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McGrath, T. M., Hulin, B. T., Pickworth, N., Clarke, A. and Timmins, R. G. (2020). Determinants of hamstring fascicle length in professional rugby league athletes. *Journal of Science and Medicine in Sport*, 23(5), pp. 524-528. https://doi.org/10.1016/j.jsams.2019.12.006

Determinants of hamstring fascicle length in professional rugby league athletes

Timothy M. McGrath[1,2,3], **Billy T. Hulin**[1,4], **Nathan Pickworth**[1], **Alex Clarke**[1], **Ryan Timmins**[5],

1. St George Illawarra Dragons Rugby League Club, Wollongong, Australia
2. Pitch Ready, Canberra, Australia
3. Elite Rehab & Sports Physiotherapy, Canberra, Australia
4. Centre for Human and Applied Physiology, School of Medicine, University of Wollongong, Wollongong, New South Wales, Australia
5. School of Behavioural and Health Sciences, Australian Catholic University, Melbourne, Australia

Corresponding author:

Ryan G. Timmins

ORCID - https://orcid.org/0000-0003-4964-1848

School of Exercise Science, Australian Catholic University, 115 Victoria Parade, Fitzroy,

3065, Melbourne, Victoria, Australia

Ryan.Timmins@acu.edu.au

Running Title:
Fascicle length determinants

Word Count:
2780

Abstract Word Count:
248

Number of tables and figures:
Tables = 1. Figures = 2. Supplementary Tables = 2

Abstract:

Objectives: Investigate the determinants of hamstring fascicle length within professional rugby league players.

Design: Retrospective cohort study

Method: Thirty-three athletes underwent a testing during the early and late pre-season periods. Fascicle length measurements of biceps femoris, 3D kinematics and elapsed time-periods at thigh angular velocities between 20deg/s to peak velocity during a single-leg eccentric hamstring strength test, GPS-derived running loads, age and previous injury history were all recorded. Fixed effect determinants for fascicle length were analyzed using multiple linear regression.

Results: Significant determinants of hamstring fascicle length were observed. Multivariate regression analysis showed modifiable factors including chronic running volumes >80% of measured peak speed collectively explained 43% of the variability in the fascicle length data, whilst peak eccentric strength-related and elapsed time under load from 20deg/s to peak thigh angular velocity collectively contributed an additional 44%. Chronic running volumes >90% of individually measured peak speed and the ‘break angle’ during a Nordic eccentric contraction were not significant contributors to the final model. Non-modifiable risk factors (age and previous injury) contributed the remaining 13%.

Conclusions: Managing high speed running exposure as well as eccentric strength training allows for ~90% of the controllable determinants in fascicle length within elite athlete populations. An important contributor to the explained variability within fascicle length (superseded only by chronic speed exposure and peak eccentric strength) was an athletes ability to achieve a prolonged contraction at long lengths during eccentric strength training rather than the angle of failure during the contraction in itself.

Keywords: Hamstring, Fascicle, Injury, Speed, Strength, Prevention, Sport

Practical Implications

- Using factors that are readily available in elite sporting settings, it was possible to determine ~90% of the variability in biceps femoris long head fascicle length with a multiple linear regression. These factors included chronic running exposure >80% of a relative maximum velocity, peak eccentric strength (during the Nordic) and time under load at longer leg lengths in the Nordic. Non-modifiable factors (age and previous history) also contributed to the explained variability in fascicle length.
- Chronic running exposure >90% of relative maximal velocity and the ‘break angle’ during a Nordic effort were not statistically significant contributors to determining fascicle length.
- These findings give practitioners the option to monitor alternative variables (instead of fascicle length itself) and be able to approximate (around 90%) of the impact it may have on fascicle adaptations in elite athletes.

Introduction

Hamstring strain injuries (HSI) are the most common non-contact lower limb injuries in team sports that involve sprinting, kicking, jumping or high-speed movements[10]. Increases in overall injury rates negatively influence team[8] and individual performances[28], which have negative financial consequences for sporting organizations and athletes[10]. As such, identifying factors associated with HSI have important applications to practitioners in team sport.

A number of non-modifiable risk factors for HSI have been identified previously, most prominently, increasing age and previous injury[2,9]. However, in recent times, a greater emphasis has been placed on modifiable risk factors and appropriate interventions, which may lead to reductions in an athlete's risk of HSI [25]. Of these modifiable risk factors, eccentric hamstring strength has received significant attention [1,3,19,20], with low levels of eccentric hamstring strength reported to increase the risk of future hamstring injury in athletes from different football codes[4,13]. Recently, it has been reported that elite footballers with biceps femoris long head (BFlh) muscle fascicles shorter than 10.56cm (determined using a receiver operating characteristic curve) were approximately four times more likely to suffer a hamstring injury in the subsequent season compared to athletes with longer fascicles[24].. These data suggest that interventions aimed at increasing BFlh fascicle lengths and eccentric knee flexor strength should be prioritized in hamstring injury prevention programs[14]. Furthermore, it has been reported that the 'break-point' angle (i.e. the point that a steady state lowering during a Nordic eccentric exercise cannot be sufficiently controlled) achieved during Nordic hamstring lowers was: 1) positively correlated to eccentric hamstring strength[19] and 2) able to be used as a field-based assessment of eccentric hamstring strength[12,19]. However, the applicability of this measure to elite sport is still unknown.

The risk of future HSI has also been related with spikes in high-speed (>24km/hr.) running volumes, which are relative to each athlete's regular performance[7,18]. However, both over- and under-exposure to maximum speed (>85% of maximum velocity) efforts and volume (i.e. distance covered) is associated with the greatest risk of non-contact lower limb injury in professional Australian footballers[15,21]. Although there is an association between running exposure and the risk of HSI, the independent use of running variables to predict future HSI may have limited clinical value, where multiple factors (including eccentric strength and fascicle length) may be needed to determine the probability of a future HSI [16].

As such, the purpose of this study was to evaluate the influence of elite physical training variables on fascicle length changes in professional rugby league players. These variables included peak hamstring eccentric strength and quality of such a movement (i.e. 'break angle'), as well as running exposure, age, and injury history across a single-season in professional rugby league players.

Methods

The study received ethical approval from the Human Research Ethics Committee (approval number 2018-135H). Thirty-three elite rugby league players (mean age: 23.9±3.9 years, mean body mass: 98.6±9.6kg, mean height: 187±4.6cm) underwent a comprehensive performance battery on three separate occasions, separated by a minimum of 56 days (i.e. 8 weeks); December 2017 (early pre-season), February 2018 (late pre-season) and May 2018 (in-season). The following was tested on each occasion: 1) peak force output during a single-leg Nordic hamstring exercise using a Nordbord (Vald Performance, Albion QLD, Australia); 2) motion analysis during a single-leg Nordic hamstring exercise using an 8-camera 3D motion capture system (Vicon, Oxford UK); and 3) measurement of BFlh fascicle length. In addition, Global Positioning System (GPS)-derived distance covered >80% and 90% of each athlete's individual peak speed over the preceding 28 (28-day chronic load) and 56 (56-day chronic load) days prior to each test was recorded via wearable GPS technology, which has demonstrated accuracy and reliability for measuring instantaneous velocity (Catapult Sports, Melbourne Victoria, Australia) [27]. Anthropometric data and previous injury history were also recorded by qualified physiotherapists.

An experienced exercise physiologist performed all motion analysis and hamstring strength testing, whilst fascicle length testing was undertaken by a reliable assessor on each occasion. The assessor who measured fascicle length has previously reported reliability metrics with intraclass correlations ranging between 0.96 to 0.97 and typical error as a percentage of coefficient of variation less than 3.4% (range 2.1 to 3.4%)[26]. Injury history and anthropometric data were collated by qualified physiotherapists. For the purposes of this investigation, the dominant leg was considered the participant's preferred leg when kicking a ball. Eccentric hamstring strength testing and motion analysis (for the break-point analysis) were captured simultaneously, with fascicle length measured before any exercise on the same day. Chronic running loads greater than 80, and 90% of each player's maximum velocity were collated from the preceding 28, and 56 days prior to each respective test.

The hamstring strength testing device (Vald Performance, Albion, Queensland, Australia) and 3D motion capture (Vicon, Oxford UK) were set-up as per the manufacturer's recommendations. Lower body plug-in gait was used for motion capture. Prior to testing, each participant was allowed a five-minute warm up consisting of one set of five double-leg repetitions as a warm-up. Testing consisted of one set of three single-leg maximum eccentric contractions on each side, with the dominant leg tested first (e.g. participants complete 3 efforts of a single-leg Nordic on their dominant leg and then undertook the same testing on their non-dominant leg – supplementary video 1). All athletes had undertaken single-leg Nordics for at least 3 months prior to the testing and were familiar with the exercise and how it differs from the double-leg version. During all efforts, the participants were advised to maintain a neutral/extended hip position. Average peak force (Newtons) across the three repetitions was recorded for each testing period. In addition, the corresponding knee angle of the tested limb at the time of reaching the below thigh angular velocities, was recorded for each maximal effort: *20deg/sec* (corresponding to the start of the forward movement), *60deg/sec* (corresponding to the period when the athlete began to 'accelerate' during the eccentric movement, and *peak angular velocity* which represented loss of control of the movement. Additionally, the elapsed time period (milliseconds) between *20-60deg/sec* and *20-peak velocity* were recorded to account for the *time under load* during the contraction. The results of the testing parameters are summarised in Table 1.

The processes used for the collection of BFlh architecture has been previously described[26] . The extrapolation technique, whilst not a direct measure of fascicle length, has been successfully validated against cadaveric tissues and as such is considered a robust way of estimating fascicle lengths[11]. Muscle thickness, pennation angle and fascicle length of the BFlh were determined utilising two-dimensional, B-mode ultrasound (frequency 12MHz; depth 8cm; field of view, 14 x 47mm) (GE Healthcare Vivid-*I*, Wauwatosa, WI). The site of assessment was determined as halfway between the ischial tuberosity and the popliteal crease, along the line of the BFlh. All assessments were undertaken in a prone position with both the hip and knee extended, with the participant having undertaken 5mins of inactivity. The ultrasound probe, with a layer of conductive gel, was placed perpendicular to the posterior thigh on top of the measured scanning site. The orientation of the probe was then manipulated by a skilled assessor, with published reliability, until a clear image was obtained[26]. .

Once the images were collected, analysis was undertaken off-line (MicroDicom, Version 0.7.8, Bulgaria). For each image, fascicle length estimation was undertaken using the equation which was validated against cadaveric tissues[11]. The equation used was:

$$FL = \sin(AA + 90°) \times MT/\sin[180° - (AA + 180° - PA)]$$

where:

FL = fascicle length, AA = aponeurosis angle, MT = muscle thickness and PA = pennation angle.

Fascicle length was reported in absolute terms (cm) from a single image and fascicle. The results of these tests are presented in Table 1.

These data were collected from training within the previous 28 and 56 day periods prior to each respective testing block. The peak speed ($m.s^{-1}$) achieved between tests and average 7-day running volume (m) greater than 80%, and 90% of peak speed was calculated for the preceding 28, and 56 days. The results of these data are summarised in Table 1. This study utilized a convenient sample of 33 players and was undertaken in an exploratory manner. Statistical analysis was performed using R-Studio Statistical package (version 1.1.423).

Results

Thirty-three athletes were included in the final analysis. The group included outside backs (n=16), edge (n=6) and middle players (n=11). Results across the group indicated fascicle lengths of 10.11cm at testing 1 (pre-season), 10.65cm at testing 2 (late-pre-season), and 10.52cm at testing 3 (in-season; Table 1). Nordic force and motion analysis results indicated a mean Nordic peak force output of 407.3N / 4.16N/kg (IQR = 321-471; 3.52-4.72), 623ms (IQR = 555-723) from start of forward movement until peak thigh angular velocity during the eccentric contraction, and 37.7deg (IQR = 42-32) knee angle at the time of peak angular velocity.

Running loads during the study period are indicated in Table 1. Results here indicate a mean maximum velocity of 8.74m$\cdot$s^{-1} (IQR = 8.3-9.2) with mean chronic load >80% of the measured maximum speed 76.8m (IQR = 33.3-107.8) and 58.9m (IQR = 31.1-79.5) for the preceding 28 and 56-day periods, respectively. Mean speed volumes >90% of the measured maximum speed measured 14 m (IQR = 3.3-20.0) and 9.7m (IQR = 3.4-13.7) for the preceding 28 and 56-day periods, respectively.

To examine the fixed-effect determinants of fascicle length, a multiple linear regression analysis was performed. This involved a backward stepwise regression from the full model (all variables included) to arrive at the final model. The analysis of variance is presented in Supplementary Table 2. This indicates that the predictors used in the final analysis to be statistically useful contributors to the final model.. This indicates that the predictors used in the final analysis to be statistically useful contributors to the final model. The summary of coefficients for the final model is indicated in Supplementary Table 1. The adjusted R-squared value for the final model on the current data set was 50.6 (F-value 8.62 on 9 and 58 df, p-value = 4.56e-08), indicating that 50.6% of the explained variability in fascicle length within the dataset was due to the variables included in the final model. The relative contribution of each variable to the final model is indicated in Figure 1 [INSERT FIGURE 1 NEAR HERE]. The most important contributor to fascicle length within the observed dataset was running volume (measured in meters) >80% of the athletes measured maximum velocity (30%). Peak Nordic force output (27%) and elapsed time under load at long lengths (17%) rounded out the three highest contributors to fascicle length changes. Peak speed (13%), previous injury (8%) and age (5%) were other statistically significant contributors to the observed variability in fascicle length within this dataset. Running volumes >90% and angle-specific thigh angular velocities (20deg/s, 60deg/s and angle of peak thigh angular velocity) were not statistically significant determinants of fascicle length within this data set.

The model assumptions (residuals plots) are highlighted in Figure 2. The model assumptions are that the residuals are independent and are normally distributed, centred around zero and have a constant variance ($\varepsilon \sim N(0,\sigma^2)$). The observations in the Residuals vs Fitted plot, Scale-Location Plot and Residuals vs Leverage Plots (Figure 2) [INSERT FIGURE 2 NEAR HERE] are centred around zero with relatively constant variance. In the normal QQ plot (Figure 3) there is some slight variance from the straight line particularly at the tails, and two observations are outside 2 standardised residuals suggesting they are potential outliers.

Discussion

This is the first study in professional team sport athletes to identify determinants of BFlh fascicle length. We demonstrated relative chronic running loads >80% of maximum velocity explained around 43% of the variability in fascicle length, whilst the often-recommended threshold >90% was not a statistically significant contributor. Our findings also demonstrated that peak eccentric hamstring force was associated with 27% of the variance in BFlh fascicle length. When combined with prolonged eccentric time under tension at long muscle lengths (17%) these two factors described around 44% of the explained variability in fascicle length. Collectively, these findings may help guide conditioning and prevention strategies for athletes in the future. If practitioners are unable to monitor fascicle length changes, managing chronic running loads >80% of maximum velocity as well as eccentric strength training may help estimate around 90% of the controllable determinants in BFlh fascicle length in their athletes.

Peak speed (13% of the observed variability) and running volume > 80% of maximum velocity during the preceding 56-day period (30% of the observed variability) were the largest collective contributors to the explained variability in fascicle length. Previous literature has advocated maintenance of chronic high speed running loads in the prevention of hamstring strain injury[5,17]. Although regular exposure >90% of the measured maximum velocity is often recommended within high performance environments for HSI prevention[22], the results of this study suggest that running loads at this velocity may not may not be statistically associated with longer fascicle lengths. In practical terms, each 2.5ms^{-1} increase in peak velocity within this cohort was associated with 0.94cm longer fascicle length. Although the findings of this study suggests that regular exposure >80% of an athletes maximum velocity might be associated with longer fascicle lengths in professional athletes, the volume required for a meaningful increase in BFlh from was practically very high, indicating a larger dataset is likely needed to confirm this finding.

Peak eccentric strength was the second most important contributor to the explained variability of fascicle length (27%). Previous research has affirmed the benefits of eccentric training in optimising fascicle length adaptation[1,3,14,20]. Within this cohort, an increase in peak force of 150N was associated with an additional 1.1cm longer fascicle. The current study found that time under load at longer lengths (between 60deg/sec and peak thigh angular velocity) during a single-leg eccentric hamstring exercise (17% of the explained variability in fascicle length), not the ‘break point’ angle of the exercise (i.e. angle of loss of control) to be statistically associated with longer fascicle lengths. Previous literature[12,19,22,23] has explored the concept of the break angle as a measure of potentially assessing HSI risk. Whilst the break point angle wasn’t associated with BFlh fascicle lengths, it would appear that it is the combined ability to sustain an elapsed time under supramaximal load that has the strongest correlation with fascicle length. In practical terms, increasing time under load by 100ms between 20deg/sec and

60deg/sec was associated with a 2.35cm longer BFlh fascicle length. This may represent a useful addition to strength training programming in HSI prevention. Interestingly, longer fascicles within this cohort was associated with a lower ratio force output per kg bodyweight with during the Nordic (1 N/kg reduction associated with an increase of 0.75cm BFlh fascicle length). Confirmation within a larger dataset is needed, though in practical terms this might indicate that maximal force output might be more favourably associated with longer fascicle lengths than force per unit of bodyweight.

Age (5%) and previous injury (8%) were the final contributors to the explained variability in fascicle length within the dataset. Having a previous HSI and increasing age have been extensively reported to augment the likelihood of an injury occurring [2,9]. Although the results of this study reaffirm the importance of these factors, it is encouraging that the majority of the model relating to longer fascicle lengths is explained by factors which can be modified through various interventions, allowing practitioners the ability to potentially address an athletes risk. Previous history was associated with a 0.3cm shorter fascicle length, and an athlete who was 10 years older was associated with 0.23cm shorter fascicles, both largely within the measurement error of BFlh fascicle length..

There are limitations associated with this study. Firstly, the data was only collected over a single professional season. Although statistically significant influences on fascicle length changes were observed, we were able to explain just over 50% of the total variability in fascicle length within this dataset, meaning that there are other statistical influences on fascicle length changes which we did not account for in this study. Although we conducted an analysis in order to achieve sufficient power within the study, continued observation over multiple seasons will further strengthen the predictive capability of these models, and further research should seek to explore additional influences on fascicle length such as heavy isometrics and other hamstring strength exercises as well as targeted flexibility and mobility work which has also been advocated in HSI injury prevention. Secondly, the measure of fascicle length is an estimation made from a validated equation. This is due to the small transducer field of view being unable to capture an entire BFlh fascicle. However, whilst the results are still an estimation, the methodology and equation employed has been validated against cadaveric samples and shows excellent agreement between dissection and estimation methods[11]. Ideally transducers with larger fields of view or panoramic functions would be used, however such equipment and techniques are not available in our laboratory.

Conclusions

Significant determinants of hamstring fascicle length were observed over a single professional rugby league season. Chronic running load >80% of maximum speed (28 days and 56 days combined) and overall maximum speed explained 43% of the observed variability in fascicle length, whilst strength-related variables collectively contributed an additional 44%. Non-modifiable risk factors (age and previous injury) collectively contributed the remaining 13%. Future research should examine absolute predictive thresholds for physical performance-based tests and re-injury risk reduction, as well as seek to include additional training modalities over and above the ones included in this study as means of further optimizing the explained influences on hamstring fascicle length for hamstring injury prevention in professional athletes.

Practical Implications

- Using multiple linear regression analysis, statistically significant determinants of fascicle length were observed in elite rugby league athletes over a single professional season.
- Based on the results of this study, modifiable risk factors collectively represented close to 90% of the explained variability in fascicle length. These factors included chronic

speed exposure >80% of measured maximum running velocity, peak eccentric strength and time under load at longer leg lengths. Non-modifiable factors (age and previous history) collectively accounted for the remaining explained variability. Speed thresholds > 90% of individual maximum velocity and the ‘break angle’ during a Nordic eccentric contraction were not statistically significant contributors.

- Inclusion of these training strategies may help optimize hamstring injury prevention training in the future

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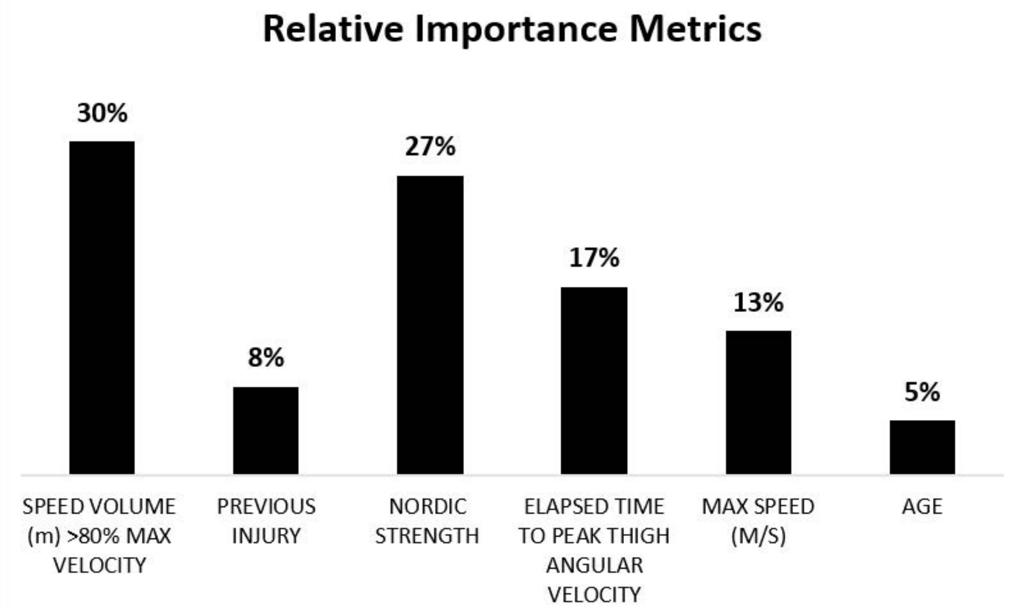
Figure 1: Average biceps femoris fascicle length results across the three testing time points

Figure 2: Contributors to biceps femoris fascicle length from the linear regression analysis

Figure 3: Residuals plots for the final model


Relative Importance Metrics
30%
8%
27%
17%
13%
5%
SPEED VOLUME (m) >80% MAX VELOCITY
PREVIOUS INJURY
NORDIC STRENGTH
ELAPSED TIME TO PEAK THIGH ANGULAR VELOCITY
MAX SPEED (M/S)
AGE

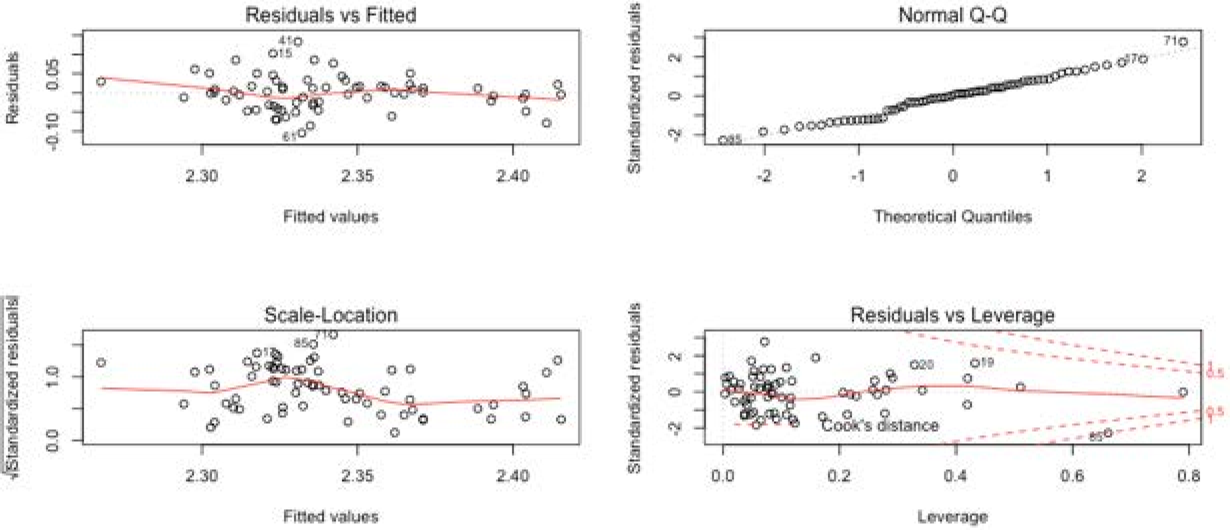

Residuals vs Fitted
Residuals
-0.10
0.05
Fitted values
2.30
2.35
2.40
41
15
61
Normal Q-Q
Standardized residuals
-2
0
2
Theoretical Quantiles
-2
-1
0
1
2
71
17
85
Scale-Location
√|Standardized residuals|
0.0
1.0
Fitted values
2.30
2.35
2.40
71
85
17
Residuals vs Leverage
Standardized residuals
-2
0
2
Leverage
0.0
0.2
0.4
0.6
0.8
20
19
85
Cook's distance
1
0.5
0.5
1

Table 1: Fascicle length, eccentric hamstring strength, Nordic performance measures as well as and GPS speed and distance measures in elite Rugby League athletes.

	Fascicle Length	**Eccentric Hamstring Measures**		**Elapsed Time During The Nordic (Milliseconds)**		**Knee Angle At Specific Thigh Angular Velocity (Deg)**			**GPS Measures**				
	Average (cm)	**Peak Force (N)**	**N/kg BW**	**20-60deg**	**20-Peak Velocity**	**20deg/s**	**60deg/s**	**Peak Velocity (deg/s)**	**Max Speed (m/s^{-1})**	**>80% (28 day)**	**>80% (56 day)**	**>90% (28 day)**	**>90% (56 day)**
Min	8.99cm	203.7	2.34	118.3	156.7	93.35	82.28	64.20	6.981	0.00	3.439	0.000	0.00
1st Qtr.	9.91cm	321.5	3.52	288.3	554.6	84.93	71.66	41.88	8.338	33.29	31.055	3.263	3.414
Median	10.44cm	387.1	3.93	365.0	636.7	78.96	65.75	36.71	8.777	60.54	45.720	10.453	6.434
Mean	10.34cm	407.3	4.16	369.1	623.3	80.43	67.26	37.70	8.743	76.82	58.918	13.957	9.701
3rd Qtr.	10.74cm	471.2	4.72	430.0	723.3	76.17	61.30	32.00	9.248	107.82	79.463	19.974	13.685
Max	11.48cm	743.7	7.36	681.7	936.7	25.53	20.37	12.67	10.195	327.00	231.866	58.565	41.006
										Measured in metres			

cm = centimetres, n = newtons of force, N/kg BW = newtons of force relative to body weight, deg/s = degrees per second, deg = degrees, GPS = Global Positioning System, m/s-^{1} = metres per second squared

Supplementary Table 1: Coefficients of multiple linear regression:

	Estimate	**Std.Error**	**t-value**	**Pr(>|t|)**
(Intercept)	8.07e+00	1.01e+00	7.96	7.1e-11
Speed >80% - 28day	-1.93e-05	4.30e-06	-4.50	3.3e-05
Speed >80% - 56day	3.43e-05	7.24e-06	4.73	1.5e-05
Previous Injury	3.04e-01	1.05e-01	2.91	0.0051
Peak Nordic Force (N)	7.31e-03	1.50e-03	4.86	9.2e-06
Time to Peak Angular Velocity	-2.12e-02	6.85e-03	-3.10	0.0030
Time to 60deg/s Angular Velocity	2.35e-02	8.63e-03	2.73	0.0084
Max Speed (m/s)	3.63e-01	8.66e-02	4.19	9.5e-05
Nordic Force / BW (N/KG)	-7.45e-01	1.61e-01	-4.62	2.2e-05
Age	-2.28e-02	1.43e-02	-1.59	0.1168
Residual standard error: 1.11 on 58 degrees of freedom. Multiple R-squared: 0.572, Adjusted R-squared: 0.506. F-Statistic: 8.62 on 9 and 58DF, p-value: 4.56e-08				

Supplementary Table 2: Analysis of Variance Type III (ANOVA):

	Df	**Sum Sq**	**F-value**	**Pr(>F)**
(Intercept)	1	78.0	63.37	7.1e-11
Speed >80% - 28day	1	24.9	20.24	3.3e-05
Speed >80% - 56day	1	27.6	22.42	1.5e-05
Previous Injury	1	10.4	8.46	0.0051
Peak Nordic Force (N)	1	29.1	23.64	9.2e-06
Time to Peak Angular Velocity	1	11.8	9.59	0.0030
Time to 60deg/s Angular Velocity	1	9.2	7.44	0.0084
Max Speed (m/s)	1	21.6	17.58	9.5e-05
Nordic Force / BW (N/KG)	1	26.3	21.34	2.2e-05
Age	1	3.1	2.54	0.11678
Residuals	58	71.4		