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Late swing running mechanics influence hamstring injury susceptibility in elite rugby athletes: A prospective exploratory analysis

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ABSTRACT

Hamstring injuries are one of the most prevalent injuries in rugby union and many other running-based sports, such as track sprinting and soccer. The majority of these injuries occur during running; however, the relationship between running mechanics and hamstring injury is unclear. Obtaining large samples of prospective injury data to examine this relationship is difficult, and therefore exploratory analysis frameworks may assist in deriving valuable information from studies with small but novel samples. The aim of this study was to undertake a prospective exploratory analysis of the relationship between running mechanics and hamstring injury. Kinematic and kinetic data of the trunk, pelvis and lower limbs were collected during maximal overground running efforts for ten elite rugby union athletes. Subsequently, hamstring injury occurrence was recorded for the following Super Rugby season, during which three athletes sustained a running-based hamstring injury. Functional principal component analysis was used to visualise patterns of variability in running mechanics during the late swing phase between athletes. Results indicated that subsequently injured athletes demonstrated a tendency for greater thoracic lateral flexion, greater hip extension moments and greater knee power absorption, compared to uninjured athletes. All variables demonstrated an ability to descriptively differentiate between injured and uninjured athletes at approximately 60% of the late swing phase. Therefore, we hypothesize that greater thoracic lateral flexion, a greater hip extension moment and greater knee power absorption between peak hip flexion and peak knee extension during the late swing phase may put rugby athletes at greater risk of running-based hamstring injury.

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1. Introduction

Rugby union is a physically demanding sport with inherently high injury rates. Frequent explosive running efforts, collisions and impacts contribute to some of the highest injury rates of all team sports (Coughlan et al., 2011; Nicholl et al., 1995; Roberts et al., 2008; Williams et al., 2013). Notably, hamstring injuries are the most common non-contact lower-limb injury in rugby

and are highly prevalent in other running-based sports including soccer and Australian Rules football (Brooks et al., 2005; Ekstrand et al., 2016; Kara, 2013; Saw et al., 2017; Woods et al., 2004). Hamstring injuries most commonly occur during high-intensity running efforts (Bourne et al., 2015; Brooks et al., 2006); therefore, understanding running mechanics and the function of the hamstring muscles during high-speed running is pivotal to exploring the mechanisms underlying hamstring injury occurrence.

The majority of the current literature indicates that hamstring injuries are most likely to occur during the late swing phase of high-speed running (Chumanov et al., 2011; Chumanov et al., 2012; Heiderscheit et al., 2005; Kenneally-Dabrowski et al., 2019; Schache et al., 2010; Schache et al., 2009; Wan et al.,

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2017; Yu et al., 2017). Peak hamstring musculotendon strain and force occur during this phase and a large amount of negative work is performed in order to decelerate the rotation of the shank around the knee (Chumanov et al., 2011; Schache et al., 2012; Yu et al., 2017). However, these predicted musculotendon mechanics have not been directly related to injury occurrence. Rather, we rely on evidence from animal models to relate these findings to the possibility of injury (Brooks et al., 1995; Garrett et al., 1987; Lieber and Friden, 1993). Currently, there is a lack of prospective studies directly linking high-speed running mechanics, or hamstring function, to injury occurrence.

The only study to prospectively investigate the relationship between running mechanics and hamstring injury occurrence reported greater thoracic lateral flexion towards the swing leg side during the late swing phase in subsequently injured soccer players (Schuermans et al., 2017). However, this study was limited to analysis of joint and segment angles and therefore only provides insight to the running motion, without considering how the forces exerted by the body when interacting with the external environment may relate to injury. Thus, quantities such as joint moments, power and work provide valuable insight to the relationship between hamstring injury and the substantial load on the hamstrings during late swing.

The lack of prospective studies in this area is likely underpinned by the difficulty in obtaining sample sizes large enough for statistical analysis. A seemingly large baseline sample may still result in a small number of prospectively occurring injuries, and therefore obtaining this data is a challenge for researchers. The difficulty in accessing this cohort is compounded by the relatively small number of athletes at the elite level and the demands of the elite sporting environment, including intense training schedules and loads. However, there is valuable information to be derived from smaller sample studies, given the novelty of prospective injury data, especially in elite cohorts. Exploratory frameworks that allow descriptive yet methodical interpretation of these datasets may be used to gain insights to injury risk factors by means of hypothesis generation (Pataky et al., 2016). One-dimensional (1D) techniques that are suitable for descriptive exploration of pattern changes between groups may be warranted for construction of hypotheses using these smaller sample sizes.

Therefore, the aim of this study was to perform a prospective exploratory analysis of the relationship between overground high-speed running mechanics and hamstring injury. Running mechanics, including lower limb joint angles, angular velocities, moments and powers as well as segment angles of the pelvis and trunk will be examined in the context of hamstring injury, in order to construct a directional hypothesis of running-related risk factors for hamstring injury.

2. Methods

2.1. Participants

Ten professional rugby players (five forwards, five backs) were recruited from a single professional rugby union team in the international Super Rugby competition. Participants were free from any injury that affected their ability to perform maximal-effort sprints and had no history of hamstring injury in the year prior to testing. The study was approved by the human research ethics committee of the Australian National University and Australian Institute of Sport and all participants provided informed consent.

2.2. Study design

Athletes underwent a biomechanical assessment of maximal overground running efforts during the Super Rugby pre-season.

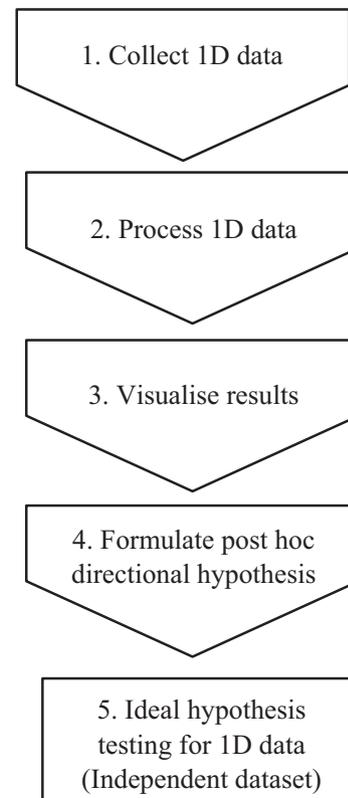


Fig. 1. Ideal exploratory analysis (Pataky et al., 2016). Step 1. Collect one-dimensional (1D) time-series data from running gait. Step 2. Process 1D data, including identification of the correct phases to be analysed (late swing phase) temporal normalisation, filtering etc. Step 3. Visualisation of results using *f*PCA to visually inspect the types of variation and scores for each variable. Step 4. Formulate a post hoc directional hypothesis based on the results of *f*PCA. Step 5. Ideal hypothesis testing using an independent dataset.

Concurrently and throughout the following Super Rugby season, hamstring injury data were collected for the entire squad from which these athletes were recruited. Therefore, hamstring injury occurrence was prospectively tracked following the running analysis, allowing the relationship between running mechanics and running-related hamstring injury to be explored. To examine this relationship, this study adopted the framework of an ideal exploratory analysis (Fig. 1) (Pataky et al., 2016). This facilitates construction of an evidence-informed directional hypothesis, which can be tested using a separate independent data set.

2.3. Biomechanical running assessment

Testing took place at the Australian Institute of Sport biomechanics laboratory, on a 110 m indoor synthetic track. First, reflective markers were placed on specific anatomical landmarks of each athlete (Fig. 2) (Besier et al., 2003; Lloyd et al., 2000). Athletes then undertook a self-selected warm up, before performing three maximal 50 m sprints. Historical testing data from this cohort indicated that athletes reached maximum velocity within the 30–50 m region of minimum effort sprinting. Therefore, a 20-camera three-dimensional motion analysis system (VICON, Oxford Metrics Ltd., Oxford, United Kingdom) sampling at 250 Hz was positioned around the 30–50 m region of the sprint to obtain trajectory data through the maximum velocity phase of each sprint. Ground reaction force (GRF) data were simultaneously collected by eight contiguous 900 × 600 mm force plates (Kistler Instrument Corp., Winterthur, Switzerland) sampling at 1000 Hz.

Data were also collected while athletes stood in a quiet standing position to establish segment lengths and joint centre positions.

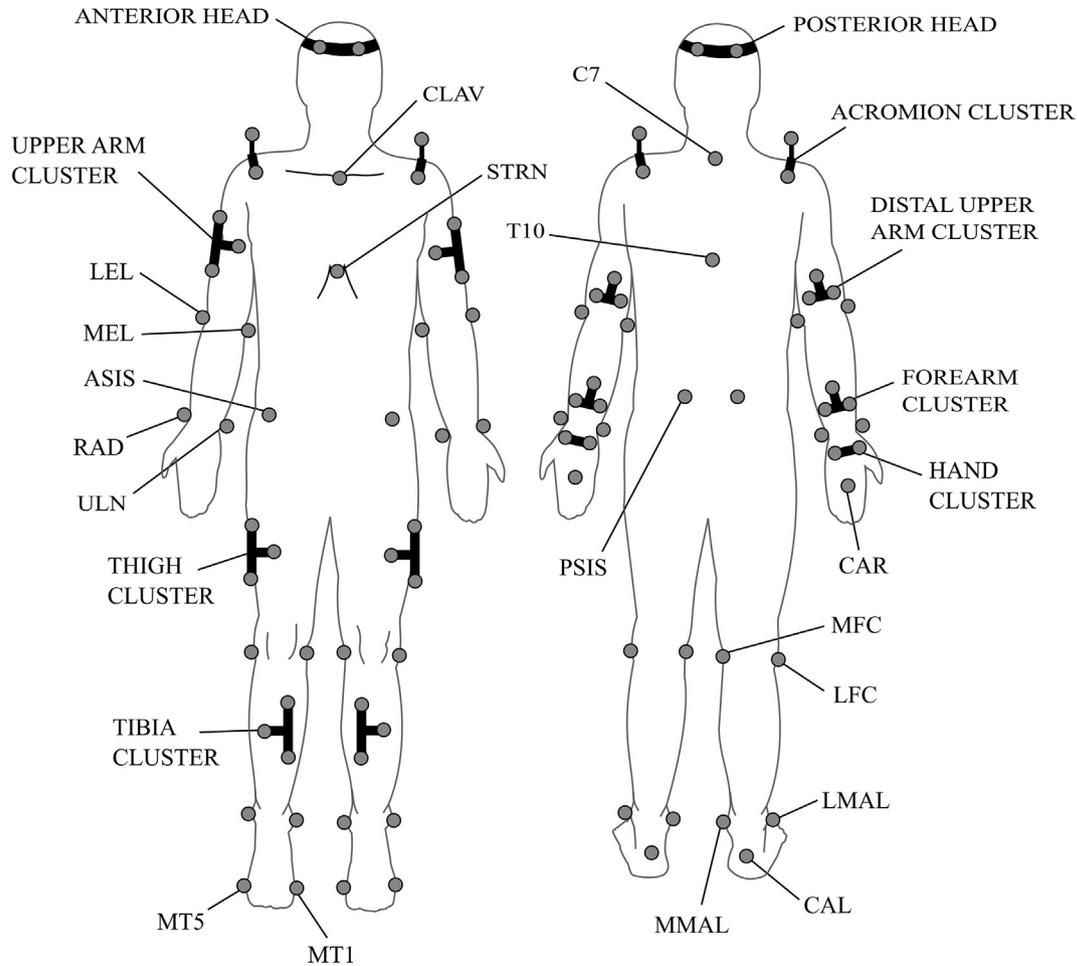


Fig 2. Reflective marker placement, anterior view (left) and posterior view (right). Anterior and posterior head markers were attached to a headband. The acromion cluster was comprised of three markers, with the centre marker placed above the acromion process. The upper arm cluster was placed halfway along the upper arm, so that the longitudinal axis was in line with the greater tuberosity and lateral humeral epicondyle. Distal upper arm clusters were placed on the posterior aspect of the distal half of the upper arm, just above the epicondyle markers of the elbow. The forearm cluster was placed just superior to the radial and ulnar wrist markers, while the hand cluster was placed distally. Thigh clusters were positioned halfway along the length of the thigh, with the longitudinal axis aligned with the greater trochanter and lateral femoral condyle. Tibia clusters were placed with the longitudinal axis along the medial border of the tibia. Individual reflective markers are defined as follows; C7, spinous process of the 7th cervical vertebra; T10, spinous process of the 10th thoracic vertebra; CLAV, sternal notch; STRN, xiphoid process of the sternum; LEL, lateral humeral epicondyle; MEL, medial humeral epicondyle; RAD, radial styloid process; ULN, ulnar styloid process; CAR, distal intermediate carpal; ASIS, anterior superior iliac spine; PSIS, posterior superior iliac spine; LFC, lateral femoral condyle; MFC, medial femoral condyle; LMAL, lateral malleoli; MMAL, medial malleoli; CAL, calcaneus; MT1, head of metatarsal one; MT5, head of metatarsal five.

The thorax and pelvis segments were defined relative to the global coordinate system. Hip joint centres were defined relative to the pelvis, using the regression equation of [Shea et al. \(1997\)](#). Knee joint centres were defined as the midpoint between markers placed on the lateral and medial femoral condyles. Ankle joint centres were established as the midpoint between lateral and medial malleoli markers ([Besier et al., 2003](#)).

Marker trajectory and GRF data were processed using Vicon Nexus Version 2.6 (VICON, Oxford Metrics Ltd., Oxford, United Kingdom). A residual analysis and visual inspection of the data were used to determine appropriate filtering levels. Marker trajectory and GRF data were filtered using a 4th order low-pass Butterworth filter, with cut-off frequencies of 15 Hz and 80 Hz, respectively. Similar cut-off frequencies have previously been used for trajectory and GRF data during gait ([Bonacci et al., 2013](#); [Sun et al., 2015](#); [Zhong et al., 2017](#)). GRF data was used to identify foot strike events using a 10 N threshold. A lower body and trunk model was used to calculate lower body and thorax kinematics and joint kinetics via inverse dynamics ([Besier et al., 2003](#)), whereby segmental inertial properties were derived from [De Leva \(1996\)](#).

Late swing phase was identified as the period of interest, as previous research indicates this is the most likely timing of hamstring injury occurrence ([Chumanov et al., 2011](#); [Chumanov et al., 2012](#); [Heiderscheit et al., 2005](#); [Kenneally-Dabrowski et al., 2019](#); [Schache et al., 2010](#); [Schache et al., 2009](#); [Wan et al., 2017](#)). Late swing phase was defined from peak knee flexion in mid-swing until foot strike. Data were averaged over three trials for each participant, and only right strides were included for analysis. Data was normalised to 100% of late swing phase. Running velocity was calculated based on the velocity of the centre of the pelvis segment averaged across a complete stride (right toe off, to the next right toe off).

2.4. Hamstring injury recording

Hamstring injury data for all hamstring injuries that occurred in the Super Rugby season following the biomechanical running assessment (including the remainder of the pre-season period) were extracted from the club Athlete Management System. A hamstring injury was defined as per [Fuller et al. \(2007\)](#) as “any physical

complaint, which was caused by a transfer of energy that exceeded the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training and resulted in a player being unable to take a full part in future rugby training or match play." All injuries extracted were "time-loss" injuries and were coded within the Athlete Management System using the Orchard Sports Injury Classification System (OSICS) at the time of injury (Orchard, 1993). Hamstring injuries were extracted by screening all injury data for injuries coded using the following OSICS diagnosis codes: TMHX (Hamstring strain), TMHS (Hamstring strain – semimembranosus/tendinosus strain, grade 1–2), TMHB (Hamstring strain – biceps femoris strain, grade 1–2) and TMHR (Grade 3 hamstring strain). Injury data included the activity at the time of injury, and therefore only hamstring injuries that occurred during running were included for analysis.

2.5. Data analysis

Biomechanical variables of interest were identified based on their relevance to hamstring function. This included, hip and knee angles, their corresponding angular velocities as well as joint moments and powers. In addition, pelvic tilt and thoracic lateral flexion were included for analysis, as these variables have been previously linked to hamstring injury occurrence (Schuermans et al., 2017). At the hip and knee joints, a positive moment represented an extension moment, positive pelvic tilt represented an anterior pelvic tilt and positive thoracic lateral flexion represented flexion towards the right (ipsilateral swing leg) side.

Functional principal component analysis (fPCA) was used to visualise patterns of variability between athletes for each biomechanical variable. Independent fPCAs were applied to each variable, using each participant's ensemble mean curves as inputs. A comprehensive description of fPCA can be found in Warmenhoven et al. (2017). For each variable, the functions representing each late swing phase were approximated using B-splines. A roughness penalty was added to the fitting procedure, which was controlled by a smoothing parameter. The data in this study did not require extensive smoothing, and therefore a small smoothing coefficient ($1e^{-15}$) was used to fit the curves. Varimax rotations were performed to assist with interpretation of each fPC. Five functional principal components (fPCs) were obtained for each variable (with this representing >90% of variation in the original data for each variable). All FDA processes were implemented using Matlab (The Mathworks Inc, MA, USA, R2017a), and customised software developed by Ramsay et al. (2009).

Visually, each fPC is presented in the same domain as the original functional observations (100% of late swing phase), and are presented as an overall mean \pm the fPCs, which have been scaled using a constant (which in this case was 2 standard deviations of the fPC scores). fPC scores were plotted and descriptively inspected for each variable, to identify any differences between injured and uninjured athletes.

3. Results

Four of the ten elite rugby athletes sustained a hamstring injury within the Super Rugby season following the biomechanical assessment of high-speed running. Three of these injuries occurred during running, and were therefore included for analysis. One injury occurred during a ruck (a contact, rather than running-based, injury) and was excluded from analysis. Six athletes did not sustain a hamstring injury following the biomechanical assessment and were included in the uninjured group. Time between the biomechanical assessment and hamstring injury for each of the injured athletes was 39 days, 139 days and 192 days, respectively.

During the biomechanical running assessment, injured and uninjured players achieved similar maximum running velocities (injured = 8.97 ± 0.31 m/s, uninjured = 8.52 ± 0.61 m/s), and were also similar in age (injured = 27.33 ± 3.21 years, uninjured = 25.33 ± 3.08 years), height (injured = 1.93 ± 0.9 m, uninjured = 1.88 ± 0.9 m), and mass (injured = 100.89 ± 13.08 kg, uninjured = 99.73 ± 13.77 kg).

After examining the first five fPCs for each of the ten variables of interest (resulting in a total of 50 separate fPCs across multiple variables; Appendix A), five fPCs from three variables descriptively differentiated between injured and uninjured athletes. Thoracic lateral flexion, knee power and hip moment each contained fPCs that appeared to distinguish between injured and uninjured athletes. Periods of variation identified in the Varimax rotated key phase of each fPC were cross-validated against the thoracic lateral flexion angle, knee power and hip moment data plotted for the two groups (Fig. 3). The graphs revealed that each of these five fPCs

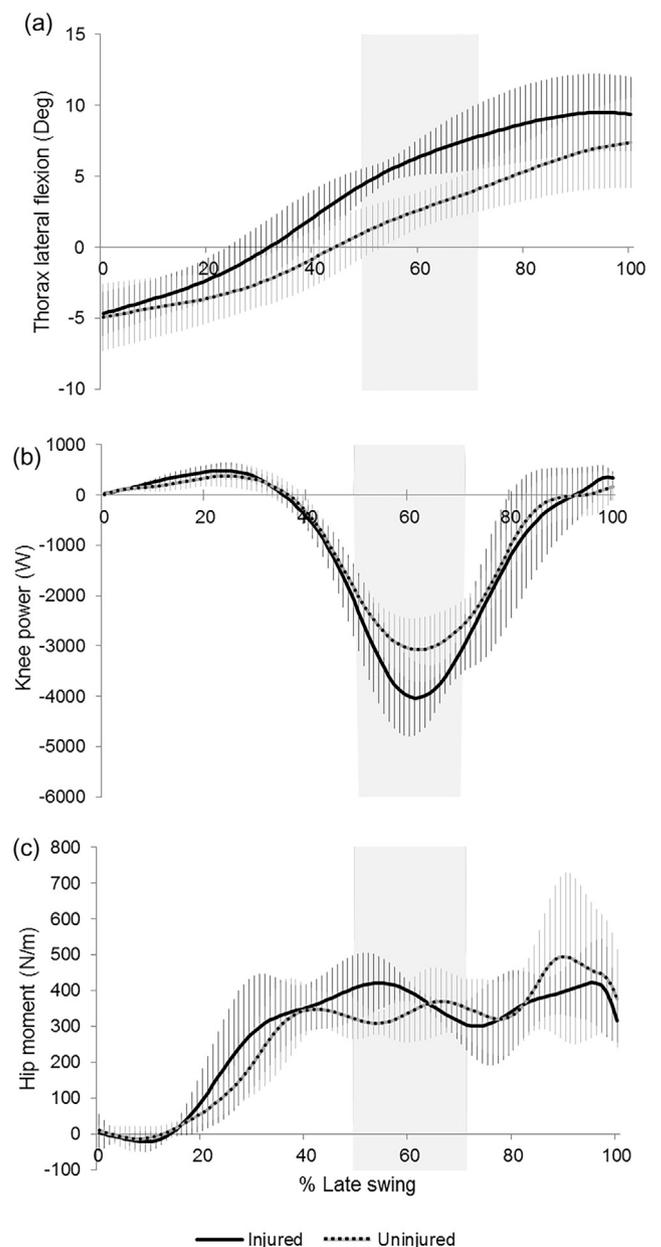


Fig. 3. (a) Thoracic lateral flexion (b) Knee power (c) Hip moment, for injured (solid line) and uninjured (dashed line) rugby athletes. The shaded region highlights the period of variation identified by fPC5 for lateral thoracic flexion, fPC1 for knee power and fPC5 for hip moment.

represented real descriptive differences between groups for these variables. The results of the entire exploratory analysis, including all variables, *fPC*s and associated *fPC* scores, can be found in Appendix A.

Thoracic lateral flexion, knee power and the hip moment all showed a tendency to discriminate between injured and uninjured

athletes during late swing. *fPC*1, *fPC*2 and *fPC*5 for thoracic lateral flexion all discriminated between these groups of athletes. Positive scorers for *fPC*1 demonstrated a tendency for greater thoracic lateral flexion towards the ipsilateral side during late swing phase, while negative scorers exhibited less lateral flexion (Fig. 4a).

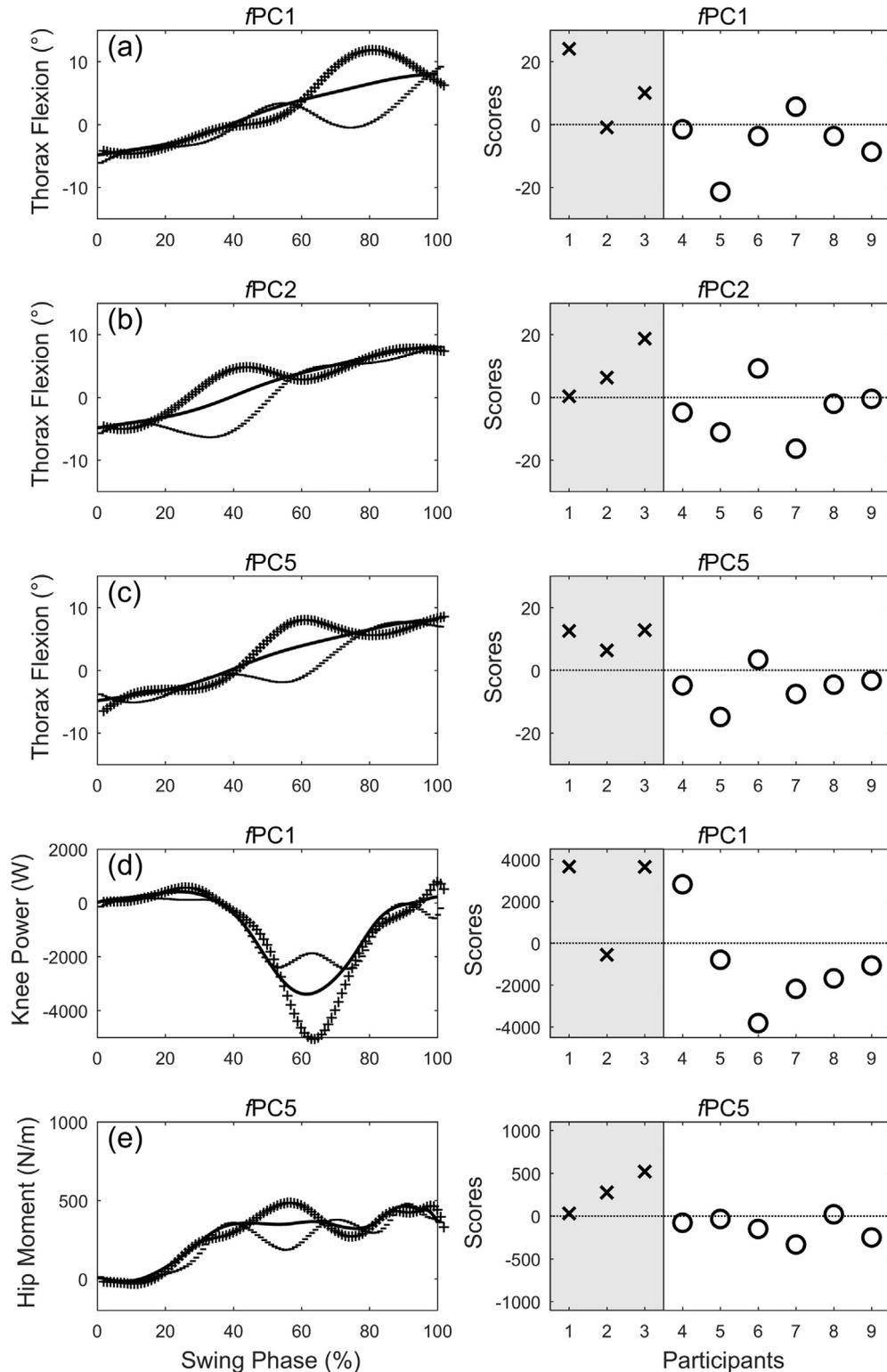


Fig. 4. *fPC*s that displayed a tendency to differentiate injured from uninjured rugby players during the late swing phase of high-speed running. Subplots are paired, with each *fPC* (left) and associated *fPC* scores (right) displayed relative to each other. On the *fPC* plots (left), the solid line represents the mean of all athletes data, while the positive, '+' and negative '-' lines represent ± 2 standard deviations of the *fPC* scores. On the right, the corresponding *fPC* scores are plotted for each athlete. Athletes one to three, represented by crosses, signify injured athletes, while noughts (athletes four to nine) represent uninjured athletes. (a) *fPC*1 for thoracic lateral flexion. (b) *fPC*2 for thoracic lateral flexion. (c) *fPC*5 for thoracic lateral flexion. (d) *fPC*1 for knee power. (e) *fPC*5 for hip moment.

Positive scorers for $fPC2$ demonstrated greater ipsilateral thoracic lateral flexion earlier in the late swing phase, with negative scorers being closer to neutral, or still flexed towards the contralateral side (Fig. 4b). $fPC5$ also reflected a difference between groups for thoracic lateral flexion during late swing (Fig. 4c). Again, positive scorers were more likely to have greater ipsilateral thoracic flexion over this section of swing phase, while negative scorers tended to have less lateral flexion, or still be flexed towards the contralateral side. For all thoracic lateral flexion $fPCs$, injured players featured predominantly as positive scorers, indicating that these athletes tended to have greater ipsilateral thoracic lateral flexion during late swing. Uninjured athletes were predominantly negative scorers, therefore displaying less, or delayed lateral flexion.

For knee power, $fPC1$ reflected a difference in power absorption at the knee during the late swing phase of high-speed running (Fig. 4d). Positive scorers showed a tendency for greater power absorption at the knee, while negative scorers tended to display lower power absorption. For $fPC1$, injured players featured predominantly as positive scorers, indicating that these athletes absorbed greater power at the knee during the late swing phase. The reverse was true for uninjured athletes.

For the hip moment, $fPC5$ described a difference in hip extension moment during this section of the swing phase (Fig. 4e). Positive scorers had a larger hip extension moment in the middle of late swing, with the reverse being true for negative scorers. For $fPC5$, injured players were all positive scorers, showing a tendency for greater hip extension moment during the middle of late swing. Uninjured players were predominantly negative scorers, reflecting a propensity for a smaller hip extension moment during late swing.

4. Discussion

The aim of this study was to prospectively analyse the relationship between high-speed running mechanics and hamstring injury during running in elite rugby athletes, in order to construct a directional hypothesis for an independent experiment. The exploratory analysis identified several variables that descriptively differentiated between injured and uninjured athletes.

Rugby athletes who subsequently sustained a hamstring injury tended to display larger thoracic lateral flexion towards the ipsilateral side, compared to the average of all athletes. This accords with the findings of Schuermans et al. (2017), who suggested that this increase in ipsilateral trunk lateral flexion may reflect a deficit in core stability, resulting in excessive trunk motion. Schuermans et al. (2017) defined core stability as ‘the ability to control the position and motion of the trunk and the pelvis to allow optimum production, transfer and control of force and motion to the terminal segment in integrated athletic activities’ as per Kibler et al. (2006). Indeed, this broad, functional definition of core stability appears to relate to the behaviour of the thorax observed in injured rugby athletes.

Core stability has, for a long time, been regarded as important for injury prevention (Willson et al., 2005). In fact, Devlin (2000) suggested that poor core stability in rugby athletes may contribute to inefficiencies in running mechanics and lead to hamstring injury. However, to date there has been no evidence to support this claim. Indeed, across all sports, there has been a distinct lack of prospective studies examining the relationship between core stability, running, and hamstring injury; with the majority of studies either retrospective in nature or failing to examine core stability functionally during running (Shield and Bourne, 2018). Schuermans et al. (2017) provided the first direct evidence objectifying the importance of core stability for preventing hamstring injury during running, and the current study supports their findings in a rugby cohort. However, further understanding of the

contributors to atypical thoracic movement is required before attribution to a lack of core stability can be made.

Knee power during the late swing phase also showed a tendency to distinguish between injured and uninjured rugby athletes. $fPC1$ for knee power identified the period of peak power absorption during the late swing phase. During this period subsequently injured rugby players predominantly exhibited greater power absorption compared to the mean of all athletes. The beginning of this identified period of interest (approximately 50% of late swing) coincided with the trough in angular velocity at the knee, indicating the beginning of the deceleration of the shank. Peak knee power absorption occurs shortly after, and we can assume this also reflects a large amount of negative work by the hamstrings in order to slow the angular rotation of the shank (Chumanov et al., 2007, 2011; Schache et al., 2012; Thelen et al., 2005). Negative work has been previously linked to injury in animal studies (Brooks et al., 1995), which supports the idea that the amount of negative work at the knee, and therefore the hamstrings, may be associated with hamstring injury susceptibility. It is also important to note that this negative work is the product of a large force while the muscle is lengthening. Therefore, future studies should aim to prospectively examine the differences in musculotendon mechanics (force, length, velocity and negative work) between injured and uninjured athletes, in order to understand which of these factors is most influential in injury occurrence. Further, increased knee power absorption and negative work during late swing have also been linked to running at faster speeds (Schache et al., 2011), and it has been suggested that late swing knee kinetics are important for running performance (Morin et al., 2015). Therefore, the findings described within this study may also have implications for performance. However, it is interesting to note that injured and uninjured athletes reached similar average maximum running speeds, and therefore displayed similar level of performance.

Finally, the extension moment produced at the hip during the late swing phase appeared to distinguish between subsequently injured and uninjured rugby athletes. The period of late swing phase identified by $fPC5$ begins as the hip starts to extend following peak hip flexion. This also signifies the change from negative to positive work at the hip, and therefore a different functionality of the hip extensor moment. During this period, rugby athletes who sustained a hamstring injury tended to have a greater hip extension moment. While the hip extension moment during late swing has not previously been a focus of hamstring injury research, a large extension moment would place competing demands on the hamstrings during this phase, when the hamstrings must also absorb negative work at the knee. Further, during this phase energy generated by the hip is typically transferred proximally to the trunk (Chapman and Caldwell, 1983; Vardaxis and Hoshizaki, 1989). Therefore, a larger hip extension moment is likely to result in a larger transfer of energy to the trunk, which may contribute to a reduced ability to control the trunk. This may explain why injured athletes tended to display greater thoracic lateral flexion during late swing. An alternative explanation may be that athletes who were subsequently injured used increased lateral flexion as a means of dissipating the increased energy transferred to the trunk.

This exploratory analysis may also provide insight to specific part(s) of late swing that are linked to hamstring injuries. The Vari-max rotated key phases for $fPC5$ for thoracic lateral flexion, $fPC1$ for knee power and $fPC5$ for hip moment all occurred at approximately 55–60% of the late swing phase (as illustrated by the shaded region in Fig. 3). During this time, the hip produced an extension moment and generated positive work to extend the hip. The knee extended rapidly, but a flexion moment and large amount of negative work was starting to slow this extension. Finally, during this period, the thorax had just started to flex to the ipsilateral side. Most

studies have only suggested the late swing phase in general as the likely timing of injury, however Heiderscheit et al. (2005) suggested a more specific timing, for which they reported hip and knee angles that correspond to the joint angles measured in this study at approximately 60% of the late swing phase. We suggest this specific period of the late swing phase, after peak hip flexion and prior to peak knee extension, should become the focus of future investigations.

This study must be interpreted in the context of its limitations. The number of included athletes was small; however, the analysis technique we have employed is part of a rigorous method, which proposes using this type of analysis to formulate a directional hypothesis. Further, the current study did not model the metatarsal phalangeal joint. However, it is anticipated that the error induced by the absence of a metatarsal phalangeal joint during the swing phase would be minimal. The segmental inertial properties used in this study were derived from males of similar age, however were not subject or rugby specific. Given that rugby athletes are typically larger than the average population, this may lead to underestimation of joint moments during the swing phase. It is also important to acknowledge that hamstring injuries are likely multifactorial, and 'risky' running mechanics alone may not result in hamstring injury. However, unfavourable running mechanics may increase an athlete's risk of injury, especially when combined with other risk factors.

Finally, this study demonstrated the potential for 1D-dimension reduction approaches (i.e. *f*PCA) to be used in the descriptive exploration of smaller sample sizes, which can be used to frame 1D hypotheses and then re-tested using more rigorous 1D hypothesis testing methods (i.e. statistical parametric mapping) on future independent data sets. By employing this method, we have been able to use a novel dataset to derive valuable information to further our understanding of the relationship between running mechanics and hamstring injury. As a result, the following 1D hypotheses can be constructed:

- It is hypothesised that thoracic lateral flexion will differ between uninjured and injured athletes across the majority of late swing (20–95%), with injured athletes having significantly greater thoracic lateral flexion across this part of late swing.
- It is hypothesised that knee power will differ between uninjured and injured athletes at approximately 55–60% of late swing, with injured athletes having significantly greater power absorption across this phase of late swing.
- It is hypothesised that hip moment measures will differ between uninjured and injured athletes at approximately 55–60% of late swing, with injured athletes having significantly greater moments across this phase of late swing.

These hypotheses can be tested for using parametric hypothesis testing techniques that are suitable for 1D data such as statistical parametric mapping (SPM), pending power assumptions for sample size are met (Pataky et al., 2016).

Declaration of Competing Interest

The authors declare that there are no conflicts of interest related to the content of this work.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2019.05.037>.

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