisions based on the best evidence available. In 1996, Sackett and colleagues wrote on evidence-based practice, '... it requires a bottom-up *approach that integrates the best external evidence with individual clinical expertise and patients' choice, it cannot result in slavish, cookbook approaches to individual patient care'*. This article, cited over 20,000 times, describes how it is impracticable to expect clinicians to base all decisions on evidence, especially if limited evidence is available.[1] Rather, evidence-based practice encompasses careful consideration of the best up-to-date research, combined with clinical expertise, whilst balancing patient preference and expectations.[2] Our preliminary findings offer considerations for clinicians and coaches across two key themes; running variables associated with HSI, and adoption of field-based methods of running analysis.

In Chapter 5, two running biomechanical features demonstrated possible relationships with HSI; anterior pelvic tilt and FVP. At a cross-sectional level, increased anterior pelvic tilt at POC (on the previously injured side) was associated with HSI. When synthesised against the limited other research in this space, the research is conflicting,[3-6] and an evidence-based synthesis on whether anterior tilt may be a cause or consequence of HSI is not yet possible. Nevertheless, clinicians and coaches should use their combined expertise to take an individualised approach, critically analysing whether running retraining techniques aimed at reducing anterior pelvic tilt should be considered in HSI prevention strategies. General considerations for running analysis and retraining are presented in a feature article I wrote for Sport Health (Sport Medicine Australia's quarterly magazine), drawing on my knowledge of the evidence as well as my expertise as a physiotherapist and athlete (Appendix 3).[7] Running drills are discussed as a valuable tool for neuromuscular retraining. For example, cues such as 'tail under' during running drills conducted as part of a warm-up may reduce anterior pelvic tilt, and subsequent hamstring load when running at high speeds.

FVP also emerged in Chapter 5 as potentially related to HSI. The pilot prospective study revealed that participants who sustained an HSI scored in the higher percentiles for variables associated with velocity (i.e. the contribution of velocity in achieving maximum horizontal power output was greater than that of force). Again, when synthesised against other research,[8-11] a definitive consensus on the association between FVP and HSI, is yet to be determined. As discussed in Chapter 5, our findings bear similarities to the limited research that exists in this space; with reports of a velocity-oriented profile,[8] or lower horizontal force propulsion outputs in athletes who retrospectively[10,12] or prospectively[9,11,12] sustained a HSI. Until further research is conducted to clarify which variables may

be of interest in different demographics, Hicks and colleagues offer excellent practical considerations for implementing FVP assessment for performance. They propose a performance-based conceptual framework, including technical training recommendations. For example, for athletes exhibiting a more velocity-based FVP (as opposed to force-based), suggestions are provided to increase horizontal propulsion through targeted training in the gym and running retraining techniques.[13] Hicks and Colleagues propose that these FVP interventions not only improve performance, but may also be applicable for HSI prevention. However, in the absence of clear direction from the literature, such as that recommended for anterior pelvic tilt, clinicians and coaches must approach the association between FVP and HSI on a case-by-case basis, employing their collective practical knowledge to determine if the translation of available evidence is appropriate.

The other major practical theme that can be drawn from this thesis are the lessons learnt for the use of field-based methods of running analysis. Adoption of field-based technology is pertinent, particularly as running speed increases and the naked eye cannot be relied upon.[14] The practical advice that can be offered from this thesis to coaches and clinicians 'on the ground' is to know what you are testing and why, choose reliable and valid methods, and when it comes to vision machine learning and artificial intelligent technology understand that the strength of the data sets is only as accurate as the data used to train them (i.e. the inputs).[15] For IMUs specifically, ensure sampling rate is appropriate (i.e. at least 200 Hz for high speed running),[16] but be conscious that too high a sampling rate can result in data overload. Thus, the use of the fewest possible sensors is recommended.[17] Consider safeguarding against factors that may increase sensor noise[18] and negatively affect synchronisation.[19] Treatments include controlling the environmental influences when possible[20] and verify that sensors are securely attached.[21,22] Also, conduct local magnetic disturbance checks,[23] move or adjust testing accordingly, or consider using a magnetometer-free system.[24] Recent 'technological forward leaps' such as increased computer processing speeds, microchip miniaturisation and improved data storage techniques, will likely rectify many of the aforementioned suggestions. However, it is more important than ever that reliance is not placed on the technology but on the skills to use it appropriately.

6.2.2 Limitations

The key limitations of this PhD were technological constraints associated with the IMU system, and low participant recruitment because of restrictions imposed by COVID-19. For the IMU system, various challenges were confronted around funding, validation and unusable observational study data. The consequences of low participant recruitment negatively impacted sample size and subsequent power. These key limitations, as well as their resultant second-order effects, will be discussed in this section.

Various obstacles were faced in finding an appropriate IMU system to utilise in real-life, field-based settings. Only a limited number of IMU sensors for the system that was deemed valid were funded for use. Thus, kinematic variables were limited by the number of sensors. Pelvic, hip and knee kinematics, as well as shank inclination (representing overstride) were prioritised. If funding for more sensors were available, measurement of trunk kinematics would have also been included (based on the findings from the systematic review). Formal validation revealed that the IMU system was inaccurate and inconsistent in measuring knee flexion and shank inclination at POC.

Consequently, these variables were removed from subsequent field-based studies. Thus, the thesis findings are limited to the available variables tested.

Low participant recruitment in the culminating observational study was another key limitation of this thesis. The principal cause of this was restrictions imposed during the COVID-19 pandemic. Fortunately, 23 sprinters were tested prior to the implementation of measures to control the spread of COVID-19 in March 2020 (i.e. social distancing, travel limits and lockdowns). Multiple teams with an abundant number of potential participants were lined up for the following sporting season through professional networks, but testing was not possible due to ongoing restrictions through to the end of 2021 (and further testing once restrictions were removed was not feasible due to candidature suspension/travel limitations with work commitments). Nevertheless, the study still went ahead, albeit with a smaller sample size and reduced statistical power.

In the subsequent field-based observational study whereby the validated IMU system was utilised, data gaps were present in five of the 23 participants' trials. As a result, five participants were removed from kinematic data analysis. A plausible reason for this unusable data is measurement error associated with increased running speed. The previous treadmill-based validation was limited to a maximal belt speed of 18km/hr, whereas the peak velocities observed during the field-based sprint was up to 7-8m/s (25-28km/h). As accuracy showed a tendency to decrease at higher velocities in the validation, the data gaps in the observational study could suggest that data quality is affected at speeds beyond the validated range. Nevertheless, the treadmill validation provided a conservative reference, and the overall pattern of measurements was informative in interpreting the remaining 18 trials within the field-based study. Suggestions to mitigate technological constraints such as these are discussed further in Section 6.2.4.

6.2.3 Strengths

This thesis exhibits two chief strengths. First, the part-time nature of the PhD candidature permitted time for each step of the process to be completed with due diligence, informing the next phase and enabling a logical progression of studies. Second, this research contributed a novel perspective through the use of portable, field-based technology.

The steps taken in this thesis would not have been possible if I had been enrolled full-time. The part-time nature allowed additional time to ensure evidence-informed, logical progression of studies. Rather than skipping immediately to an observation study, a review of the current literature was conducted first to identify gaps and inform variables of interest. The ability to test these variables in the field was then carefully considered and trialled through validation of portable technologies, before observational research was completed. Each stage of this process was timely, involving vigilant planning ahead of ethics submission, approval, study execution and finally, publication. The part-time nature of the study also permitted extra time along the way to explore alternative technologies, accommodate processing and funding delays, and facilitate the conduct of a year-long surveillance period for the culminating observational study.

This thesis aimed to utilise field-based technology to replicate real-life conditions and ensure maximum research translation potential. Even with general running, many biomechanical characteristics are difficult to estimate with the naked eye. Since the emphasis was on biomechanical analysis of high-speed running, the speed of movement makes it particularly difficult

to focus and differentiate between phases of running. Finding valid and reliable field-based methods for biomechanical analysis is an ongoing challenge for coaches and clinicians. Fortunately, some technologies are already validated, with the validation details published for dissemination and use (such as the FVP method in this thesis). But numerous other technologies, such as the wide array of IMU systems on the market, are only tested internally without publicly available data and results.[25] The studies conducted in this thesis provide transparency of methods used to validate one IMU system, including 'lessons learnt', that future researchers can use to build on as technology continues to evolve.

6.2.4 Directions for Future Research

'Using the TRIPP Framework as a model for sports injury prevention (introduced in Chapter 1), more work is still required within TRIPP Stage 2 to better understand the association between running biomechanics and HSI. This thesis offers important findings to inform future planning and trials at both TRIPP Stage 2 and 3. This section proposes the next phase; where we hope to go with this research in the foreseeable future.'

For future work within TRIPP Stage 2, given the multifactorial nature of HSI, future prospective studies should include biomechanical variables of interest in all-inclusive predictive models alongside other potential risk factors such as increased age, previous injury (HSI and others), and reduced strength.[26,27] To understand the link between risk factors and HSI across sporting disciplines, large sample sizes are needed across varying levels and demographics. The sample size should ensure sufficient statistical power and generalisability of results. Further, the study population should include multiple teams, and span at least one season (including the preseason) or one year.[28] Providentially, a large, prospective cohort study with a three-year surveillance period is currently underway in collegiate football players. The protocol aims to develop HSI risk prevention models based on demographic, clinical, patient reported outcomes, strength, magnetic resonance imaging and on-field sprint biomechanical data. It is not stated which on-field sprint biomechanical collection method would be utilised nor which variables analysed, but our systematic review was referenced thus hopefully assisting to inform the protocol.[29]

Recent advantages in technology will enable more exhaustive kinematic risk factor analysis in future studies. For the IMU system we used, the Noraxon 'MyoMOTION' (Noraxon USA Inc., Scottsdale, AZ, United States), there was an 8 sensor limit for an optimal sampling rate of 200 Hz using two receivers.[30] Noraxon's newer model, the 'Ultium', is capable of using 16 sensors using only one receiver at a sampling rate of 300 Hz.[31] Sensor and sampling rate limits vary across products, but typically there is an inverse relationship between the number of sensors and possible sampling rate.[32] Nevertheless, technological advances permit evaluation of more kinematic variables. Variables that should be accounted for in future research into the association between running biomechanics and HSI are trunk kinematics, knee angle and measures of overstride. Knee angle and shank inclination (as a representative of overstride) were planned to be included in our observational study, however validation testing revealed that our IMU system was not recommended for evaluating these variables. Newer iterations of technology may improve the accuracy and consistency of these variables through enhanced processing, refined synchronisation and in-sensor data storage.[31]

Technology will continue to refine methods for kinetic analysis too. Currently FVP is a feasible option but with the advancement of vision-based machine learning and AI, the process will likely become more streamlined into the future. And while IMUs are not currently recommended for high-speed kinetic running analysis,[33,34] the possibilities for the future are limitless. The relationship between kinematics and kinetics has been described at slower running speeds in laboratory settings.[35,36] The opportunity to correlate step-by-step kinematic and kinetic outcomes during high-speed running in field-based settings present significant opportunity to better understand the association between running biomechanics and HSI. Step-by-step analysis will also determine which phase of sprinting injury prevention strategies should focus on.[37]

It is recommended that once biomechanical variables of interest are decided and validation is required, researchers should contact respective technological companies directly to source a 'beta product' or one that is under development. Although some publishers are expediting methods of publication and knowledge share, this PhD journey demonstrates how protracted the academic process prior to knowledge share can be. In the period from pilot testing to formal validation, then observational testing to the end of surveillance, a newer IMU version arose. Working with the industry to test what they are about to release (rather than what is already released) will safeguard researchers work with a product that has the best chance of extended real-world application. Finally, as well as sharing research findings, future studies should ensure the dissemination of lessons learned from working with technology. This will inform the ongoing research and development that is needed to stay updated in the technology realm.

Although more work is required at TRIPP Stage 2, HSI prevention work at TRIPP Stage 3 is well underway both in academia[38-40] and by clinicians 'on the ground'. Future inclusion of running biomechanical interventions in these trials, may be approached from three angles; primary prevention, secondary prevention and tertiary prevention.[41] For primary and tertiary prevention, running biomechanical interventions aim to eliminate or reduce factors which respectively contribute to HSI causation and consequence. Noting all participants in our observational study who sustained a hamstring strain injury (both respectively and prospectively) had a history of HSI, it cannot be determined whether the preliminary biomechanical findings maybe a cause or consequence of HSI. Nevertheless, further research at TRIPP Stage 2, will inform whether interventions to reduce anterior tilt or increase horizontal force will fall into the primary prevention, tertiary prevention or both prevention realms. I foresee these future interventions utilising technology as assessment but also as re-retraining tools.[42,43] For example, an IMU worn on the pelvis may vibrate whenever a sprinter drops into excessive anterior tilt, or an IMU worn on the shank may 'beep' whenever an athlete overstrides. Nevertheless, before this can be achieved, further work at TRIPP Stage 2, needs to first clarify variables and thresholds of interest.

As for the secondary prevention realm, some great work has been started by Wollin and colleagues.[44] They used hamstring isometric strength testing as an early indicator for HSI. If a significant reduction in strength was evident, the athlete's subsequent training load was managed until strength was restored. In their proof-of-concept pilot study, this secondary prevention strategy demonstrated potential in reducing HSI occurrence when compared to controls.[44] Future studies may consider whether these fluctuations in hamstring isometric strength are related to FVP, and thus whether changes in FVP may also be an early indicator for HSI.

6.3 Concluding Remarks

This thesis provided insights into the relationship between high-speed running and HSI, and how the use of portable technology may assist in understanding this complex relationship. Emerging evidence revealed that how an athlete runs (specifically increased anterior pelvic tilt and a velocity-oriented FVP) may be associated with HSI. Our findings and lessons learnt will pave the way for future research in this space. The thesis also offered practical insights into using technology for running biomechanical analysis in field-based, real-world settings. I look forward to seeing how our novel contribution informs future research and is translated into effective injury prevention strategies.

3.4 References

1. Sackett DL, Rosenberg WMC, Gray JAM, Haynes RB, Richardson WS. Evidence based medicine: what it is and what it isn't: it's about integrating individual clinical expertise and the best external evidence. *BMJ*. 1996;312(7023):71-72. doi:10.1136/bmj.312.7023.71
2. Prill R, Mouton C, Klugorová J, Królikowska A, Karlsson J, Becker R. Implementation of evidence-based medicine in everyday clinical practice. *Knee Surg Sports Traumatol Arthrosc*. 2023;31(8):3034-3036. doi:10.1007/s00167-023-07468-y
3. Daly C, McCarthy Persson U, Twycross-Lewis R, Woledge RC, Morrissey D. The biomechanics of running in athletes with previous hamstring injury: a case-control study. *Scand J Med Sci Sports*. 2016;26(4):413-420. doi:10.1111/sms.12464
4. Higashihara A, Ono T, Tokutake G, et al. Hamstring muscles' function deficit during overground sprinting in track and field athletes with a history of strain injury. *J Sports Sci*. 2019;37(23):2744-2750. doi:10.1080/02640414.2019.1664030
5. Schuermans J, Van Tiggelen D, Palmans T, Danneels L, Witvrouw E. Deviating running kinematics and hamstring injury susceptibility in male soccer players: cause or consequence? *Gait Posture*. 2017;57:270-277. doi:10.1016/j.gaitpost.2017.06.268
6. Kenneally-Dabrowski C, Brown NAT, Warmenhoven J, et al. Late swing running mechanics influence hamstring injury susceptibility in elite rugby athletes: A prospective exploratory analysis. *J Biomech*. 2019;92:112-119. doi:10.1016/j.jbiomech.2019.05.037
7. Wolski L. Running drills: As part of hamstring injury management. The nuts and bolts. Journal Article. *Sport Health*. 2020;38(1):26-29. doi:10.3316/informit.237341120323269
8. Ishoi L, Krommes K, Husted RS, Juhl CB, Thorborg K. Diagnosis, prevention and treatment of common lower extremity muscle injuries in sport - grading the evidence: a statement paper commissioned by the Danish Society of Sports Physical Therapy (DSSF). Review. *Br J Sports Med*. 2020;54(9):528-537. doi:10.1136/bjsports-2019-101228
9. Edouard P, Lahti J, Nagahara R, et al. Low horizontal force production capacity during sprinting as a potential risk factor of hamstring injury in football. *Int J Environ Res Public Health*. 2021;18(15):7827. doi:10.3390/ijerph18157827
10. Mendiguchia J, Samozino P, Martinez-Ruiz E, et al. Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *Int J Sports Med*. 2014;35(8):690-695 6p. doi:10.1055/s-0033-1363192
11. Lahti J, Mendiguchia J, Edouard P, Morin J-B. A novel multifactorial hamstring screening protocol: association with hamstring muscle injuries in professional football (soccer) - a prospective cohort study. *Biol Sport*. 2022;39(4):1021-1031. doi:10.5114/biolsport.2022.112084
12. Mendiguchia J, Edouard P, Samozino P, et al. Field monitoring of sprinting power-force-velocity profile before, during and after hamstring injury: two case reports. *J Sports Sci*. 2016;34(6):535-541. doi:10.1080/02640414.2015.1122207
13. Hicks DS, Drummond C, Williams KJ, Pickering C, van den Tillaar R. Individualization of training based on sprint force-velocity profiles: a conceptual framework for biomechanical and

technical training recommendations. *Strength Cond J*. 2023;45(6):711-725. doi:10.1519/SSC.0000000000000790
14. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol*. 2000;89:1991-1999. doi:10.1007/s40279-019-01110-z
15. Mundt M. Bridging the lab-to-field gap using machine learning: a narrative review. *Sports Biomech*. 2023:1-20. doi:10.1080/14763141.2023.2200749
16. Macadam P, Cronin J, Neville J, Diewald S. Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: a systematic review. *Gait Posture*. 2019;73:26-38. doi:10.1016/j.gaitpost.2019.07.123
17. Baker LM, Yawar A, Lieberman DE, Walsh CJ. Predicting overstriding with wearable IMUs during treadmill and overground running. *Sci Rep*. 2024;14(1):6347-6347. doi:10.1038/s41598-024-56888-4
18. Akbari A, Thomas X, Jafari R. Automatic noise estimation and context-enhanced data fusion of IMU and Kinect for human motion measurement. presented at: IEEE 14th International Conference on Wearable and Implantable Body Sensor Networks (BSN); 09-12 May 2017 2017; Eindhoven, Netherlands.
19. Verdel N, Mohorcic M, Drobnic M, Supej M, Depolli M. Time synchronization in wireless IMU sensors for accurate gait analysis during running. presented at: IEEE International Workshop on Sport, Technology and Research (STAR) 14-16 Sept 2023 2023; Cavalese - Trento, Italy.
20. Benson LC, Räisänen AM, Clermont CA, Ferber R. Is this the real life, or is this just laboratory? A scoping review of IMU-based running gait analysis. *Sensors*. 2022;22(5):1722. doi:10.3390/s22051722
21. Camomilla V, Dumas R, Cappozzo A. Human movement analysis: the soft tissue artefact issue. *J Biomech*. 2017;62:1-4. doi:10.1016/j.jbiomech.2017.09.001
22. Zeng Z, Liu Y, Li P, Wang L. Validity and reliability of inertial measurement units measurements for running kinematics in different foot strike pattern runners. *Front Bioeng Biotechnol*. 2022;10:1005496. doi:10.3389/fbioe.2022.1005496
23. Robert-Lachaine X, Mecheri H, Larue C, Plamondon A. Effect of local magnetic field disturbances on inertial measurement units accuracy. *Appl Ergon*. 2017;63:123-132. doi:10.1016/j.apergo.2017.04.011
24. Weygers I, Kok M, Konings M, Hallez H, De Vroey H, Claeys K. Inertial sensor-based lower limb joint kinematics: a methodological systematic review. *Sensors*. 2020;20(3):673. doi:10.3390/s20030673
25. Zeng Z, Liu Y, Hu X, Tang M, Wang L. Validity and reliability of inertial measurement units on lower extremity kinematics during running: a systematic review and meta-analysis. *Sports Med* 2022;8(1):86. doi:10.1186/s40798-022-00477-0
26. Green B, Bourne MN, van Dyk N, Pizzari T. Recalibrating the risk of hamstring strain injury (HSI): a 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. *Br J Sports Med*. 2020;54(18):1081-1088. doi:10.1136/bjsports-2019-100983
27. Liveris NI, Tsarbou C, Papageorgiou G, et al. The complex interrelationships of the risk factors leading to hamstring injury and implications for injury prevention: a group model building approach. *Appl Sci*. 2024;14(14):6316. doi:10.3390/app14146316
28. W. FC, Ekstrand J, Junge A, et al. Review: consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Scand J Med Sci Sports*. 2006;16(2):83-92. doi:10.1111/j.1600-0838.2006.00528.x
29. Heiderscheit BC, Blemker SS, Opar D, et al. The development of a HAMstring InjuRy (HAMIR) index to mitigate injury risk through innovative imaging, biomechanics, and data analytics: protocol for an observational cohort study. *BMC Sports Sci Med Rehabil*. 2022;14(1):1-128. doi:10.1186/s13102-022-00520-3

30. Noraxon. *myoMOTION Sensor and Receiver User Manual*. 2020. https://www.noraxon.com/download/myomotion-system-user-manual/?wpdmdl=18194&refresh=6850efabde90a1750134699
31. Inc. NUSA. *Ultium motion hardware user manual*. Vol. 2025. 2024. https://www.noraxon.com/our-products/ultium-motion/
32. González-Alonso J, Oviedo-Pastor D, Aguado HJ, Díaz-Pernas FJ, González-Ortega D, Martínez-Zarzuela M. Custom IMU-based wearable system for robust 2.4 GHz wireless human body parts orientation tracking and 3D movement visualization on an avatar. *Sensors*. 2021;21(19):6642. doi:10.3390/s21196642
33. Kenneally-Dabrowski CJ, Serpell BG, Spratford W. Are accelerometers a valid tool for measuring overground sprinting symmetry? *Int J Sports Sci Coach*. 2018;13(2):270-277. doi:10.1177/1747954117716790
34. Gurchiek RD, McGinnis RS, Needle AR, McBride JM, van Werkhoven H. The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *J Biomech*. 2017;61:263-268. doi:10.1016/j.jbiomech.2017.07.035
35. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Kinematic correlates of kinetic outcomes associated with running-related injury. *J Appl Biomech*. 2019:1-8. doi:10.1123/jab.2018-0203
36. Wille CM, Lenhart RL, Wang S, Thelen DG, Heiderscheit BC. Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running. *J Orthop Sports Phys Ther*. 2014;44(10):825-30. doi:10.2519/jospt.2014.5367
37. Nagahara R, Matsubayashi T, Matsuo A, Zushi K. Kinematics of transition during human accelerated sprinting. *Biol open*. 2014;3(8):689-699. doi:10.1242/bio.20148284
38. Rudisill SS, Varady NH, Kucharik MP, Eberlin CT, Martin SD. Evidence-based hamstring injury prevention and risk factor management: a systematic review and meta-analysis of randomized controlled trials. *Am J Sports Med*. 2023;51(7):1927-1942. doi:10.1177/03635465221083998
39. Silvers-Granelli H, Silverman R, Bizzini M, Thorborg K, Brophy RH. The 11+ injury prevention programme decreases rate of hamstring strain injuries in male collegiate soccer players. *Br J Sports Med*. 2024;58(13):701-708. doi:10.1136/bjsports-2023-107323
40. Afonso J, Reurink G, Clemente FM, Ramirez-Campillo R, Pizzari T, Andrade R. Revisiting the hamstring injury prevention and rehabilitation literature: filling the gaps. *Br J Sports Med*. 2023;58(5):243-244. doi:10.1136/bjsports-2023-106878
41. Fletcher GS. *Clinical epidemiology the essentials*. 6th ed. vol 6th. Wolters Kluwer; 2020.
42. Zhou L, Fischer E, Tunca C, et al. How we found our IMU: guidelines to IMU selection and a comparison of seven IMUs for pervasive healthcare applications. *Sensors*. 2020;20(15):4090. doi:10.3390/s20154090
43. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Real-time biofeedback of performance to reduce braking forces associated with running-related injury: an exploratory study. *J Orthop Sports Phys Ther*. 2019;49(3):136-144. doi:10.2519/jospt.2019.8587
44. Wollin M, Thorborg K, Drew M, Pizzari T. A novel hamstring strain injury prevention system: post-match strength testing for secondary prevention in football. *Br J Sports Med*. 2020;54(9):498-499. doi:10.1136/bjsports-2019-100707

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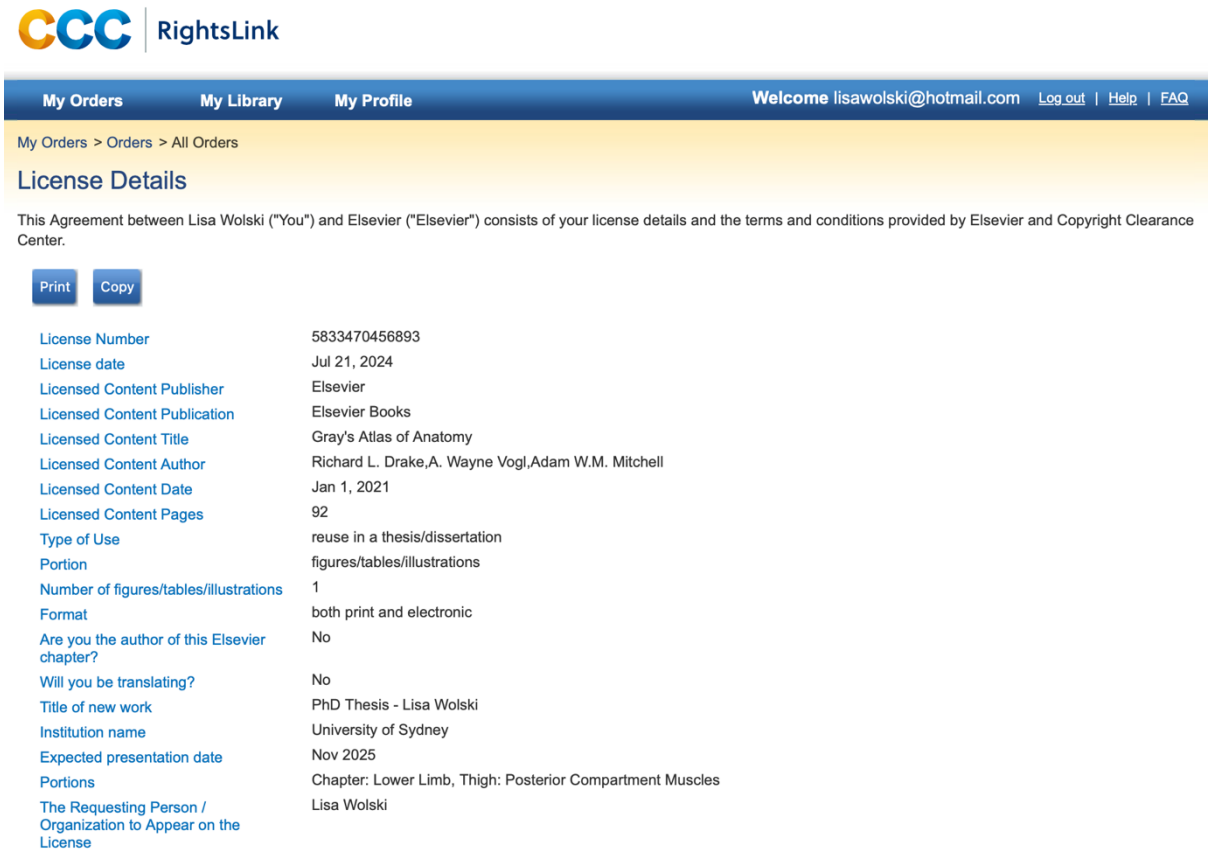

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- Figure 1.3: Running Phases
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- Figure 1.4: 'Prevention Continuum' or Natural History of Disease

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Appendix 2: Manual of Procedures

A2.1 Validation Study Data Collection Procedures

A2.1.1 Motion Analysis System (MAS) Setup and Calibration

i) Check air conditioning units are working and set to an appropriate temperature.

ii) Turn on Camera Power Box (at least 1 hour before data collection to warm up the system)

iii) Log-on to the lab computer

iv) Open the Cortex program: C:/ProgramFiles/Cortex

v) Create a new folder for each participant

- Load template project file (R:\ESSusers\Lisa\ValidationStudy) and save in new folder (yyyymmdd)
- Save the new file in yyyymmdd format

vi) Click File > Load Project, open the project file in the new folder. Save the project file.

vii) Position Cameras

Camera	Height
1	Neck raised Legs half length
2	Neck raised Legs half length
3	Neck lowered Legs extended
4	Neck raised Legs half length
5	High Rig
6	High Rig
7	Ceiling
8	High Rig
9	High Rig
10	Neck raised Legs half length
11	Neck lowered Legs extended
12	High Rig
13	High Rig
14	Ceiling

Table A2.1: Camera Orientation

viii) Check Camera Settings

- Setup. Eagle Settings:
  - Frame Rate: 200
  - Shutter Speed: 500
- Zoom: 'zoom out' to maximum setting.
- Focus: Infinity

Camera	Focal Length	Brightness	Threshold
1	24	100	500
2	30	100	500
3	35	100	500
4	18	100	500
5	18	100	500
6	35	100	500
7	21	100	500
8	18	100	500
9	28	100	500
10	35	100	500
11	18	100	500
12	35	100	500
13	35	100	500
14	21	100	500

Table A2.2: Camera settings

ix) Configure Force Plate.

- Kistler Large Yellow Dot (9287B SN 925969)
- FxFy Range: 3, Fz Range: 3
- Frequency: 200Hz
- Dimensions: 600x900mm
- Check all four corners of force plate functioning

Channel	1	2	3	4	5	6	7	8
Signal	X1+X	X3+4	Y1+4	Y2+3	Z1	Z2	Z3	Z4
Range 1 (mv/N)	38.745	38.399	39.028	38.628	19.250	19.591	19.599	19.289
Range 2 (mv/N)	19.372	19.200	19.514	19.314	9.625	9.795	9.799	9.644
Range 3 (mv/N)	3.875	3.841	3.883	3.845	1.918	1.951	1.953	1.922
Range 4 (mv/N)	1.937	1.921	1.942	1.922	0.959	0.976	0.976	0.961

Table A2.3: Force Plate Sensitivity Matrix

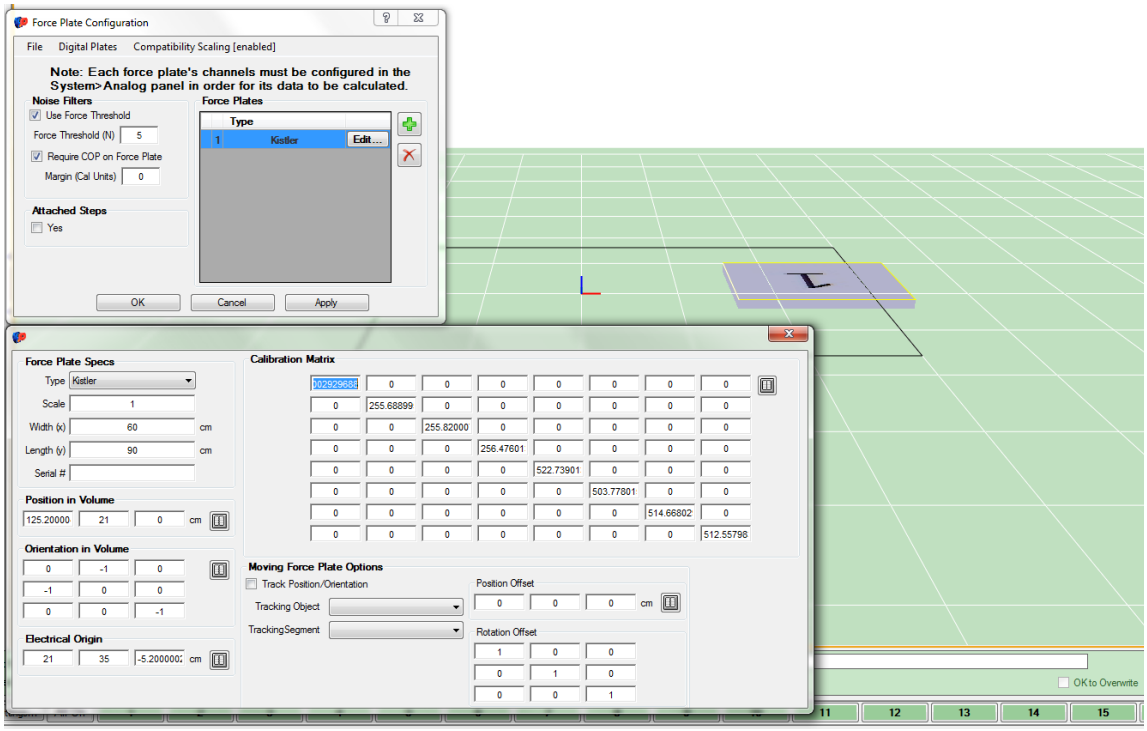


Figure A2.1: Force plate configuration

x) Perform Seed Calibration. The origin is directly over the third force sensor of the Green Dot force plate.

+X towards the acceleration track roller door (West)

+Y towards the back wall of the lab (South)

+Z upwards

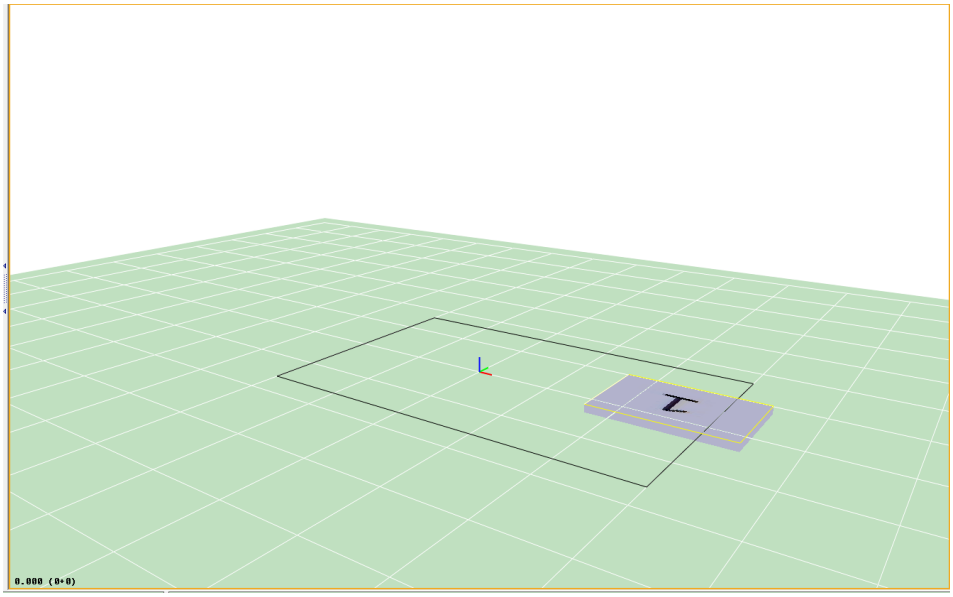


Figure A2.2: Seed axis configuration: Red – X, Green – Y, Blue - Z

(Picture also displays position of force plate)

xi) Perform Wand Calibration

- Use the 504 mm wand.

- Move the wand through the capture volume so it is aligned with the X, Y and Z axis for an even amount of time, i.e. 30 seconds for each axis (total 90 seconds)
- Accuracy should be less than 0.5 mm, i.e. < 504.5 and > 503.5
- Save the Cortex Project File after the Seed & Wand calibrations are complete

xii) Position treadmill (Model FQTM250, Fitquip, Australia) facing East over force plate, under left rear base as per Figure A1.3

xiii) Zero force plate using manual switch

xiv) Check settings ready for trail:

Tracking > Centroid Parameters >	Min Horizontal Lines per Marker:	2
	Max Horizontal Lines per Marker:	50
	Shape Analysis:	normal
> Tracking Parameters >	Max Residual (mm):	15
	Max Speed (mm/frame):	350
	Marker Size (mm):	15
	Max Prediction Error (mm):	30
	Min. Cameras to use:	3
> Identifying Parameters >	To reconsider (std.dev.):	10
	Max Acceptable (std.dev.):	4

xv) MAS ready for trial

Figure A2.3: Treadmill in position

A2.1.2 Noraxon IMU System Setup

i) IMU system:

- Noraxon's 'MyoMotion' sensor, receiver and software (Noraxon USA Inc., Model 680 receiver, Model 610 sensor)
- IMUs specifications:
    - >8 hours operating time (3 hours to re-charge)
    - Size: 37.6mm x 52mm x 18.1mm in size
    - Weight: 34g
    - Sampling rate up to 200Hz
    - Gyro speed up to 2000 degrees/second
    - Acceleration range up to 16G.

Figure A2.4: Noraxon MyoMotion sensor

ii) Ensure three sensors are fully charged using charging station

iii) Load Noraxon MR3 Software Windows laptop

iv) Connect single receiver to SS (high speed) USB port of the computer

Figure A2.5: Noraxon receiver set up

v) Configure hardware

- Input serial numbers against relevant body part where sensor will be placed

vi) Open device settings:

- Select sampling rate of 200Hz
- Enable acceleration data
- Connect Noraxon Myosync (as per Figure A1.6)
    - Channel 2 Sync Out to receiver
    - Channel 1 Sync Out to Channel 9 on MAS
- Check Hardware sync box on Noraxon software

Figure A2.6: Noraxon Myosync connection to Receiver and MAS

vii) Create a new subject.

- Naming conventions: 'Validation_SubX'
- Configure available devices, select 'Pelvis', 'Left thigh' and 'Left Shank' body segments
- Select 'Measure' to activate sensors

viii) Noraxon system ready for trial

A2.1.3 Administration

i) Information sheet provided for participant to read.

ii) General introduction of the procedures explained to the participant.

iii) Informed consent signed by participant.

iv) Participant's name, age, sex, height and body mass are measured / recorded

v) *First Aid Assistance.*

- In a medical emergency, dial 0-000 and ask for an ambulance. Provide the ambulance with instructions as to which gate to enter University grounds. Indicate the nature of the emergency. A member of staff or another person should go to that gate to direct the ambulance when it arrives. Notify Security - Dial 3
- In a situation requiring first aid, the nearest First Aid Officer should be contacted to render assistance.
- First aid officers / kit locations:
    - Gatehouse (24 hours) - All Security Officers: 19230
    - H Block - Ground Floor Corridor - Diane Eager: 19142
    - There is a basic First Aid room (including a bed) in E Block.

- A wheelchair is located in E Block for transport if required.

- Nearest External Medical Services:
  - John Street Medical Centre - 56 John St. Lidcombe. Ph. 9649 7201 or 9649 9391 (M-F 8am - 6pm)
  - Auburn Hospital - Norval St. Auburn. Ph. 9563 9500 (24 hours)
  - Bankstown Hospital - Eldridge Rd. Bankstown. Ph. 9722 8000 (24 hours)
- Poison Information Centre telephone assistance 13 11 26

A2.1.4 Biomechanical Data Collection

i) Participants change into minimal clothing and own running shoes (participant advised of appropriate clothing requirements prior to trial day)

ii) Cover any reflective strips on clothing and/or running shoes

iii) Fix IMUs to left shank, left thigh and pelvis. Instructions as follows:

- Left shank (Sensor 1 – with marks on the top and bottom indicating the midline of the sensor)
  - Mark a dot in the centre of the runner's left head of fibula and left lateral malleolus
  - Draw a line connecting these two dots
  - Take the sensor out of the charging dock and place double sided tape on back
  - With the green light flashing on the top of the sensor, stick the sensor 3-4cm above the lateral malleolus (on the flattest surface possible). The two marks of on the top and bottom should align with the line drawn on the shank. Note the X axis on the sensor should point up
  - Reinforce with elastic adhesive bandage
- Left thigh (Sensor 2)
  - With the green light flashing on the top of the sensor, stick the sensor using double sided tape on the mid, lateral thigh. Note the X axis on the sensor should point up
  - Reinforce with elastic adhesive bandage
- Pelvis (Sensor 3)
  - With the green light flashing up, place the sensor into the bracket within the Noraxon pelvic strap. Reinforce small piece of tape.
  - Affix pelvic strap to participant using clips. Adjust straps to ensure secure fit. The front of strap should rest at/ slightly below anterior superior iliac spines. The sensor at the back should rest at the top of the sacrum (slightly below L5). The strap to be in contact with the skin below clothing so it does not slide from its position

iv) Fix retro-reflective markers to anatomical landmarks using double sided tape

Number	Marker name	Location
1	L_ASIS	Left ASIS
2	R_ASIS	Right ASIS
3	L_PSIS	Left PSIS
4	R_PSIS	Right PSIS

5	L_GT	Left greater trochanter
6	L_TH_1	Left mid-thigh (cluster top left)
7	L_TH_2	Left mid-thigh (cluster top right)
8	L_TH_3	Left mid-thigh (cluster bottom right)
9	L_TH_4	Left mid-thigh (cluster bottom left)
10	L_LAT_KNEE	Left lateral condyle
11	L_MED_KNEE	Left medial condyle
12	L_TTUB	Left tibial tuberosity
13	L_HFIB	Left head of fibula
14	L_LEG_1	Left lower leg (cluster top left)
15	L_LEG_2	Left lower leg (cluster top right)
16	L_LEG_3	Left lower leg (cluster bottom right)
17	L_LEG_4	Left lower leg (cluster bottom left)
18	L_LMAL	Left lateral malleolus
19	L_MMAL	Left medial malleolus
20	L_D5MT	Left 5th metatarsal joint
21	L_D1MT	Left 1st metatarsal joint
22	L_HLX	Left hallux

Table A2.4: Marker names and locations

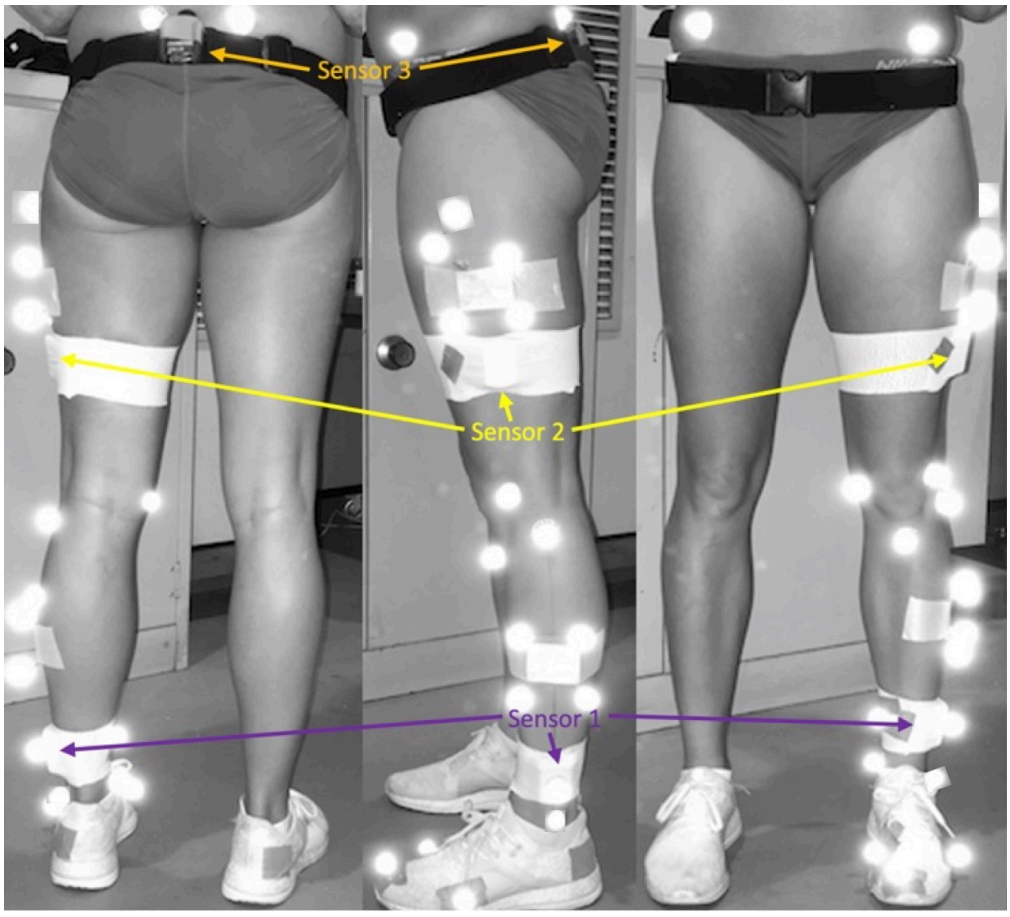


Figure A2.7: Marker and IMU placement

v) Static Reference Data (collected for both Cortex and Noraxon simultaneously)

- Static Reference Trial to determine the following:
  - Marker and IMU Identification Template
  - An anatomical reference position for subsequent trials
  - Sagittal Plane Static Lower Limb Posture
- The participant stands on the centre of the treadmill belt facing East, hands on hips with even weight distribution for at least 4 seconds

vi) Dynamic Reference Data (for Cortex only)

- Movement of the pelvis, hip joint, knee joint and ankle joint complex will be recorded by the motion analysis system
- Participant is asked to march on the spot with hands on hips for 30 seconds

vii) Motion Analysis of Running

- Warm up: Participant conducts self-determined warm up
- Participant instructed on treadmill safety and how to change speeds
- Participant given time to practice trial procedure before allowed up to 5 mins to rest / prepare for data collection
- Test data: Running at 12, 14, 16 and 18 km/hr (at least 5 seconds at each speed)
  - Start Cortex before Noraxon
  - Once complete stop Noraxon before Cortex

viii) Cortex Biomechanical Data Processing

- Ensure marker names are correct
  - Check trial data for any marker switchers and unidentified markers then rectify as necessary
- Review Point of Contact data
  - Check force plate data for noise
- Save copy to a 'Clean' folder. Output files:
  - Raw video (.vc*)
  - Tracked ASCII (.trc)
  - Tracked binary (.trb)
  - 3D motion capture (.c3d)
  - Force (.anb)
- Export to Visual 3D (V3D)
- Click file → Export to V3D
  - Static only (for static export)
  - Dynamic only (for dynamic export)

ix) Noraxon Biomechanical Data Processing

- Check all signals and export record to (.mat) Matlab file

A2.1.5 Visual 3D - Data Processing

i) Create biomechanical model

- Enter markers / anatomical landmarks (as per Table A1.5)
- Enter virtual marker calculations:
  - LEFT_HIP
    - ML: -0.36*ASIS_Distance*RPV_ML_Direction

        - AP: -0.19*ASIS_Distance*RPV_AP_Direction
        - AXIAL: -0.30*ASIS_Distance*RPV_Axial_Direction
    - L_TTUB_Projected:
        - Starting Point: L_HFIB
        - Ending Point: L_LMAL
        - Lateral object: L_MMAL
        - Project from: L_TTUB
    - L_MAL_Centre:
        - Starting Point: L_LMAL
        - Ending Point: L_MMAL
    - L_KNEE
        - Starting Point: L_TTUB_Projected
        - Ending Point: L_TTUB
        - Lateral object: L_MAL_Centre
        - Project from: L_HFIB
- Enter pelvic coda segment (used for hip angle relative to pelvis)
    - R.ASIS: R_ASIS
    - L.ASIS: L_ASIS
    - R.PSIS: R_PSIS
    - L.PSIS: L_PSIS
    - Calibration targets: Box checked to use calibration targets for tracking
- Input V3D body segment definitions (bilateral pelvis with a unilateral lower limb biomechanical model)

Segments	**Properties:** Segment Mass / Segment Geometry	**Proximal definition**	**Distal markers**	**Target Tracking Marker**
Pelvis2	0.142*Mass / Cylinder	NA	NA	NA
Left thigh	0.1*Mass / Cone	Lateral: L_GT Joint Centre: LEFT_HIP	Lateral: L_LAT_KNEE Medial: L_M_KNEE	L_TH_1 L_TH_2 L_TH_3 L_TH_4
Left Shank	0.0465*Mass / Cone	Lateral: L_LAT_KNEE Medial: L_M_KNEE	Lateral: L_LMAL Medial: L_MMAL	L_LEG_1 L_LEG_2 L_LEG_3 L_LEG_4

Table A2.5: Body segment definitions

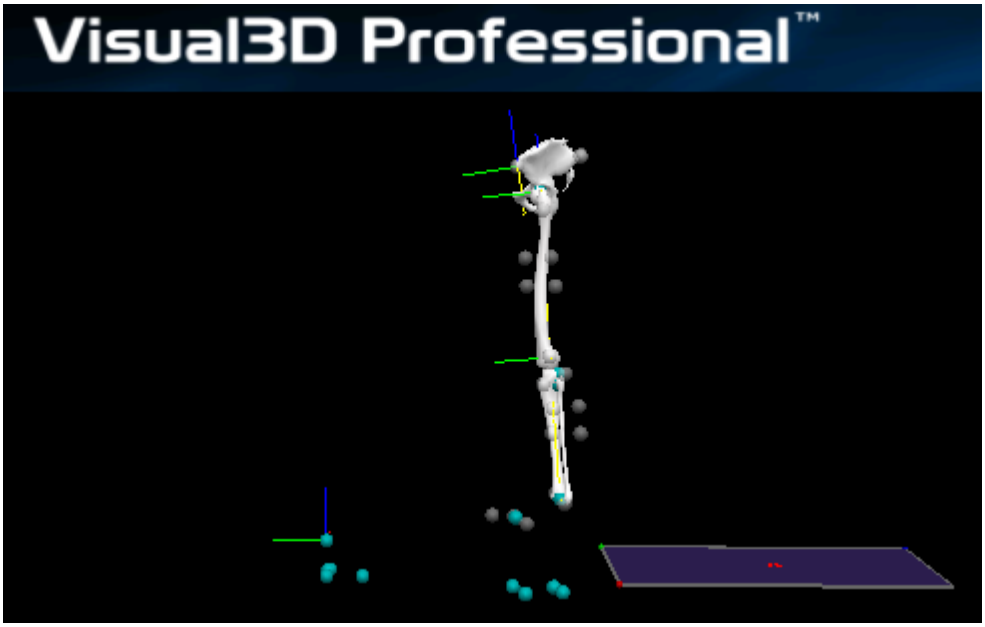


Figure A2.8: V3D Static Reference (view from left side)

ii) Save as 'left side' model file

iii) Find and open relevant V3D trail file

iv) Create / add static calibration file

- Select hybrid model from .c3d file → check static reference → OK

v) Prepare software workspace

- Click on picture file MDH (model template file) with dark green arrow
- Open V3D 'left side MDH' model file
- Select Models tab → click on black → click on skeleton picture to turn on

vi) Click on Signals and Events → check video *(scroll on mouse for zoom or hold left button for rotation)*

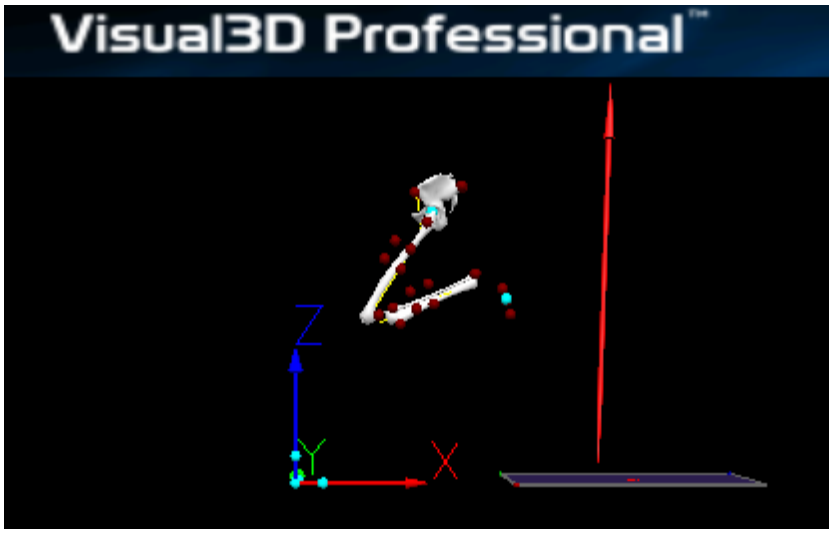


Figure A1.9: V3D Trail (view from left side). Left lower limb swing phase. Red arrow denotes right ground contact.

vii) Export to Matlab

- Click on pipeline picture → open pipeline → open

```
Export_Data_To_Matfile
/SIGNAL_TYPES=TARGET+TARGET+TARGET+ANALOG+ANALOG+ANALOG+ANALOG
+ANALOG+ANALOG+ANALOG+ANALOG+ANALOG+LINK_MODEL_BASED+DERIVED
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORIGINA
L+ORIGINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORIGINAL+PR
OCESSED
/SIGNAL_NAMES=L_D1MT+L_GT+L_HLX+F1X1+F1X3+F1Y1+F1Y2+F1Z1+F1Z2+F1Z3+
F1Z4+Sync+Shank_Angle+Hip_Toe_X
/FILE_NAME=c:\users\mhal8291\desktop\lisa pilot\lisa_pilot.mat
! /FOLDER=
! /CREATE_FOLDER_PATH=FALSE
/MATLAB_NAMES=L_D1MT+L_GT+L_HLX+F1X1+F1X3+F1Y1+F1Y2+F1Z1+F1Z2+F1Z3
+F1Z4+Sync+Shank_Angle+Hip_Toe_X
! /PARAMETER_NAMES=
! /PARAMETER_GROUPS=
! /OUTPUT_PARAMETER_NAMES=
/USE_NAN_FOR_DATANOTFOUND=TRUE
;
```

Figure A.2.10: Copy of Pipeline

- Under Export data to Matfile (click on)→ edit → change file name → change output file to browse
- Return to original subject file → rename same as step above .mat
- Click on execute pipeline button → OK

viii) Save V3D → File → Save Workspace as → same name in same file (as .cmz file)

A2.1.6 Visual 3D - Data Processing

i) Matlab (The MathWorks Inc., Natick, USA) software is utilised for further data processing and POC detection

- Open working file (Matlab .m code file and current trial directory must be in same folder)
- Open .m code file (see Annex A)
- Click 'Run'
- Select .mat trial file for Noraxon then select corresponding .mat trial file for MAS
- The script will find the synchronisation pulse and align the data from both systems. Check alignment (as per Figure A1.11)

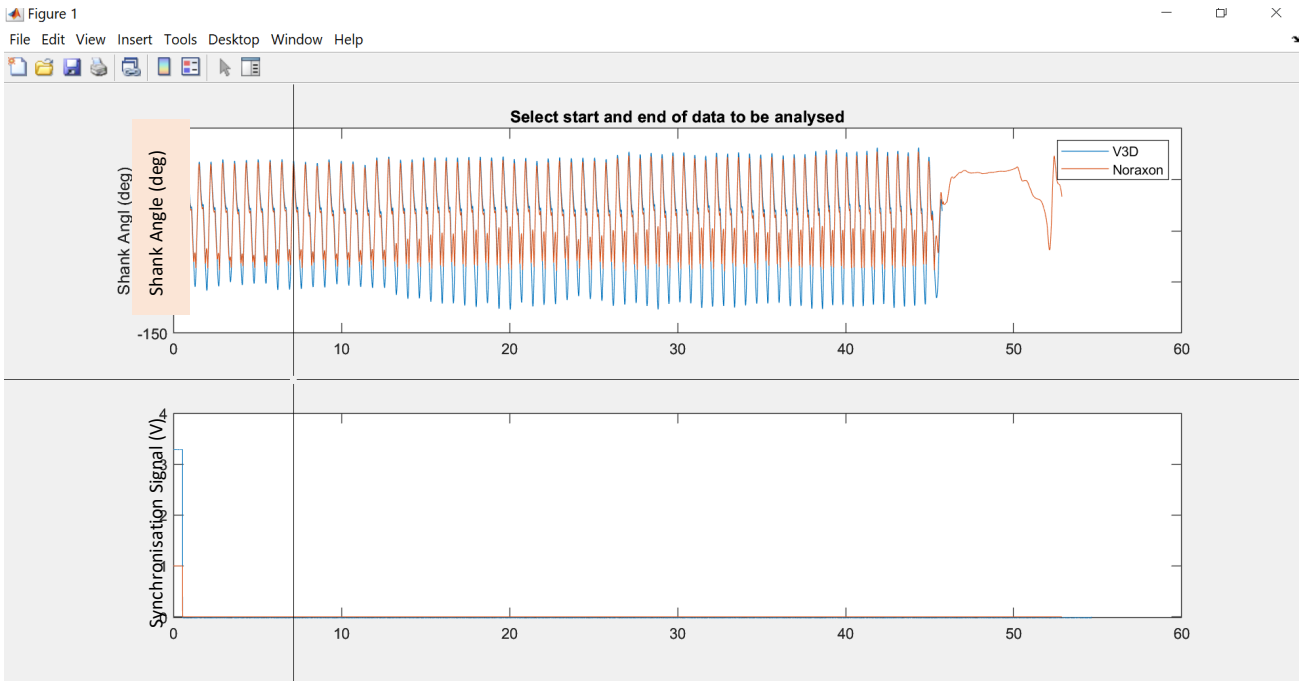


Figure A2.11: Example Matlab output visualising V3D and Noraxon kinematic data (shank angle) and Synchronisation Signal

- Select start and end of running data to be analysed
- A graph displaying the summed vertical force will be displayed (Figure A1.12)
- Select a threshold force to be used to detect POC using the force plate

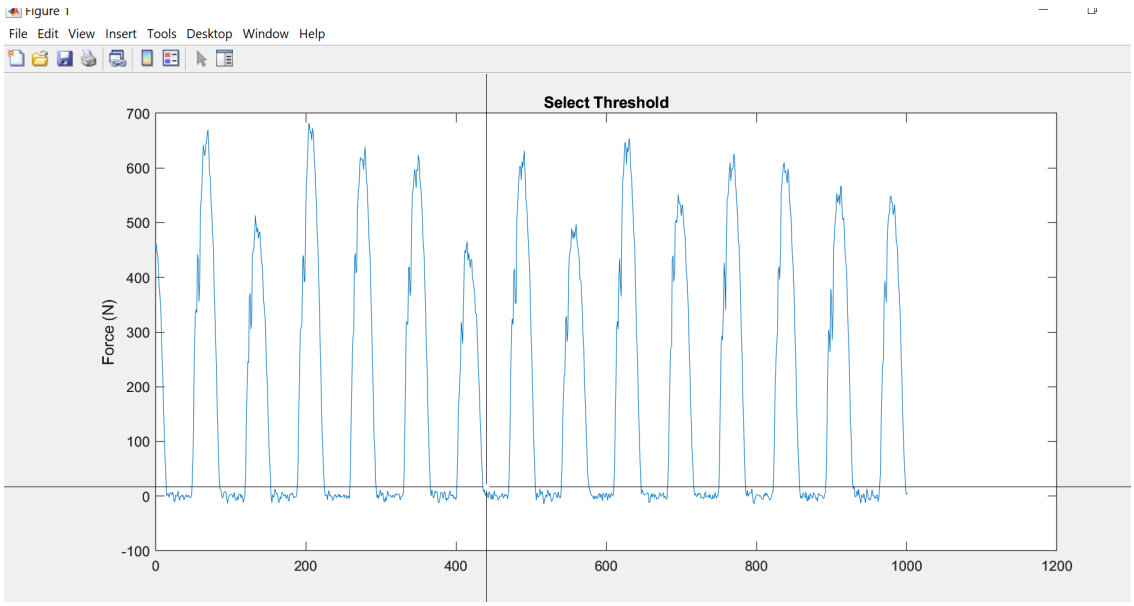


Figure A2.12: Selection of force threshold to identify POC

- Check each cycle and adjust contact time as appropriate (Figure A1.13)

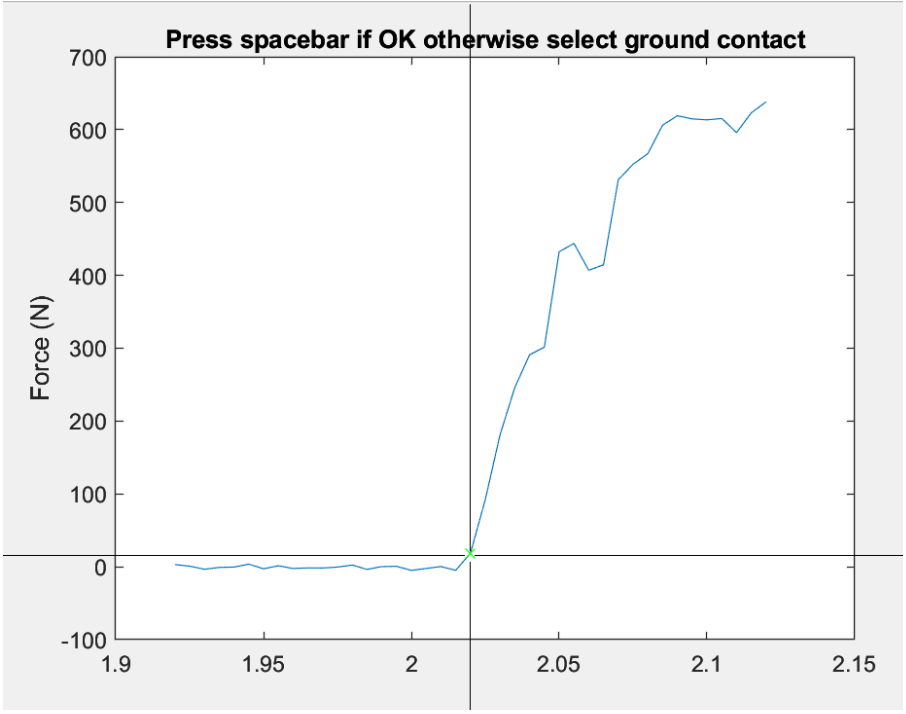


Figure A2.13: POC identification and checking using force plate data

- A graph with hip flexion and knee flexion angle from the Noraxon data will appear
- Identify POC (as determined by Noraxon) using shank acceleration (earth-based Y axis) and hip flexion data. The first negative minima in acceleration trace after maximal hip flexion is manually identified for each stride cycle by moving curser as appropriate and confirming with space bar

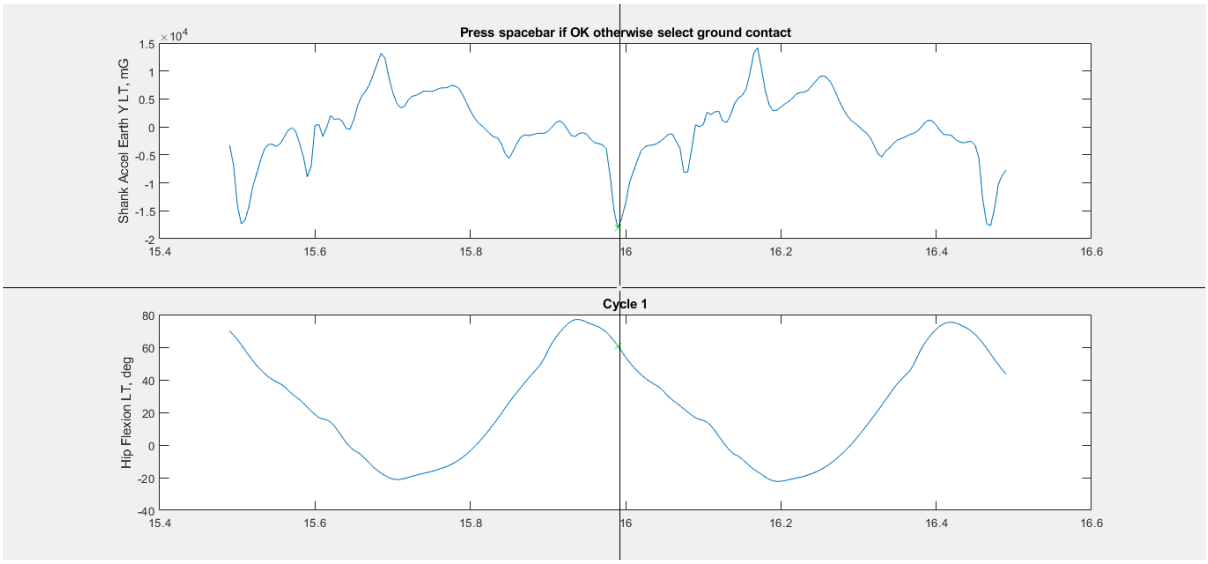


Figure A2.14: POC detection method

- Continue step above for all stride cycles
- Shank acceleration (earth-based Y axis), hip flexion and knee flexion graphs of all cycles continuously (with POC marked) will then appear. Review then close

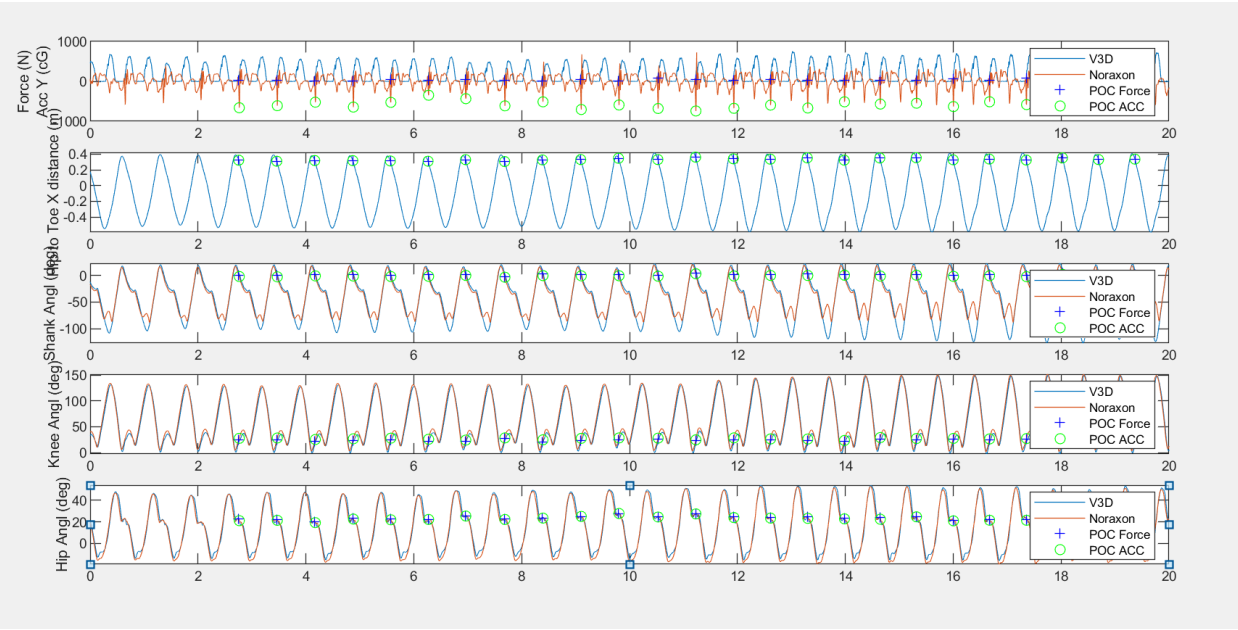


Figure A2.15: Continuous output cycle graphs

- The code will then be running in the background, to create an excel file of all data. Once done the command window will clear
- New 'output' (Matlab figure, Matlab data and Excel) files will be saved in same working folder

A2.2 Cross-sectional and Cohort Study Data Collection Procedures

A2.2.1 Force Velocity Profiling Set Up

i) The validated *MySprint* iPhone application was utilised to quantify sprint FVP in order to characterise kinetics of acceleration (for first 30m only).

- *MySprint* user specifications:
    - Developed by Pedro Jimenez Reyes
    - Version 1.10 installed on iPhone XR running iOS 13
    - Videos filmed with iPhone's build in camera on 'Slo-mo' for 1080p at 240fps

ii) Grass track set up as per *MySprint* application instructions:

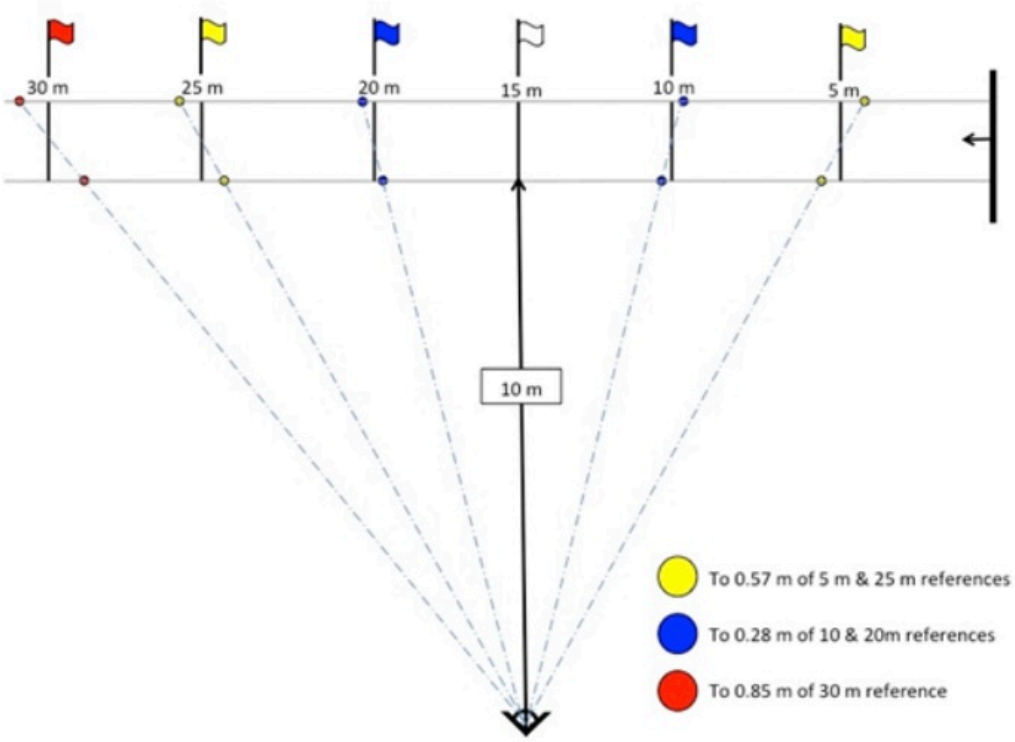


Figure A2.16 : *MySprint* FVP reference system

- Blue cones mark start (0m) and finish (40m)
- Yellow poles denote 5, 10, 15, 20, 25 and 30m. These poles are offset in accordance with Figure A1.16 to correct parallax
- iPhone mounted on tripod 10m from the track enabling smooth rotational movement during the sprint recording (athlete maintained in centre of video image)

iii) On Home screen click 'Tests' then select FVP icon

iv) Add User

- Name: Participant initials (add number after if duplicates)
- Complete weight and height, and save

v) To prepare for recording, click on user and mount phone horizontal orientation on tripod

A2.2.2 Noraxon Setup

i) IMU system:

- Detail as per validation study (Section 1.2)

ii) Ensure five sensors fully charged using charging station

iii) Load Noraxon MR3 Software Windows laptop

iv) Connect dual receiver to USB port of the computer
(Note: Only single receiver used for Validation Study)

Figure A2.17: Noraxon MyoMotion dual receiver

v) Configure hardware
- Input serial numbers against relevant body part where sensor will be placed
- Detail as per validation study (Chapter 4) with addition of second thigh (Sensor 2) and shank (Sensor 1) IMUs for bilateral data collection

vi) Open device settings:
- Select sampling rate of 200Hz
- Enable acceleration data

vii) Create a new subject:
- Naming conventions: Participant number followed by initials e.g. 1 AB
- Configure available devices, select 'Pelvis', 'Left thigh', 'Right thigh', 'Left Shank' and 'Right Shank' body segments
- Select 'Measure' to activate sensors

viii) Noraxon system ready for trial

A2.2.3 Administration

i) Information sheet provided for participant to read
ii) Informed consent signed by participant
iii) General introduction of the procedures explained to the participant
iv) Participant's name, age, gender, height and weight are measured / recorded
v) Record current temperature (°C) and air pressure (hPa) – measured with iPhone XR running iOS 13 (Apple weather application)
vi) *First Aid Assistance:*
- In a medical emergency, dial 0-000 and follow directions of operator
- In a situation requiring first aid, the nearest first aid post at the sporting ground should be contacted to render assistance. If there is no first aid post, the researcher will provide support

A2.2.4 Biomechanical Data Collection

i) Participants change into minimal clothing and own running shoes (participant advised of appropriate clothing requirements prior to trial day)

ii) IMUs fixed to pelvis, and left and right thigh using double-sided tape, elastic adhesive bandage and straps as per Figure A1.7 (but on both sides and no retroreflective markers)

iii) Static Reference Data (for Noraxon)

- Static Reference Trial to determine the following:
  - IMU Identification Template
  - Sagittal Plane Static Lower Limb Posture
- The participant stands still, hands on hips with even weight distribution for 30 seconds

iv) Complete 40m Sprint Trial

- Warm up: Participant conducts own warm up
- Participant given time to practice trial procedure before allowed up to 5 mins to rest / prepare for data collection
- Prior to trial, commence Noraxon recording
- Test data: One 40m maximal sprint from a 3-point crouch start (initiated by participant)
- Trail is filmed using MySprint application while Noraxon MyoMotion data recorded simultaneously
- Noraxon recording is stopped before IMUs are removed

A2.2.5 Biomechanical Data Processing

i) Force-Velocity Profiling

- The MySprint *application* is used to determine start and, 5, 10, 15, 20, 25 and 30m split times.
  - Scroll through captured video on *MySprint* application to select appropriate frames
  - The start of sprint is the first frame when to their thumb leaves the ground
  - Subsequent splits are determined by aligning the participant's hip with the respective agility poles
  - Record each split time in milliseconds

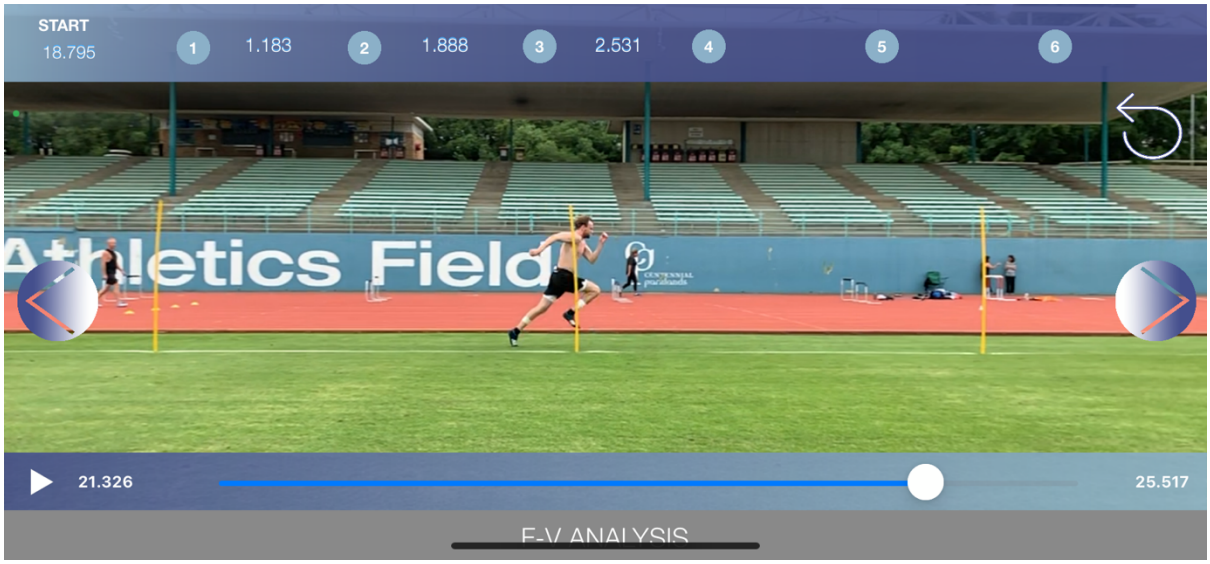


Figure A2.18: Screenshot from *MySprint* application (determining split times)

- Download 'fvpsprint_splits-and-speed' Excel spreadsheet from https://jbmorin.net/downloads-/
    - Input height, weight, temperature, air pressure and split times in relevant yellow boxes
    - Follow instructions on spreadsheet to run Excel solver in order to generate full profile including graphs

ii) Kinematic data processing

- Noraxon trail data saved as both .slk and .mat files

iii) Matlab (The MathWorks Inc., Natick, USA) software is utilised for further data processing and POC detection

- Open working file (Matlab .m code file and current trial directory must be in same folder)
- Open .m code file (see Annex B)
- Click 'Run'
- Select start and end of running data to be analysed
- A graph with hip flexion and knee flexion angle from the Noraxon data will appear
- Identify POC (as determined by Noraxon) using shank acceleration (earth-based Y axis) and hip flexion data. The first negative minima in acceleration trace after maximal hip flexion is manually identified for each stride cycle by moving curser as appropriate and confirming with space bar

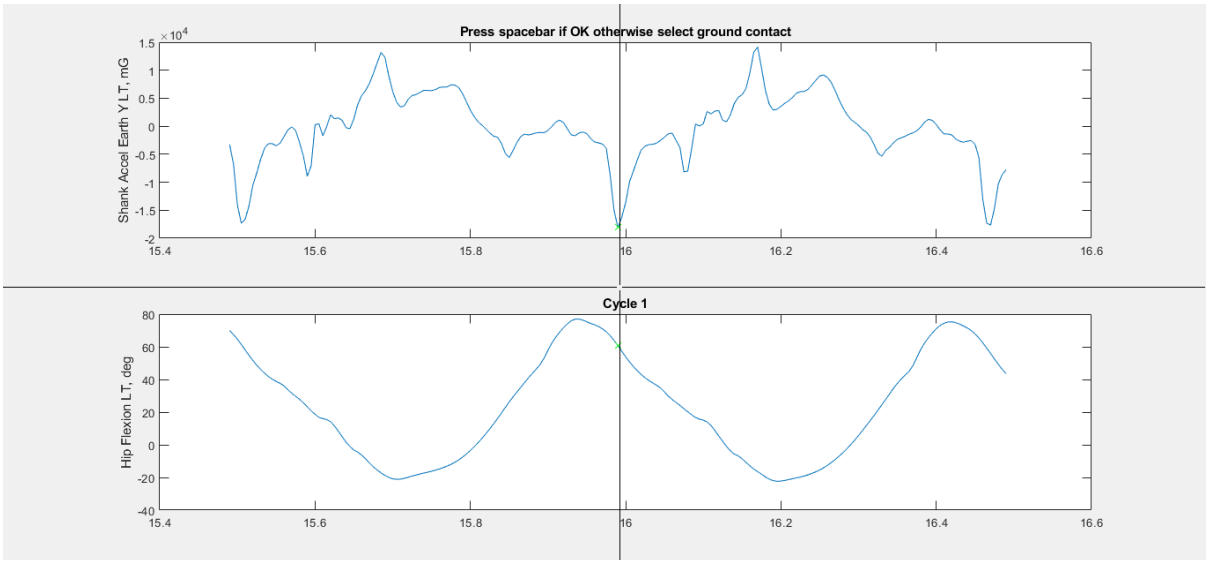


Figure A2.19: POC detection method

- Continue step above for all stride cycles. Once complete, the normalised cycle graphs will appear for shank acceleration (earth-based Y axis), hip flexion and knee flexion. Review then close

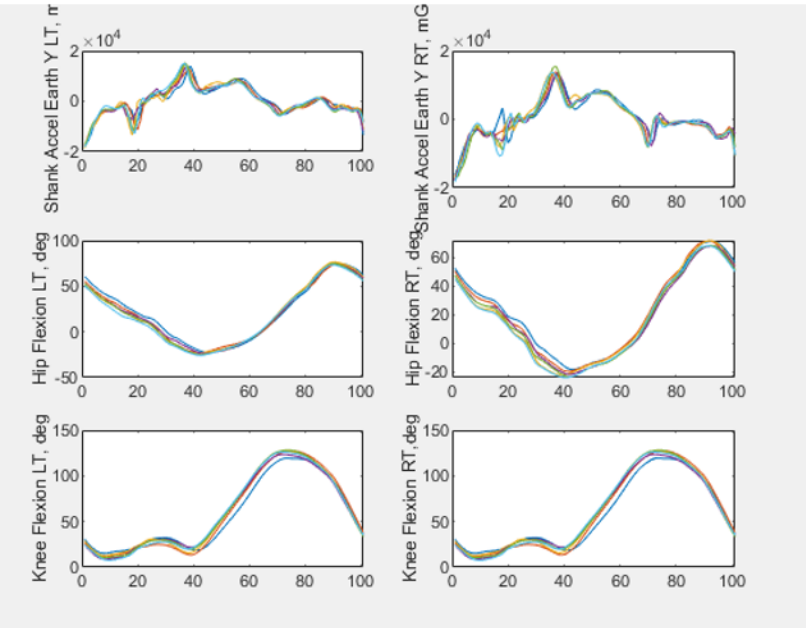


Figure A2.20: Normalised output cycle graphs

- Shank acceleration (earth-based Y axis), hip flexion and knee flexion graphs of all cycles continuously (with POC marked) will then appear. Review then close

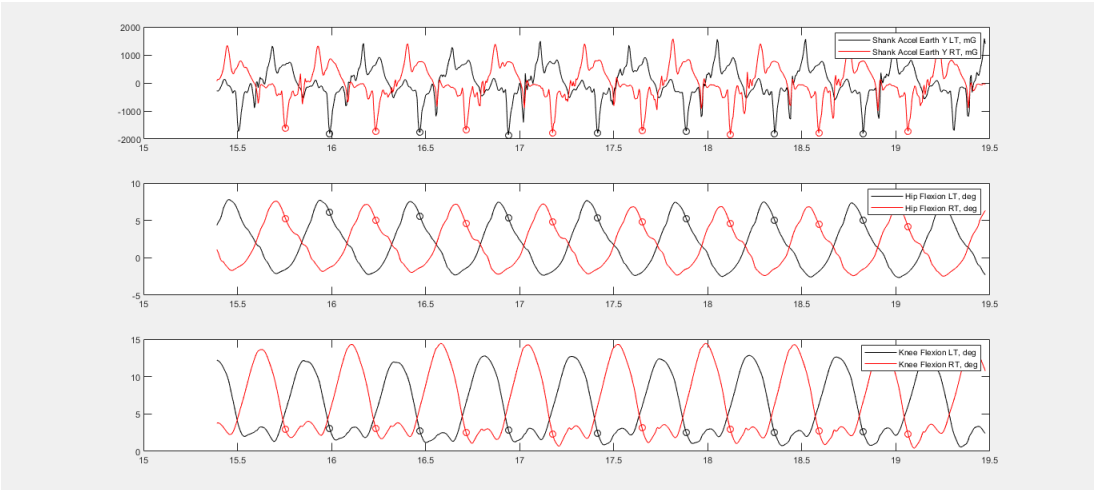


Figure A2.21: Continuous output cycle graphs

- The code will then be running in the background, to create an excel file of all data. Once done the command window will clear
- New 'output' (Matlab figure, Matlab data and Excel) files will be saved in same working folder

iv) Variability tests for calculation of clinically meaningful difference (to supplement Table 1 on Page 6 of the Observational Paper publication in Chapter 5)

- Table A2.6 and A2.7 below detail measures of minimal detectable change (SWC: Smallest Worthwhile Change; MWC: Moderate Worthwhile Change; LWC: Largest Worthwhile Change; TE: Typical Error of Measurement; CV%: Coefficient of Variation Percentage) for variables of interest
- For anterior pelvic tilt (the variable which demonstrated a potential relationship with retrospective HSI), the calculated smallest worthwhile change was very close to the actual the mean difference between the groups, however future studies may consider using MWC or LWC noting TE is greater than the SWC. CV% is also not reliable for anterior pelvic tilt as the mean is very close to zero (thus exaggerating the percentile variation)

IMU Variable	HSI History by Side μ (SD)	Control by Side μ (SD)	SWC	MWC	LWC	TE	CV%	Recommendation
Anterior Pelvic Tilt at POC (º)	3.1 (5.6)	1.7 (7.1)	1.5	4.3	8.6	1.7	420.2	Use MWC/LWC (TE > SWC). CV large because μ close to zero
Hip Flexion at POC (º)	56.7 (7.4)	55.2 (9.0)	1.8	5.4	10.8	2.1	16.3	Use MWC/LWC
Step time (s)	0.238 (0.011)	0.237 (0.011)	0.002	0.006	0.013	0.002	4.6	SWC acceptable
Stride time (s)	0.473 (0.02)	0.474 (0.026)	0.005	0.016	0.031	0.006	5.5	SWC acceptable

Table A2.6: Minimal detectable change calculations for HSI History by Side

IMU Variable	HSI History by Participant μ (SD)	Control by Participant μ (SD)	SWC	MWC	LWC	TE	CV%	Recommendation
Anterior Pelvic Tilt at POC (º)	3.1 (7.2)	1.7 (10.1)	2.0	6.1	12.1	2.7	1011.8	Use MWC/LWC (TE > SWC). CV large because μ close to zero
Hip Flexion at POC (º)	56.7 (8.8)	55.2 (12.4)	2.5	7.4	14.9	3.3	21.1	Use MWC/LWC (TE > SWC)
Step time (s)	0.238 (0.001)	0.237 (0.013)	0.003	0.008	0.016	0.004	5.8	SWC acceptable
Stride time (s)	0.473 (0.026)	0.474 (0.037)	0.007	0.022	0.045	0.010	8.0	SWC acceptable

Table A2.7: Minimal detectable change calculations for HSI History by Participant

A2.Annex A Matlab code – Validation

```
clear
close all

[FileName_Noraxon,PathName_Noraxon] = uigetfile('*.mat','Select the Noraxon file');
cd(PathName_Noraxon)
load([PathName_Noraxon FileName_Noraxon])

[FileName_V3d,PathName_V3D] = uigetfile('*.mat','Select the motion capture file');
load([PathName_V3D FileName_V3d])
%%
 start_sync=find(Sync{1}>0.3,1);
 start_sync_Noraxon=find(Data{1,2}>0.1,1);
 time_V3D=(0:1/FRAME_RATE{1}:(length(Sync{1})-1)/FRAME_RATE{1})-(start_sync-1)/FRAME_RATE{1};
 time_Noraxon=(0:1/samplingRate:(length(Data{1,2})-1)/samplingRate)-(start_sync_Noraxon-1)/samplingRate;
 subplot(2,1,1)
 plot(time_V3D(start_sync:length(Sync{1})),Shank_Angle{1}(start_sync:length(Sync{1}),1),...
    time_Noraxon(start_sync_Noraxon:length(Data{1,20})),Data{1,20}(start_sync_Noraxon:length(Data{1,20}),1))
 title('Select start and end of data to be analysed')
 ylabel('Shank Angl (deg)')
 legend({'V3D','Noraxon'})
 subplot(2,1,2)
 plot(time_V3D(start_sync:length(Sync{1})),Sync{1}(start_sync:length(Sync{1}),1),...
    time_Noraxon(start_sync_Noraxon:length(Data{1,2})),Data{1,2}(start_sync_Noraxon:length(Data{1,20}),1))
%%
[start_stop,~,~]=ginput(2);
start_stop_V3D=round(start_stop*FRAME_RATE{1});
start_stop_Noraxon=round(start_stop*samplingRate);

%%
x=[start_stop_V3D(1)+start_sync start_stop_V3D(2)+start_sync];
X=[start_stop_Noraxon(1)+start_sync_Noraxon start_stop_Noraxon(2)+start_sync_Noraxon];
t1=0:1/FRAME_RATE{1}:(x(2)-x(1))/FRAME_RATE{1};
t2=0:1/samplingRate:(X(2)-X(1))/samplingRate;
Force=-(F1Z1{1}(:)+F1Z2{1}(:)+F1Z3{1}(:)+F1Z4{1}(:));
subplot(1,1,1)
plot(Force(x(1):x(1)+1000))
ylabel('Force (N)')
title('Select min force level to subtract 2 points')
[x_min_force,~,~]=ginput(2);
x_min_force=round(x_min_force);
Force=Force-mean(Force(x_min_force(1)+x(1):x_min_force(2)+x(1)));
plot(Force(x(1):x(1)+1000))
ylabel('Force (N)')
title('Select Threshold')
[~,threshold_Force,~]=ginput(1);
close all

%%
figure(1)
subplot(5,1,1);plot(t1,Force(x(1):x(2)), t2, Data{1,29}(X(1):X(2))/10); ylabel({'Force (N)';'Acc Y (cG)'}); legend({'Force'; 'Acc'})
subplot(5,1,2);plot(t1,Hip_Toe_X{1}(x(1):x(2))); ylabel('Hip to Toe X distance (m)')
subplot(5,1,3);plot(t1,Shank_Angle{1}(x(1):x(2),1),t2, Data{1,20}(X(1):X(2))); ylabel('Shank Angl (deg)'); legend({'V3D'; 'Noraxon'})
subplot(5,1,4);plot(t1,Knee_Angle{1}(x(1):x(2),1),t2, Data{1,6}(X(1):X(2))); ylabel('Knee Angl (deg)'); legend({'V3D'; 'Noraxon'})
subplot(5,1,5);plot(t1,Hip_Angle{1}(x(1):x(2),1),t2, Data{1,3}(X(1):X(2))); ylabel('Hip Angl (deg)'); legend({'V3D'; 'Noraxon'})
%%
%Finding ground Contact
indx_search_FORCE=find(Force(x(1):x(2))>threshold_Force);
indx_bigjumps_FORCE_Start=indx_search_FORCE(find(diff(indx_search_FORCE)>1)+1);
indx_bigjumps_FORCE_End=[indx_search_FORCE(find(diff(indx_search_FORCE)>1)); indx_search_FORCE(length(indx_search_FORCE))];
if length(indx_bigjumps_FORCE_End)>length(indx_bigjumps_FORCE_Start)
   indx_bigjumps_FORCE_End(1)=[];
end
indx_bigjumps_FORCE=[indx_bigjumps_FORCE_Start,indx_bigjumps_FORCE_End]-1;


%Finding Peak hip-tow X distance (V3D)
threshold_hip_toe=0;
indx_search_hip_toe=find(Hip_Toe_X{1}(x(1):x(2))>threshold_hip_toe);
indx_bigjumps_hip_toe_Start=indx_search_hip_toe(find(diff(indx_search_hip_toe)>1)+1);
```

```
indx_bigjumps_hip_toe_End=[indx_search_hip_toe(find(diff(indx_search_hip_toe)>1));
indx_search_hip_toe(length(indx_search_hip_toe))];
if length(indx_bigjumps_hip_toe_End)>length(indx_bigjumps_hip_toe_Start)
   indx_bigjumps_hip_toe_End(1)=[];
end
indx_bigjumps_hip_toe=[indx_bigjumps_hip_toe_Start,indx_bigjumps_hip_toe_End];
Indx_bigjumps_hip_toe=indx_bigjumps_hip_toe;
clear indx_bigjumps_hip_toe
%%
%Finding Peak Shank angle (V3D)
threshold_V3D=0;
indx_search_V3D=find(Shank_Angle{1}(x(1):x(2),1)>threshold_V3D);
indx_bigjumps_V3D_Start=indx_search_V3D(find(diff(indx_search_V3D)>1)+1);
indx_bigjumps_V3D_End=[indx_search_V3D(find(diff(indx_search_V3D)>1)); indx_search_V3D(length(indx_search_V3D))];
if length(indx_bigjumps_V3D_End)>length(indx_bigjumps_V3D_Start)
   indx_bigjumps_V3D_End(1)=[];
end
indx_bigjumps_V3D=[indx_bigjumps_V3D_Start,indx_bigjumps_V3D_End];
for i=1:size(indx_bigjumps_V3D,1)
   peak_knee_ext_index(i)=find(Shank_Angle{1}(indx_bigjumps_V3D(i,1)+x(1):indx_bigjumps_V3D(i,2)+x(1),1)==...
      max(Shank_Angle{1}(indx_bigjumps_V3D(i,1)+x(1):indx_bigjumps_V3D(i,2)+x(1),1)))+indx_bigjumps_V3D(i,1);
   %finding the same cycles for the force and hip-toe as shank
   Ground_contact_index(i,:)=indx_bigjumps_FORCE(find(indx_bigjumps_FORCE(:,1)>peak_knee_ext_index(i)-2,1),:);
   indx_bigjumps_hip_toe(i,:)=Indx_bigjumps_hip_toe(find(Indx_bigjumps_hip_toe(:,1)+50>peak_knee_ext_index(i),1),:);
   peak_hip_toe_index(i)=find(Hip_Toe_X{1}(indx_bigjumps_hip_toe(i,1)+x(1):indx_bigjumps_hip_toe(i,2)+x(1))==...
      max(Hip_Toe_X{1}(indx_bigjumps_hip_toe(i,1)+x(1):indx_bigjumps_hip_toe(i,2)+x(1))))+indx_bigjumps_hip_toe(i,1);

end
Ground_contact_index=Ground_contact_index+1;

%%
%Finding Peak Shank angle (Noraxon)
threshold_Noraxon=0;
indx_search_Noraxon=find(Data{1,20}(X(1):X(2))>threshold_Noraxon);
indx_bigjumps_Noraxon_Start=indx_search_Noraxon(find(diff(indx_search_Noraxon)>1)+1);
indx_bigjumps_Noraxon_End=[indx_search_Noraxon(find(diff(indx_search_Noraxon)>1));
indx_search_Noraxon(length(indx_search_Noraxon))];
if length(indx_bigjumps_Noraxon_End)>length(indx_bigjumps_Noraxon_Start)
   indx_bigjumps_Noraxon_End(1)=[];
end
indx_bigjumps_Noraxon=[indx_bigjumps_Noraxon_Start,indx_bigjumps_Noraxon_End];
for i=1:size(indx_bigjumps_Noraxon,1)
   peak_Noraxon_index(i)=find(Data{1,20}(indx_bigjumps_Noraxon(i,1)+X(1):indx_bigjumps_Noraxon(i,2)+X(1))==...
      max(Data{1,20}(indx_bigjumps_Noraxon(i,1)+X(1):indx_bigjumps_Noraxon(i,2)+X(1))),1)+indx_bigjumps_Noraxon(i,1);
   %finding the same cycles for acc as shank
   Ground_contact_Acc_index(i,1)=find(Data{1,30}(indx_bigjumps_Noraxon(i,1)+X(1):indx_bigjumps_Noraxon(i,2)+X(1))==...
      max(Data{1,30}(indx_bigjumps_Noraxon(i,1)+X(1):indx_bigjumps_Noraxon(i,2)+X(1))),1)+indx_bigjumps_Noraxon(i,1);

end



%% CHECK FORCE GROUND CONTACT
Ground_contact_index=Ground_contact_index-1;
for i=1:size(Ground_contact_index,1)
   Force_OK=0;
   figure(99)
   while Force_OK==0
      plot(t1(Ground_contact_index(i,1)-20:Ground_contact_index(i,1)+20),Force(Ground_contact_index(i,1)+x(1)-1-
20:Ground_contact_index(i,1)+x(1)-1+20))
      hold on
      plot(t1(Ground_contact_index(i,1)),Force(Ground_contact_index(i,1)+x(1)-1),'gx')
      hold off
      ylabel('Force (N)')
      title('Press spacebar if OK otherwise select ground contact')
      [x_force,~,button]=ginput(1);
      if button == 32
         Force_OK=1;
      elseif button==1
         Ground_contact_index(i,1)=find(t1>x_force,1);
      end
```

```
    end
end
close (99)
%%
    clear Indx_bigjumps_hip_toe

peak_shank_angle=Shank_Angle{1}(peak_knee_ext_index+x(1)-1,1);
peak_hip_toe_x=Hip_Toe_X{1}(peak_hip_toe_index+x(1)-1);
contact_shank_angle=Shank_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1);
contact_hip_toe_x=Hip_Toe_X{1}(Ground_contact_index(:,1)+x(1)-1);

contact_knee_angle=Knee_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1);
contact_hip_angle=Hip_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1);
contact_pelvis_angle=Pelvis_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1);
%%

%%
% figure(1)
% subplot(5,1,1);plot(t1,Force(x(1):x(2)), t2, Data{1,29}(X(1):X(2))/10); ylabel({'Force (N)';'Acc Y (cG)'}); legend({'Force'; 'Acc'})
% subplot(5,1,2);plot(t1,Hip_Toe_X{1}(x(1):x(2))); ylabel('Hip to Toe X distance (m)')
% subplot(5,1,3);plot(t1,Shank_Angle{1}(x(1):x(2),1),t2, Data{1,20}(X(1):X(2))); ylabel('Shank Angl (deg)'); legend({'V3D'; 'Noraxon'})
% subplot(5,1,4);plot(t1,Knee_Angle{1}(x(1):x(2),1),t2, Data{1,6}(X(1):X(2))); ylabel('Knee Angl (deg)'); legend({'V3D'; 'Noraxon'})
% subplot(5,1,5);plot(t1,Hip_Angle{1}(x(1):x(2),1),t2, Data{1,3}(X(1):X(2))); ylabel('Hip Angl (deg)'); legend({'V3D'; 'Noraxon'})
%
% subplot(5,1,1)
% hold on
% plot(t1(Ground_contact_index(:,1)),Force(Ground_contact_index(:,1)+x(1)-1),'gx')
% hold off
%
% subplot(5,1,3)
% hold on
%
% plot(t1(peak_knee_ext_index),Shank_Angle{1}(peak_knee_ext_index+x(1)-1,1),'k+')
% plot(t1(Ground_contact_index(:,1)),Shank_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1),'gx')
% hold off
%
% subplot(5,1,2)
% hold on
% plot(t1(peak_hip_toe_index),Hip_Toe_X{1}(peak_hip_toe_index+x(1)-1),'k+')
% plot(t1(Ground_contact_index(:,1)),Hip_Toe_X{1}(Ground_contact_index(:,1)+x(1)-1),'gx')
% hold off
%
% subplot(5,1,4)
% hold on
%
% plot(t1(peak_knee_ext_index),Knee_Angle{1}(peak_knee_ext_index+x(1)-1,1),'k+')
% plot(t1(Ground_contact_index(:,1)),Knee_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1),'gx')
% hold off
%
% subplot(5,1,5)
% hold on
%
% plot(t1(peak_knee_ext_index),Hip_Angle{1}(peak_knee_ext_index+x(1)-1,1),'k+')
% plot(t1(Ground_contact_index(:,1)),Hip_Angle{1}(Ground_contact_index(:,1)+x(1)-1,1),'gx')
% hold off

%% CHECK ACC GROUND CONTACT

for i=2:size(Ground_contact_Acc_index,1)
    ACC_OK=0;
    figure(99)
    while ACC_OK==0
        subplot(2,1,1)
        plot(t2(Ground_contact_Acc_index(i,1)-100:Ground_contact_Acc_index(i,1)+100),Data{1,29}(Ground_contact_Acc_index(i,1)+X(1)-1-
100:Ground_contact_Acc_index(i,1)+X(1)-1+100))
        title(['Cycle ' num2str(i)])
        ylabel(channelNames{1,29})
        hold on
        plot(t2(Ground_contact_Acc_index(i,1)),Data{1,29}(Ground_contact_Acc_index(i,1)+X(1)-1),'gx')
        title('Press spacebar if OK otherwise select ground contact')
        hold off
```

```
    subplot(2,1,2)
    plot(t2(Ground_contact_Acc_index(i,1)-100:Ground_contact_Acc_index(i,1)+100),...
      Data{1,3}(Ground_contact_Acc_index(i,1)-100:Ground_contact_Acc_index(i,1)+100))
    title(['Cycle ' num2str(i)])
    ylabel(channelNames{1,3})
    hold on
    plot(t2(Ground_contact_Acc_index(i,1)),Data{1,3}(Ground_contact_Acc_index(i,1)),'gx')
    hold off
    [x_acc,~,button]=ginput(1);
    if button == 32
      ACC_OK=1;
    elseif button==1
      Ground_contact_Acc_index(i,1)= round(x_acc*samplingRate);
    end
  end
end
close (99)


%%
peak_shank_angle_Noraxon=Data{1,20}(peak_knee_ext_index*samplingRate/FRAME_RATE{1}+X(1)-1);
%find correct peak angle for shank using Noraxon
%%
contact_shank_angle_Noraxon=Data{1,20}(Ground_contact_Acc_index(:,1)+X(1)-1);
contact_shank_angle_Noraxon_Force=Data{1,20}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}+X(1)-1);

contact_knee_angle_Noraxon=Data{1,6}(Ground_contact_Acc_index(:,1)+X(1)-1);
contact_knee_angle_Noraxon_Force=Data{1,6}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}+X(1)-1);

contact_hip_angle_Noraxon=Data{1,3}(Ground_contact_Acc_index(:,1)+X(1)-1);
contact_hip_angle_Noraxon_Force=Data{1,3}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}+X(1)-1);

contact_pelvis_angle_Noraxon=Data{1,14}(Ground_contact_Acc_index(:,1)+X(1)-1);
contact_pelvis_angle_Noraxon_Force=Data{1,14}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}+X(1)-1);

time_contact=(Ground_contact_index(:,1)+x(1)-1)/FRAME_RATE{1};
%%
close(1)
figure(1)
subplot(5,1,1);plot(t1,Force(x(1):x(2)), t2, Data{1,29}(X(1):X(2))/10); ylabel({'Force (N)';'Acc Y (cG)'}); legend({'Force'; 'Acc'})
subplot(5,1,2);plot(t1,Hip_Toe_X{1}(x(1):x(2))); ylabel('Hip to Toe X distance (m)')
subplot(5,1,3);plot(t1,Shank_Angle{1}(x(1):x(2),1),t2, Data{1,20}(X(1):X(2))); ylabel('Shank Angl (deg)'); legend({'V3D'; 'Noraxon'})
subplot(5,1,4);plot(t1,Knee_Angle{1}(x(1):x(2),1),t2, Data{1,6}(X(1):X(2))); ylabel('Knee Angl (deg)'); legend({'V3D'; 'Noraxon'})
subplot(5,1,5);plot(t1,Hip_Angle{1}(x(1):x(2),1),t2, Data{1,3}(X(1):X(2))); ylabel('Hip Angl (deg)'); legend({'V3D'; 'Noraxon'})
subplot(5,1,1)
hold on
plot(t1(Ground_contact_index(:,1)),Force(Ground_contact_index(:,1)+x(1)-1),'b+')
%plot(t2(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}),Data{1,29}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{
1}+X(1)-1),'b+')
plot(t2(Ground_contact_Acc_index(:,1)),Data{1,29}(Ground_contact_Acc_index(:,1)+X(1)-1)/10,'go')
hold off
%%
subplot(5,1,1)
legend({'V3D'; 'Noraxon'; 'POC Force'; 'POC ACC'})
%%
subplot(5,1,2)
hold on
plot(t1(Ground_contact_index(:,1)),Hip_Toe_X{1}(Ground_contact_index(:,1)+x(1)-1),'b+')
plot(t1(Ground_contact_index(:,1)),Hip_Toe_X{1}(Ground_contact_index(:,1)+x(1)-1),'go')
hold off

subplot(5,1,3)
hold on
plot(t2(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}),Data{1,20}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}
+X(1)-1),'b+')
plot(t2(Ground_contact_Acc_index(:,1)),Data{1,20}(Ground_contact_Acc_index(:,1)+X(1)-1),'go')
hold off
legend({'V3D'; 'Noraxon'; 'POC Force'; 'POC ACC'})

subplot(5,1,4);
hold on
```

```
plot(t2(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}),Data{1,6}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}+
X(1)-1),'b+')
plot(t2(Ground_contact_Acc_index(:,1)),Data{1,6}(Ground_contact_Acc_index(:,1)+X(1)-1),'go')
hold off
legend({'V3D'; 'Noraxon'; 'POC Force'; 'POC ACC'})

subplot(5,1,5);
hold on
plot(t2(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}),Data{1,3}(Ground_contact_index(:,1)*samplingRate/FRAME_RATE{1}+
X(1)-1),'b+')
plot(t2(Ground_contact_Acc_index(:,1)),Data{1,3}(Ground_contact_Acc_index(:,1)+X(1)-1),'go')
hold off
legend({'V3D'; 'Noraxon'; 'POC Force'; 'POC ACC'})

%%

%Variables to export
if FRAME_RATE{1}==samplingRate
   Ground_contact_YN(1:length(t1))=0; Ground_contact_YN(Ground_contact_index(:,1))=1;
   Ground_contact_Acc_YN(1:length(t1))=0; Ground_contact_Acc_YN(Ground_contact_Acc_index(:,1))=1;
   export_data=[Data{1,1}(X(1):X(2)),Ground_contact_YN', Ground_contact_Acc_YN', Force(x(1):x(2)),Data{1,30}(X(1):X(2)),...
      Hip_Toe_X{1}(x(1):x(2)),Shank_Angle{1}(x(1):x(2),1),Data{1,20}(X(1):X(2)),...
      Knee_Angle{1}(x(1):x(2),1),Data{1,6}(X(1):X(2)), Hip_Angle{1}(x(1):x(2),1),Data{1,3}(X(1):X(2)),...
      Pelvis_Angle{1}(x(1):x(2),1),Data{1,14}(X(1):X(2))];
   export_data_legend={'Time (s)','Ground_contact_YN', 'Ground_contact_Acc_YN','Total Force Z (N)', 'Acc Y Earth based (mG)', 'Hip-Toe
(m)',...
      'Shank Angle V3D (deg)', 'Shank Angle Noraxon (deg)', 'Knee Angle V3D (deg)', 'Knee Angle Noraxon (deg)',...
      'Hip Angle V3D (deg)', 'Hip Angle Noraxon (deg)','Pelvis Tilt V3D (deg)', 'Pelvis Pitch Noraxon (deg)'};
end

export_data_points=[time_contact,peak_shank_angle, peak_shank_angle_Noraxon, peak_hip_toe_x, contact_shank_angle,
contact_shank_angle_Noraxon, ...
   contact_hip_toe_x,contact_knee_angle,contact_knee_angle_Noraxon, ...
   contact_hip_angle,contact_hip_angle_Noraxon, contact_pelvis_angle,contact_pelvis_angle_Noraxon];
export_data_points_legend={'Time of contact (s)','peak shank angle (deg)', 'peak shank angle Noraxon (deg)', 'peak hip toe X distance (m)',
'contact shank angle (deg)',...
   'contact shank angle Noraxon using acc (deg)', 'contact hip toe X distance (m)','contact knee angle (deg)',...
   'contact knee angle Noraxon using acc (deg)', 'contact hip angle (deg)',...
   'contact hip angle Noraxon using acc (deg)', 'contact pelvis angle (deg)',...
   'contact pelvis angle Noraxon using acc (deg)'};

%%
cd(PathName_Noraxon)
hgsave ([FileName_Noraxon(1:length(FileName_Noraxon)-4) '_output'])
save ([FileName_Noraxon(1:length(FileName_Noraxon)-4) '_output'])
%%
filename_xls=[FileName_Noraxon(1:length(FileName_Noraxon)-4) '_output.xlsx'];
if FRAME_RATE{1}==samplingRate
   xlswrite(filename_xls,export_data_legend, 'Data', 'A1');
   xlswrite(filename_xls,export_data, 'Data', 'A2');
end
xlswrite(filename_xls,export_data_points_legend, 'Data points', 'A1');
xlswrite(filename_xls,export_data_points, 'Data points', 'A2');

clc
```

A2.Annex B Matlab code – Cohort

```
clear


[FileName_Noraxon,PathName_Noraxon] = uigetfile('*.mat','Select the Noraxon file');
cd(PathName_Noraxon)
load([PathName_Noraxon FileName_Noraxon])

%adjust_angle=input('Enter the angle measured during calibration from photo ...  ');%from the photo
%Data{1,20}(:)=Data{1,20}(:)-adjust_angle;
%% Calcualating velocities
j=51;
for i=[2:9,16:18]
   Data{1,j}(:,1)=[0;diff(Data{1,i}(:))/(1/samplingRate)];
   channelNames{1,j}(:)=['Vel ' channelNames{1,i}(:)' '/s'];
   j=j+1;

end

%%
figure(1)
subplot(2,1,1)
   plot(Data{1, 1},Data{1, 2},Data{1, 1},Data{1, 3})
   title('Select start and end of data to be analysed')
   ylabel('Hip Flexion angles (degrees)')
   legend({channelNames{1,2},channelNames{1,3}})
subplot(2,1,2)
   plot(Data{1, 1},Data{1, 8},Data{1, 1},Data{1, 9})
   ylabel('Knee Flexion angles(degrees)')
   legend({channelNames{1,8},channelNames{1,9}})
[start_stop,~,~]=ginput(2);
X=round(start_stop*samplingRate);

%%
%Finding Peak L hip angle (Noraxon)
threshold_Noraxon=10;
L_indx_search_Noraxon=find(Data{1,2}(X(1):X(2))>threshold_Noraxon);
L_indx_bigjumps_Noraxon_Start=L_indx_search_Noraxon(find(diff(L_indx_search_Noraxon)>1)+1);
L_indx_bigjumps_Noraxon_End=[L_indx_search_Noraxon(diff(L_indx_search_Noraxon)>1);
L_indx_search_Noraxon(length(L_indx_search_Noraxon))];
if length(L_indx_bigjumps_Noraxon_End)>length(L_indx_bigjumps_Noraxon_Start)
   L_indx_bigjumps_Noraxon_End(1)=[];
end
L_indx_bigjumps_Noraxon=[L_indx_bigjumps_Noraxon_Start,L_indx_bigjumps_Noraxon_End];
for i=1:size(L_indx_bigjumps_Noraxon,1)
   L_peak_Noraxon_index(i)=find(Data{1,2}(L_indx_bigjumps_Noraxon(i,1)+X(1):L_indx_bigjumps_Noraxon(i,2)+X(1))==...
      max(Data{1,2}(L_indx_bigjumps_Noraxon(i,1)+X(1):L_indx_bigjumps_Noraxon(i,2)+X(1))),1)+L_indx_bigjumps_Noraxon(i,1);
   L_Ground_contact_Acc_index(i,1)=find(Data{1,37}(L_indx_bigjumps_Noraxon(i,1)+X(1):L_indx_bigjumps_Noraxon(i,2)+X(1))==...
      min(Data{1,37}(L_indx_bigjumps_Noraxon(i,1)+X(1):L_indx_bigjumps_Noraxon(i,2)+X(1))),1)+L_indx_bigjumps_Noraxon(i,1);
end
L_Ground_contact_Acc_index=L_Ground_contact_Acc_index+X(1)-1;
L_Ground_contact_Acc_index(length(L_Ground_contact_Acc_index))=[];
%%
%Finding Peak R hip angle (Noraxon)
threshold_Noraxon=10;
R_indx_search_Noraxon=find(Data{1,3}(X(1):X(2))>threshold_Noraxon);
R_indx_bigjumps_Noraxon_Start=R_indx_search_Noraxon(find(diff(R_indx_search_Noraxon)>1)+1);
R_indx_bigjumps_Noraxon_End=[R_indx_search_Noraxon(find(diff(R_indx_search_Noraxon)>1));
R_indx_search_Noraxon(length(R_indx_search_Noraxon))];
if length(R_indx_bigjumps_Noraxon_End)>length(R_indx_bigjumps_Noraxon_Start)
   R_indx_bigjumps_Noraxon_End(1)=[];
end
R_indx_bigjumps_Noraxon=[R_indx_bigjumps_Noraxon_Start,R_indx_bigjumps_Noraxon_End];
for i=1:size(R_indx_bigjumps_Noraxon,1)
   R_peak_Noraxon_index(i)=find(Data{1,3}(R_indx_bigjumps_Noraxon(i,1)+X(1):R_indx_bigjumps_Noraxon(i,2)+X(1))==...
      max(Data{1,3}(R_indx_bigjumps_Noraxon(i,1)+X(1):R_indx_bigjumps_Noraxon(i,2)+X(1))),1)+R_indx_bigjumps_Noraxon(i,1);
   R_Ground_contact_Acc_index(i,1)=find(Data{1,43}(R_indx_bigjumps_Noraxon(i,1)+X(1):R_indx_bigjumps_Noraxon(i,2)+X(1))==...
      min(Data{1,43}(R_indx_bigjumps_Noraxon(i,1)+X(1):R_indx_bigjumps_Noraxon(i,2)+X(1))),1)+R_indx_bigjumps_Noraxon(i,1);
end
R_Ground_contact_Acc_index=R_Ground_contact_Acc_index+X(1)-1;
```

```
R_Ground_contact_Acc_index(length(R_Ground_contact_Acc_index))=[];
%% CHECK ACC L GROUND CONTACT

for i=1:size(L_Ground_contact_Acc_index,1)
   ACC_OK=0;
   figure(99)
   while ACC_OK==0
      subplot(2,1,1)
      plot(Data{1,1}(L_Ground_contact_Acc_index(i,1)-100:L_Ground_contact_Acc_index(i,1)+100),...
         Data{1,37}(L_Ground_contact_Acc_index(i,1)-100:L_Ground_contact_Acc_index(i,1)+100))
      title(['Cycle ' num2str(i)])
      ylabel(channelNames{1,37})
      hold on
      plot(Data{1,1}(L_Ground_contact_Acc_index(i,1)),Data{1,37}(L_Ground_contact_Acc_index(i,1)),'gx')
      title('Press spacebar if OK otherwise select ground contact')
      hold off
      subplot(2,1,2)
      plot(Data{1,1}(L_Ground_contact_Acc_index(i,1)-100:L_Ground_contact_Acc_index(i,1)+100),...
         Data{1,2}(L_Ground_contact_Acc_index(i,1)-100:L_Ground_contact_Acc_index(i,1)+100))
      title(['Cycle ' num2str(i)])
      ylabel(channelNames{1,2})
      hold on
      plot(Data{1,1}(L_Ground_contact_Acc_index(i,1)),Data{1,2}(L_Ground_contact_Acc_index(i,1)),'gx')
      hold off
      [x_acc,~,button]=ginput(1);
      if button == 32
         ACC_OK=1;
      elseif button==1
         L_Ground_contact_Acc_index(i,1)= round(x_acc*samplingRate);
      end
   end
end
close (99)

%% CHECK ACC R GROUND CONTACT
for i=1:size(R_Ground_contact_Acc_index,1)
   ACC_OK=0;
   figure(99)
   while ACC_OK==0
      subplot(2,1,1)
      plot(Data{1,1}(R_Ground_contact_Acc_index(i,1)-100:R_Ground_contact_Acc_index(i,1)+100),...
         Data{1,43}(R_Ground_contact_Acc_index(i,1)-100:R_Ground_contact_Acc_index(i,1)+100))
      title(['Cycle ' num2str(i)])
      ylabel(channelNames{1,43})
      hold on
      plot(Data{1,1}(R_Ground_contact_Acc_index(i,1)),Data{1,43}(R_Ground_contact_Acc_index(i,1)),'gx')
      title('Press spacebar if OK otherwise select ground contact')
      hold off
      subplot(2,1,2)
      plot(Data{1,1}(R_Ground_contact_Acc_index(i,1)-100:R_Ground_contact_Acc_index(i,1)+100),...
         Data{1,3}(R_Ground_contact_Acc_index(i,1)-100:R_Ground_contact_Acc_index(i,1)+100))
      title(['Cycle ' num2str(i)])
      ylabel(channelNames{1,3})
      hold on
      plot(Data{1,1}(R_Ground_contact_Acc_index(i,1)),Data{1,3}(R_Ground_contact_Acc_index(i,1)),'gx')
      hold off
      [x_acc,~,button]=ginput(1);
      if button == 32
         ACC_OK=1;
      elseif button ==1
         R_Ground_contact_Acc_index(i,1)= round(x_acc*samplingRate);
      end
   end
end
close (99)

%%
figure(1)
%Shank ACC
subplot(3,1,1)
plot(Data{1,1}(X(1):X(2)),Data{1,37}(X(1):X(2))/10,'k')
```

```
hold on
plot(Data{1,1}(X(1):X(2)),Data{1,43}(X(1):X(2))/10,'r')
plot(Data{1,1}(L_Ground_contact_Acc_index(:,1)),Data{1,37}(L_Ground_contact_Acc_index(:,1))/10,'ko')
plot(Data{1,1}(R_Ground_contact_Acc_index(:,1)),Data{1,43}(R_Ground_contact_Acc_index(:,1))/10,'ro')
hold off
legend({channelNames{1,37},channelNames{1,43}})
%Hip
subplot(3,1,2)
plot(Data{1,1}(X(1):X(2)),Data{1,2}(X(1):X(2))/10,'k')
hold on
plot(Data{1,1}(X(1):X(2)),Data{1,3}(X(1):X(2))/10,'r')
plot(Data{1,1}(L_Ground_contact_Acc_index(:,1)),Data{1,2}(L_Ground_contact_Acc_index(:,1))/10,'ko')
plot(Data{1,1}(R_Ground_contact_Acc_index(:,1)),Data{1,3}(R_Ground_contact_Acc_index(:,1))/10,'ro')
hold off
legend({channelNames{1,2},channelNames{1,3}})
%Knee
subplot(3,1,3)
plot(Data{1,1}(X(1):X(2)),Data{1,8}(X(1):X(2))/10,'k')
hold on
plot(Data{1,1}(X(1):X(2)),Data{1,9}(X(1):X(2))/10,'r')
plot(Data{1,1}(L_Ground_contact_Acc_index(:,1)),Data{1,8}(L_Ground_contact_Acc_index(:,1))/10,'ko')
plot(Data{1,1}(R_Ground_contact_Acc_index(:,1)),Data{1,9}(R_Ground_contact_Acc_index(:,1))/10,'ro')
hold off
legend({channelNames{1,8},channelNames{1,9}})

%%
%time normalise signals
clear norm_data

num_cycles = min(length(L_Ground_contact_Acc_index),length(R_Ground_contact_Acc_index));
for i=[2,4,6,8,19:24,33:38,2+49,4+49,6+49,8+49]
   norm_data(:,i,:)=time_norm_data(Data{1,i}, 101, L_Ground_contact_Acc_index(1:num_cycles-1),...
      L_Ground_contact_Acc_index(2:num_cycles)-1);
end
%for pelvis (time normalised for each left and right)
for i=16:18
   norm_data(:,i+29,:)=time_norm_data(Data{1,i}, 101, L_Ground_contact_Acc_index(1:num_cycles-1),...
      L_Ground_contact_Acc_index(2:num_cycles)-1);
   channelNames{1,i+29}=[channelNames{1,i}(1:find(channelNames{1,i}(:)==',')-1) ' LT,'];
   norm_data(:,i+32,:)=time_norm_data(Data{1,i}, 101, R_Ground_contact_Acc_index(1:num_cycles-1),...
       R_Ground_contact_Acc_index(2:num_cycles)-1);
    channelNames{1,i+32}=[channelNames{1,i}(1:find(channelNames{1,i}(:)==',')-1) ' RT,'];
end
for i=59:61
   norm_data(:,i+3,:)=time_norm_data(Data{1,i}, 101, L_Ground_contact_Acc_index(1:num_cycles-1),...
      L_Ground_contact_Acc_index(2:num_cycles)-1);
   channelNames{1,i+3}=[channelNames{1,i}(1:find(channelNames{1,i}(:)==',')-1) ' LT,'];
   norm_data(:,i+6,:)=time_norm_data(Data{1,i}, 101, R_Ground_contact_Acc_index(1:num_cycles-1),...
       R_Ground_contact_Acc_index(2:num_cycles)-1);
    channelNames{1,i+6}=[channelNames{1,i}(1:find(channelNames{1,i}(:)==',')-1) ' RT,'];
end

for i=[3,5,7,9,25:29,39:44,3+49,5+49,7+49,9+49]
    norm_data(:,i,:)=time_norm_data(Data{1,i}, 101, R_Ground_contact_Acc_index(1:num_cycles-1),...
       R_Ground_contact_Acc_index(2:num_cycles)-1);
end

%%
figure(2)
%Shank ACC
subplot(4,2,1)
plot(squeeze(norm_data(:,37,:)))
ylabel(channelNames{1,37})

subplot(3,2,2)
plot(squeeze(norm_data(:,43,:)))
ylabel(channelNames{1,43})

%Hip F/E
subplot(3,2,3)
plot(squeeze(norm_data(:,2,:)))
```

```
ylabel(channelNames{1,2})

subplot(3,2,4)
plot(squeeze(norm_data(:,3,:)))
ylabel(channelNames{1,3})

%Knee F/E
subplot(3,2,5)
plot(squeeze(norm_data(:,8,:)))
ylabel(channelNames{1,8})

subplot(3,2,6)
plot(squeeze(norm_data(:,8,:)))
ylabel(channelNames{1,8})

%%
%Variables to export

L_Ground_contact_Acc_YN(1:length(Data{1,1}))=0; L_Ground_contact_Acc_YN(L_Ground_contact_Acc_index(:,1))=1;
R_Ground_contact_Acc_YN(1:length(Data{1,1}))=0; R_Ground_contact_Acc_YN(R_Ground_contact_Acc_index(:,1))=1;
export_data=[Data{1,1}(X(1):X(2)),L_Ground_contact_Acc_YN(X(1):X(2))', R_Ground_contact_Acc_YN(X(1):X(2))', Data{1,37}(X(1):X(2)),...
   Data{1,43}(X(1):X(2)),Data{1,2}(X(1):X(2)), Data{1,3}(X(1):X(2)),Data{1,4}(X(1):X(2)),Data{1,5}(X(1):X(2)),Data{1,6}(X(1):X(2)),...
   Data{1,7}(X(1):X(2)),Data{1,8}(X(1):X(2)), Data{1,9}(X(1):X(2)),Data{1,16}(X(1):X(2)),Data{1,17}(X(1):X(2)),Data{1,18}(X(1):X(2)),...
   Data{1,51}(X(1):X(2)),Data{1,52}(X(1):X(2)),Data{1,53}(X(1):X(2)),Data{1,54}(X(1):X(2)),Data{1,55}(X(1):X(2)),...
   Data{1,56}(X(1):X(2)),Data{1,57}(X(1):X(2)),Data{1,58}(X(1):X(2)),Data{1,59}(X(1):X(2)),Data{1,60}(X(1):X(2)),Data{1,61}(X(1):X(2))];
export_data_legend={'Time (s)','L_Ground_contact_YN', 'R_Ground_contact_Acc_YN',channelNames{1,37},...
   channelNames{1,43},channelNames{1,2}, channelNames{1,3},channelNames{1,4},channelNames{1,5},channelNames{1,6},...
   channelNames{1,7},channelNames{1,8},
channelNames{1,9},channelNames{1,16},channelNames{1,17},channelNames{1,18},channelNames{1,51},...
   channelNames{1,52},channelNames{1,53},channelNames{1,54},channelNames{1,55},channelNames{1,56},channelNames{1,57},...
   channelNames{1,58},channelNames{1,59},channelNames{1,60},channelNames{1,61}};

export_data_points_L=[Data{1,1}(L_Ground_contact_Acc_index(:,1)),Data{1,2}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,4}(L_Ground_contact_Acc_index(:,1)),Data{1,6}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,8}(L_Ground_contact_Acc_index(:,1)), Data{1,16}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,17}(L_Ground_contact_Acc_index(:,1)),Data{1,18}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,51}(L_Ground_contact_Acc_index(:,1)),Data{1,53}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,55}(L_Ground_contact_Acc_index(:,1)),Data{1,57}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,59}(L_Ground_contact_Acc_index(:,1)),Data{1,60}(L_Ground_contact_Acc_index(:,1)),...
   Data{1,61}(L_Ground_contact_Acc_index(:,1))];
export_data_points_R=[Data{1,1}(R_Ground_contact_Acc_index(:,1)),Data{1,3}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,5}(R_Ground_contact_Acc_index(:,1)), Data{1,7}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,9}(R_Ground_contact_Acc_index(:,1)), Data{1,16}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,17}(R_Ground_contact_Acc_index(:,1)),Data{1,18}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,52}(R_Ground_contact_Acc_index(:,1)),Data{1,54}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,56}(R_Ground_contact_Acc_index(:,1)),Data{1,58}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,59}(R_Ground_contact_Acc_index(:,1)),Data{1,60}(R_Ground_contact_Acc_index(:,1)),...
   Data{1,61}(R_Ground_contact_Acc_index(:,1))];
export_data_points_legend_L={'Time of contact Left(s)',channelNames{1,2},...
   channelNames{1,4},channelNames{1,6},channelNames{1,8}, channelNames{1,16},...
   channelNames{1,17},channelNames{1,18},channelNames{1,51},channelNames{1,53},...
   channelNames{1,55},channelNames{1,57},channelNames{1,59},channelNames{1,60},channelNames{1,61}};
export_data_points_legend_R={'Time of contact Right(s)',channelNames{1,3},...
   channelNames{1,5},channelNames{1,7},channelNames{1,9}, channelNames{1,16},...
   channelNames{1,17},channelNames{1,18},channelNames{1,52},channelNames{1,54},...
   channelNames{1,56},channelNames{1,58},channelNames{1,59},channelNames{1,60},channelNames{1,61}};



%% saving data
cd(PathName_Noraxon)
figure(1)
hgsave ([FileName_Noraxon(1:length(FileName_Noraxon)-4) '_output'])
figure(2)
hgsave ([FileName_Noraxon(1:length(FileName_Noraxon)-4) '_normalised_output'])
save ([FileName_Noraxon(1:length(FileName_Noraxon)-4) '_output'])
%%
filename_xls=[FileName_Noraxon(1:length(FileName_Noraxon)-4) '_output.xlsx'];

xlswrite(filename_xls,export_data_legend, 'Data', 'A1');
xlswrite(filename_xls,export_data, 'Data', 'A2');
```

```
xlswrite(filename_xls,export_data_points_legend_L, 'Data points', 'A1');
xlswrite(filename_xls,export_data_points_L, 'Data points', 'A2');
xlswrite(filename_xls,export_data_points_legend_R, 'Data points', 'Q1');
xlswrite(filename_xls,export_data_points_R, 'Data points', 'Q2');

t_norm=0:100;
cycles{1,1}='Normalised time (% Cycle)';
for j=1:size(norm_data,3)
   cycles{1,j+1}=['Cycle ' num2str(j)];
end
%%
for i =[2:9,45:50,51:58,62:67]
   xlswrite(filename_xls,cycles, channelNames{1,i}(1:find(channelNames{1,i}(:)==',')-1), 'A1');
   xlswrite(filename_xls,[t_norm',squeeze(norm_data(:,i,:))], channelNames{1,i}(1:find(channelNames{1,i}(:)==',')-1),'A2');
end
%
clc

clear
```

Appendix 3: Sport Health Feature Article

A3.1 Outline

Below is a feature article I was asked to write for Sport Health (Sport Medicine Australia's quarterly magazine). It details general considerations for running analysis and retraining, drawing on my knowledge of the evidence as well as my expertise as a physiotherapist and athlete:

Wolski, L. Running drills: As part of hamstring injury management. The nuts and bolts. Journal Article. *Sport Health*. 2020;38(1):26-29. doi: 10.3316/informit.237341120323269

Running dr

as part of hamstring injury management. The nuts and bolts...

Hamstring strain injury (HSI) poses a significant problem for sports involving high speed running. We know the cause of HSI is multifactorial and even with a goal-orientated, evidence-based rehab program, there's still a reasonable chance HSI may become a recurrent issue.

You have addressed muscle strength and graduated speed exposure (in the rehab program). You have also likely considered fitness, power, motor control, stability, mobility, sleep habits, and fear avoidance. What else is there?

Preliminary research suggests a potential link between running biomechanics and subsequent technique variations and HSI. Trunk kinematics appear to play an important role, with lateral trunk sway being a recurrent finding across prospective studies. There is also emerging evidence indicating that athletes who sustain HSI generate less horizontal propulsive force. More research is needed to determine if these preliminary findings are either caused by or a consequence of HSI. Either way, the way an athlete runs could be a factor influencing HSI recurrence.

So how do we address running technique in our HSI rehab programs?

A Skip

It's hard to break old habits. You essentially need to make new habits that override them. Technical changes are difficult to focus on at high speeds. Running drills are a valuable gait retraining technique that allow a runner to create new habits through neuromuscular retraining.

Lauren Shelley and I presented the workshop *'Learn to Drill like Bolt! Running Drills for Hamstring Injury Management'* at the 2019 ASICS SMA National Conference.

The findings we presented were informed by a recent systematic review undertaken, combined with extensive clinical experience working with high performance athletes. The following is a synopsis of what was covered in the workshop.

Two types of HSI have been identified based on mechanism of injury; the stretch type and the high-speed running type. Stretching type HSIs occur when the hamstrings elongate, occurring during slow or fast end-range

ills

> **Amateurs practice till they get it right. Professionals practice till they can't get it wrong.**
> Anonymous

movements. High-speed running type is typically more common and sustained during non-contact sprinting. This information will mostly pertain to HSI of the highspeed running type.

Understanding the hamstring activity throughout the gait cycle is essential in order to appreciate the concept of what you aim to achieve when prescribing drills. The biceps femoris is the muscle most commonly affected by high-speed running HSIs. It endures an eccentric contraction double peak, first during late stance, and secondly during late swing. The biceps femoris reaches maximal length during the second half of the swing phase whilst working eccentrically to decelerate hip flexion and knee extension in preparation for initial contact. Muscle actuated forward dynamic simulation and analysis of real-time HSI reveal the hamstring to be most susceptible to injury during terminal swing. Based on this, the tendency could be to focus on correcting 'front side mechanics'; however, there are many other factors to consider throughout the gait cycle that may be contributing to cumulative hamstring fatigue and ultimate strain.

Once the athlete has progressed to the stage in their rehab where they can run, the first step is to conduct a baseline assessment of their biomechanics. Sports clubs don't always have the money, resources, or time to employ research-grade methods of analysis (3D motion analysis, high sampling rate inertial measure units, etc.) so we must resort to more practical >

A RUN

methods, like video analysis or the trained naked eye. Your approach should aim to objectively assess sagittal (side on) and frontal (front on) planes of view, focusing particular attention on the following areas:

- **Trunk**. At top speed, are there any signs of excessive lateral deviation or trunk flexion?

- **Pelvis.** Most fast runners will normally have a certain degree of anterior tilt, but does it increase with fatigue?

- **Front side mechanics.** Is the athlete over-striding and landing too far in-front of their centre of mass at initial contact? In upright running, the lower limb should be close to vertical at initial contact to ensure maximum friction, minimising braking forces allowing for peak horizontal force propulsion.

- **Back side mechanics.** Inefficient swing mechanics can result in suboptimal late swing limb placement in preparation for contact. The phase of sprint is important here. During acceleration leg clearance should be low. In upright running there should be simultaneous hip and knee flexion.

- **Foot placement at initial contact.** Which part of the foot hits the ground first? The athlete should be on their mid-forefoot if running fast. Heel striking when sprinting is commonly associated with over-stride.

- **Arms.** A reflex linkage exists between the arms and legs. A common fault acknowledged by sprint coaches is poor control of elbow extension, which will affect turnover efficiency at top speed. After the initial drive phase, shoulder extension should be achieved by driving the elbow back (not forearm). Also, encourage closure of the forearm at the front.

- **Ankle stiffness.** To optimise the 'stretch-shortening cycle', the ankle needs to maintain dorsiflexion from mid-swing to initial contact. Landing on an excessively plantarflexed or 'compliant' ankle will increase braking forces, increasing hamstring load.

> **'Toe up, heel up, knee up'**
> Emil Rizk

This list is not exhaustive but provides a start to biomechanical analysis. Your findings in these areas will direct the focus of your running drills. But first, reflect on the relevance of findings in a multifactorial context. Some technical variations may be protective, others maladaptive and mediating potential ongoing symptoms. Some may have no relevance at all to your athlete's HSI! Prioritise findings via careful critical reasoning on a case-by-case basis (preferably with a multidisciplinary performance team) before you consider changing anything.

If you determine that running technique may be a risk factor to address in your athlete, what drills do you prescribe to fix it?
The best drills to consider are those that the athlete is already familiar with and undertakes as part of their regular training. Your aim is to simply change the emphasis of the drill with a complementary objective in mind. Ask the athlete to show you their 'regular' drills, then refine as you see appropriate. For instance, if you note excessive trunk sway, you may ask the athlete to concentrate on having a stable core. If the athlete is overstriding, you could ask them to focus their attention on push (not reach) or landing under their hips. You may consider prescribing additional drills with a specific objective in mind. For example, the 'A Run' drill can be great for correcting 'back-side mechanics'.

Photos – common/ handy running drills.
After each drill, ask your athlete to do a 'conversion' run through over a distance that is reflective of their sport, focusing on the feedback received. The type of start (standing, crouch, rolling, etc.) should also be sport specific. If you have knowledge of the

B SKIP

mechanism of injury and the phase of sprint in which the injury occurred (acceleration, top speed, deceleration), place particular focus on that area.

As per the standard stages of skill acquisition, the goal would be that the 'habit' developed from conscious repetition would eventually evolve into unconscious mastery during running. The old saying that practice makes perfect is incorrect; only perfect practice makes perfect. Quality repetition is key to success with these programs. If one verbal cue isn't working, try another. If it can't be corrected with a cue, step back into the clinic and consider addressing potential movement restrictions or weaknesses. The following are other factors that should be considered:

- **Feedback types.** If the athlete isn't responding to verbal feedback, try another form such as practical demonstration (just make sure you are competent!) or video review.

- **Velocity.** Initially, the drill may be conducted at low intensities in a tempo or 'rhythmical' style (or even start with a walkthrough), before progressing to faster speeds. Force propulsion can be cued at higher intensities.

- **Range of motion.** As coordination and outer range strength improve, you may increase the range of motion of the drill. The 'B' skip and straight leg drills are great drills to work on outer range hamstring control but ensure the 'claw' or 'pull back' before contact.

- **Distance.** What distance does the athlete usually do drills over? What distance can they maintain form before fatigue?

- **Surface.** Are drills being completed on the same running surface as the competition goal?

- **Shoes.** What shoes would they normally wear for drills and competition?

- **Equipment.** What equipment does the athlete use in their sport? Progress drills by adding a distraction, such as holding a ball.

- **Direction.** Most athletes complete their drills in a linear fashion; however, you may choose to progress drills by adding a change of direction.

Finally, there are many modifiable and non-modifiable risk factors for HSI. Running biomechanics may be a five percenter; it may be zero percenter, or it may represent a significant risk factor for HSI recurrence. A comprehensive case-by-case assessment is required to determine whether a particular running technique is relevant to address. If so, then refinement of running drills may be useful tool to utilise for running gait retraining. Who knows, with some specific running coaching, they could even end up running faster than they did before...

About the Author

Lisa Wolski is a Musculoskeletal Physiotherapist and Officer in the Australian Army working in the field of Human Performance Optimisation. She has extensive experience in the field of sports physiotherapy, including travelling internationally with Australian Defence Force and civilian sporting teams. Lisa is a PhD candidate at the University of Sydney, investigating the relationship between running biomechanics and hamstring strain injury. She is also a trained sprinter, having competed at numerous Australian Athletics Championships and the prestigious Stawell Gift.

Acknowledgements

- Lauren Shelley, Sports Physio HPNZ
- Emil Rizk, Olympic Sprint Coach NSW

Contact author for references

Appendix 4: Ethics Documentation

A4.1 Outline

Attached below are the ethics approval letters for the validation and observational studies (detailed in Chapter 4 and 5 respectively), as well as template copies of the relevant recruitment letter, participant information and consent forms used for the observational study.

Research Integrity & Ethics Administration
Human Research Ethics Committee

Wednesday, 18 April 2018

Dr Alycia Fong Yan
Exercise Health and Performance; Faculty of Health Sciences
Email: alycia.fongyan@sydney.edu.au

Dear Alycia

The University of Sydney Human Research Ethics Committee (HREC) has considered your application.

After consideration of your response to the comments raised your project has been approved.

Approval is granted for a period of four years from **17/04/2018** to **17/04/2022**

Project title: **Validation and Reliability study of the Noraxon sensor during Running at Different Speeds**

Project no.: **2018/133**

First Annual Report due: **17/04/2019**

Authorised Personnel: **Fong Yan Alycia; Wolski Lisa; Pappas Evangelos; Hiller Claire; Halaki Mark;**

Documents Approved:

Date Uploaded	Version number	Document Name
09/02/2018	Version 1	Participation Consent Form - Reliability Study
09/02/2018	Version 1	Recruitment Poster - Reliability Study
12/04/2018	Version 2	Validation Recruitment Poster Clean
12/04/2018	Version 2	PIS Validation Clean
12/04/2018	Version 2	Participant Consent Form Validation Clean
12/04/2018	Version 2	PIS Reliability Clean

Condition/s of Approval

- Research must be conducted according to the approved proposal.
- An annual progress report must be submitted to the Ethics Office on or before the anniversary of approval and on completion of the project.
- You must report as soon as practicable anything that might warrant review of ethical approval of the project including:
  - Serious or unexpected adverse events (which should be reported within 72 hours).
  - Unforeseen events that might affect continued ethical acceptability of the project.
- Any changes to the proposal must be approved prior to their implementation (except where an amendment is undertaken to eliminate *immediate* risk to participants).

- Personnel working on this project must be sufficiently qualified by education, training and experience for their role, or adequately supervised. Changes to personnel must be reported and approved.

- Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, as relevant to this project.

- Data and primary materials must be retained and stored in accordance with the relevant legislation and University guidelines.

- Ethics approval is dependent upon ongoing compliance of the research with the *National Statement on Ethical Conduct in Human Research*, the *Australian Code for the Responsible Conduct of Research*, applicable legal requirements, and with University policies, procedures and governance requirements.

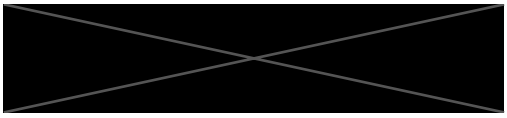
- The Ethics Office may conduct audits on approved projects.

- The Chief Investigator has ultimate responsibility for the conduct of the research and is responsible for ensuring all others involved will conduct the research in accordance with the above.

This letter constitutes ethical approval only.

Please contact the Ethics Office should you require further information or clarification.

Sincerely



Associate Professor Rita Shackel
Chair
Human Research Ethics Committee (HREC 3)

The University of Sydney HRECs are constituted and operate in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007) and the NHMRC's Australian Code for the Responsible Conduct of Research (2007).

Research Integrity & Ethics Administration
HUMAN RESEARCH ETHICS COMMITTEE

Friday, 18 January 2019

Dr Alycia Fong Yan
Exercise Health and Performance; Faculty of Health Sciences
Email: alycia.fongyan@sydney.edu.au

Dear Alycia,

Your request to modify this project, which was submitted on 23/12/2018, has been considered.

This project has been approved to proceed with the proposed amendments.

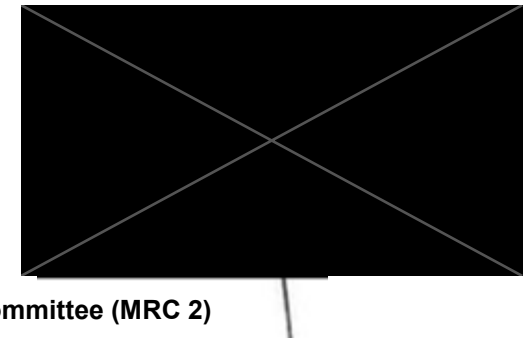
Protocol Number:	**2018/133**
Protocol Title:	**Validation and Reliability study of the Noraxon sensor during Running at Different Speeds**
Annual Report Due:	**17/04/2019**

Documents Approved:

Date Uploaded	Version Number	Document Name
23/12/2018	Version 003	PIS Clean

Please contact the ethics office should you require further information.

Sincerely,



Assoc Prof Mark Arnold
Chair, Modification Review Committee (MRC 2)

The University of Sydney of Sydney HRECs are constituted and operate in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007) and the NHMRC's Australian Code for the Responsible Conduct of Research (2007)

Research Integrity & Ethics Administration
HUMAN RESEARCH ETHICS COMMITTEE

Friday, 10 January 2020

Dr Alycia Fong Yan
Exercise Health and Performance; Faculty of Health Sciences
Email: alycia.fongyan@sydney.edu.au

Dear Alycia,

Your request to modify this project, which was submitted on 25 November 2019, has been considered.

After consideration of your response to the comments raised, this project has been approved to proceed with the proposed amendments.

Protocol Number: **2018/674**

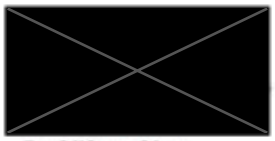
Protocol Title: **Prospective Cohort Study Investigating Aberrant Running Biomechanics as a Risk Factor for Hamstring Strain Injury**

Documents Approved:

Date Uploaded	Version Number	Document Name
29/12/2019	Version 3	Cover Letter CLEAN
29/12/2019	Version 3	Track and Field Cover Letter CLEAN
29/12/2019	Version 2	Track and Field PCF CLEAN
29/12/2019	Version 2	Hamstring Assessment Form
23/11/2019	Version 2	Baseline Player Information CLEAN
23/11/2019	Version 3	PCF CLEAN
23/11/2019	Version 1	PIS - TRACK AND FIELD
23/11/2019	Version 2	Organisation Consent Form CLEAN
11/11/2019	Version 3	PIS CLEAN

Please contact the ethics office should you require further information.

Sincerely,



Dr **Clifton Chan**
Chair
Modification Review Committee (MRC 1)

The University of Sydney of Sydney HRECs are constituted and operate in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007) and the NHMRC's Australian Code for the Responsible Conduct of Research (2007)

THE UNIVERSITY OF SYDNEY

Discipline of Exercise & Sports Science
Faculty of Health Sciences

ABN 15 211 513 464

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Lecturer, Exercise and Sports Science

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Email:
alycia.fongyan@sydney.edu.au
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Attn:

To Whom It May Concern,

RE: 'Prospective Cohort Study Investigating Aberrant Running Biomechanics as a Risk Factor for Hamstring Strain Injury'

We would like to invite your sporting club/squad to participate in a research study investigating the way athletes run as a risk factor for Hamstring Strain Injury (HSI). As you are likely already aware, HSI poses a significant problem for amateur and professional athletes, particularly due to its high recurrence rate.

There is emerging evidence that the way athletes run may be a contributing risk factor for HSI. A large cohort prospective study utilising Force-Velocity Profiling and the Noraxon Myomotion inertial measurement units (IMUs) System is planned to determine whether a relationship exists between HSI and aberrant running biomechanics. Five IMUs will be used to capture players' running biomechanics. This will be completed at the club's local ground and will take approximately 5 minutes per player (excluding warm up). The research team is available to complete this testing over a number of sessions (to minimise disruption to regular training). Once the testing of each player is complete, the athletes will be required to report any future hamstring injuries via an SMS injury surveillance system. If required, a physiotherapist will be available to assess and provide diagnoses at a time/day/location convenient for the athlete. The athletes will be monitored via this SMS system for one year after initial testing. If no hamstring strain injury occurs, no follow up is necessary.

The results of this study may consequently inform future injury prevention programs. Your club/squad will have the option of receiving overall results via telephone call or written confirmation. A copy of the final publication (in which all club and participant data will be de-identified) will also be provided.

Participation in this study would be profoundly appreciated. Should you be interested please contact our PhD student researcher, Lisa Wolski:

lwol3022@sydney.edu.au
You will find a copy of the Participant Information Statement and Consent Form attached. Please pass this onto any interested players.

Kind Regards,

Dr Alycia FONG YAN| Lecturer
The University of Sydney
Faculty of Health Sciences, Discipline of Exercise and Sport Science

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'Prospective Cohort Study Investigating Aberrant Running Biomechanics as a Risk Factor for Hamstring Strain Injury'

PARTICIPANT INFORMATION STATEMENT – TRACK AND FIELD ATHLETES

(1) What is this study about?

You are invited to take part in a research study investigating the relationship between running biomechanics and hamstring strain injury. This will involve once off testing of your running biomechanics. One year later, a comparison of running biomechanics baseline results will be conducted between those that got injured and those that did not. These results will consequently inform future injury prevention programs.

You have been invited to participate in this study because you are a potential volunteer. This Participant Information Statement tells you about the research study. Knowing what is involved will help you decide if you want to take part in the research. Please read this sheet carefully and ask questions about anything that you don't understand or want to know more about.

Participation in this research study is voluntary. By giving your consent to take part in this study you are telling us that you:

- ✓ Understand what you have read.
- ✓ Agree to take part in the research study as outlined below.
- ✓ Agree to the use of your personal information as described.

You will be given a copy of this Participant Information Statement to keep.

(2) Who is running the study?

Lisa Wolski is conducting this study as the basis for the degree of PhD in Health Sciences at The University of Sydney. This will take place under the supervision of Dr Alycia Fong Yan, Dr Mark Halaki, Dr Evangelos Pappas and Dr Claire Hiller from the University of Sydney.

(3) What will the study involve for me?

At the commencement of the study, you will be asked questions about your injury history, age, height, weight, playing position and dominant leg. After that, five portable sensors will be attached to your body via straps and tape. The sensors will then need to be calibrated with the computer system. This will require a short period of holding still in certain positions. Following this, you will be asked to conduct your usual training warm up. Guidance will be provided with the warm up if need be.

Once you are warm, you will be familiarised with the testing procedure, which is one standing start, maximum effort 60m sprint. You will be given the opportunity to conduct some practice sprints. Once you are confident you are ready, testing will begin. During the test, the portable sensors will be detecting and recording your movement. There will be 6 agility poles you will run past in the first 30m, which will be profiling your acceleration phase. Once you have completed the sprint, the sensors will be removed and you may cool down, or return to your usual training session.

Before testing, you will review and complete a consent form. In order to participate in the study you must consent to release any potential hamstring injury data. Following the running assessment, you will receive a weekly text (for one year's duration) asking whether or not you have sustained a hamstring injury that has affected your ability to train or compete. This text requires a 'yes' OR 'no' response. If you answer yes, a physiotherapist will contact you to arrange an appropriate time/day/location to assess you free of charge. This physiotherapist is for initial assessment only and will not provide on-going treatment. It is your decision whether you source further physiotherapy as needed. If you sustain a hamstring injury and want to report it sooner than when the weekly text is due, please contact Lisa Wolski on 0411585689 or lwol3022@uni.sydney.edu.au

If you do not respond 'yes' or 'no' to the weekly text, you will be sent a reminder text. If after two reminder texts, you still do not respond, you will be contacted by one of the study investigators to check study participation.

(4) How much of my time will the study take?

ASSESSMENT: The total time you will be required is dependant on the time you require for warm up:

- 5minutes for pre-test interview and application of sensors
- Warm up
- 2minutes for test and removal of sensors

WEEKLY TEXT: As per question (3) above, you will be required to respond 'yes' or 'no' to a weekly text.
FOLLOW UP: The total time you will be required is dependant on whether or not you sustain a hamstring injury in the upcoming year

- If you report a hamstring injury, you will need to be available for a 'free of charge' assessment by a physiotherapist
- If not do not report a hamstring injury no further assessment will be required

(5) Who can take part in the study?

Participants must be male or female athletes/players participate in a sport that involves sprinting. Included athletes must not have a current medical condition or injury that affects their ability to sprint pain free.

(6) Do I have to be in the study? Can I withdraw from the study once I've started?

Being in this study is completely voluntary and you do not have to take part. Your decision whether to participate will not affect your current or future relationship with the researchers or anyone else at the University of Sydney.

If you decide to take part in the study and then change your mind later, you are free to withdraw at

any time. You can do this by contacting Lisa Wolski and advising her of your decision in person or by phone 0411585689. There are no consequences for withdrawing from the study.

If you decide to withdraw from the study, we will not collect any more information from you. Please let us know at the time when you withdraw what you would like us to do with the information we have collected about you up to that point. If you wish your information will be removed from our study records and will not be included in the study results, up to the point that we have analysed and published the results.

(7) Are there any risks or costs associated with being in the study?

The assessment involves physical activities. There is a small risk of experiencing fatigue while doing physical activities. During the sprint, there is a risk of injury (such as muscle strain) but this risk is low, especially because you will be in a controlled environment and have completed a comprehensive warm up. Furthermore, being a professional or development squad athlete, your body will be habituated to high loads, thus one 60m sprint should not be too demanding. If you get injured, the research team will give you first aid and seek further medical attention as needed.

Participating in physical activities also has a small risk of experiencing post-exercise muscle soreness. You will complete an adequate cool down to minimise the risk of post-exercise muscle soreness.

The analysis of movement requires adhesive materials to be placed on your skin. There is a small risk of skin reaction to adhesive materials. You will be asked if you are allergic to adhesive material. If you are not sure, a skin test will be completed. If needed, a variety of hypoallergenic tape options are available. If a suitable option is not available, you will be excluded from the study.

(8) Are there any benefits associated with being in the study?

Our research aims to increase understanding of risk factors for hamstring strain injury. So, volunteering your time may help prevent this disabling injury in the future.

(9) What will happen to information about me that is collected during the study?

By providing your consent, you are agreeing to us collecting personal information about you for the purposes of this research study. Your information will only be used for the purposes outlined in this Participant Information Statement, unless you consent otherwise.

Your information will be stored securely and your identity/information will be kept strictly confidential, except as required by law. Study findings may be published, but you will not be individually identifiable in these publications.

We will keep the information we collect in this study in perpetuity and we may use it in future projects. By providing your consent you are allowing us to use your information in future projects. Please note your data will be de-identified in perpetuity. We don't know at this stage what these other projects will involve. We will seek ethical approval before using the information in these future projects.

(10) Can I tell other people about the study?

Yes, you are welcome to tell other people about the study.

(11) What if I would like further information about the study?

When you have read this information, Lisa Wolski will be available to discuss it with you further and answer any questions you may have. If you would like to know more at any stage during the study, please feel free to email lwol3022@uni.sydney.edu.au

(12) Will I be told the results of the study?

You have the right to receive feedback about the overall results of this study. You can tell us that you wish to receive feedback either by mail or email. This feedback will be in the form of a one page lay summary. You will receive this feedback after the study is finished.

(13) What if I have a complaint or any concerns about the study?

Research involving humans in Australia is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). The ethical aspects of this study have been approved by the HREC of the University of Sydney (Project #2018/674). As part of this process, we have agreed to carry out the study according to the *National Statement on Ethical Conduct in Human Research (2007).* This statement has been developed to protect people who agree to take part in research studies.

If you are concerned about the way this study is being conducted or you wish to make a complaint to someone independent from the study, please contact the university using the details outlined below. Please quote the study title and protocol number.

The Manager, Ethics Administration, University of Sydney:

- **Telephone:** +61 2 8627 8176
- **Email:** ro.humanethics@sydney.edu.au
- **Fax:** +61 2 8627 8177 (Facsimile)

This information sheet is for you to keep

THE UNIVERSITY OF SYDNEY

Discipline of Exercise & Sports Science
Faculty of Health Sciences

ABN 15 211 513 464

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'Prospective Cohort Study Investigating Running Mechanics as a Risk Factor for Hamstring Strain Injury'

PARTICIPANT CONSENT FORM – TRACK AND FIELD ATHLETES

I, ... [PRINT NAME], agree to take part in this research study.

In giving my consent I state that:

- I understand the purpose of the study, what I will be asked to do, and any risks/benefits involved.
- I have read the Participant Information Statement and have been able to discuss my involvement in the study with the researchers if I wished to do so.
- The researchers have answered any questions that I had about the study and I am happy with the answers.
- I understand that being in this study is completely voluntary and I do not have to take part. My decision whether to be in the study will not affect my relationship with the researchers or anyone else at the University of Sydney now or in the future.
- I understand that I can withdraw from the study at any time.
- I understand that personal information about me that is collected over the course of this project will be stored securely and will only be used for purposes that I have agreed to. I understand that information about me will only be shared with others with my permission, except as required by law.
- I understand that the results of this study may be published, and that publications will not contain my name or any identifiable information about me.

I consent to:

- **Video-recording** YES ☐ NO ☐
- **Release of previous hamstring injury data** YES ☐ NO ☐
- **Release of hamstring injury data in upcoming year** YES ☐ NO ☐
- **Data kept in perpetuity** YES ☐ NO ☐
- **Being contacted about further studies** YES ☐ NO ☐

I would like to receive feedback about the overall results of this study YES ☐ NO ☐

If you answered **YES**, please indicate your preferred form of feedback/contact and address:

☐ Postal: _____

_____

☐ Email: _____

.....

Signature

.....

PRINT name

.....

Date