Title: THE RELATIONSHIP BETWEEN MATCH-PLAY CHARACTERISTICS OF ELITE RUGBY LEAGUE AND INDIRECT MARKERS OF MUSCLE DAMAGE

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Abstract

Purpose: Whilst exercise-induced muscle damage (EIMD) after a rugby league match has been well documented, the specific match actions that contribute to EIMD are unclear. Accordingly, the purpose of this study was to examine the relationship between the physical demands of elite rugby league matches and subsequent EIMD. *Methods:* Twenty-eight performances were captured using 10 Hz global positioning systems. Upper and lower body neuromuscular fatigue, creatine kinase (CK) and perceived muscle soreness were assessed 24 h before and at 12, 36 and 60 h after a competitive match. *Results:* High-intensity running was *moderately* higher in backs (6.6 ± 2.6 m·min^{-1}) compared to forwards (5.1 ± 1.6 m·min^{-1}), whereas total collisions were *moderately* lower (31.1 ± 13.1 *cf.* 54.1 ± 37.0). Duration (r = 0.9, CI: 0.77 to 0.96), total distance covered (r = 0.86, CI: 0.7 to 0.95) and distance covered over 18 km·h^{-1} (r = 0.76, CI: 0.51 to 0.91) were associated with increased CK concentration post-match. Total collisions and repeated high-intensity efforts (RHIE) were associated with *large* decrements in upper body neuromuscular performance (r = -0.48, CI: -0.74 to 0.02 and r = -0.49, CI: -0.77 to 0.05, respectively), muscle soreness (r = -0.68, CI: -0.87 to -0.1 and r = -0.66, CI: -0.89 to 0.21, respectively), and CK concentration (r = 0.67, CI: 0.42 to 0.85 and r = 0.73, CI: 0.51 to 0.87, respectively). *Conclusion:* Match duration, high-intensity running and collisions were associated with variations in EIMD markers, suggesting recovery is dependent on individual match demands.

Key words: Time-motion analysis, recovery, neuromuscular fatigue, physical demands

Introduction

Exercise-induced muscle damage (EIMD) after rugby league match-play is well documented. This EIMD is characterised by elevations in myofibrillar proteins in plasma,[1-3] decrements in neuromuscular function[3-5] and increases in perceived muscle soreness[6] that last several days after competition. Symptoms of EIMD might therefore compromise the quality of a player's performance in the days after the original insult,[3] particularly where congested training and competitive schedules occur.[1]

The precise match actions that cause EIMD are poorly understood. Team sports, including rugby league, involve frequent bouts of high-intensity or maximal activity intermittently separated by prolonged bouts of low-intensity work. All players are subject to collisions at a rate of ~0.6 – 1.0 per minute[6,7] and perform approximately ~0.4 – 0.8 rapid accelerations per minute[8] and high-intensity sprinting movements[9] during match-play. Such actions are likely to result in EIMD associated with physical trauma to the muscle[6] and repeated eccentric contractions.[10] However, the type and frequency of these high-intensity bouts are largely dependent on position[11] meaning considerable match-to-match variability of these movements exist.[12] As such, there is potential for the magnitude of EIMD to vary between individual players,[6] although the extent to which these match actions are associated with post-match recovery has received limited attention. Indeed, previous studies in rugby have either assessed the relationship between EIMD and the frequency and nature of contact[4,6,13] or examined changes in creatine kinase concentration alone to quantify muscle damage.[14] Thus, the purpose of this study was to determine the potential relationship between the physical demands of elite rugby league match-play and post-match neuromuscular, perceptual and biochemical fatigue.

Method

Subjects

After institutional ethical approval, seventeen elite rugby league players (age: 24.5 ± 4.4 y, stature: 1.84 ± 0.06 m, body mass: 98.5 ± 10.3 kg) from an English Super League team volunteered to participate in the study. Data were collected over four competitive matches during the 2014 Super League season, with a total of 28 individual performances recorded for forwards (n = 17) and backs (n = 11). The matches analysed comprised 1 win and 3 losses with an aggregated score of 19 ± 5 points. Only players who were deemed free of injury and fit to play in a match during the time of testing participated in the study. Players were familiarised with all experimental procedures before testing.

Design

After a rest day, players reported to the training ground at approximately 09:00 on the day before the match. During this time, baseline measurements for creatine kinase (CK) activity, repeated plyometric push-up (RPP), counter-movement jump (CMJ) flight time and perceived muscle soreness were taken. The next day players competed in a rugby league match, during which the physical demands of selected players were measured using a global positioning system (GPS) device. Measurements of biochemical (CK) responses, followed by neuromuscular and perceptual measures (RPP, CMJ, muscle soreness) were then repeated at

12, 36 and 60 h after the match. An example of the training schedule and recovery strategies used around a match are outlined in Table 1.

Table 1 near here

Procedures

Movement demands of match play

Movement demands of the matches were recorded using 10 Hz MinimaxX GPS units (Team 2.5, Catapult Innovations, Melbourne, Australia) that were simultaneously activated at pitch side before the warm-up. Distance covered was calculated according to four movement categories: walking or jogging (0-12 $km \cdot h^{-1}$), cruising (12-14 $km \cdot h^{-1}$), striding (14-18 $km \cdot h^{-1}$) and high-intensity running (>18 $km \cdot h^{-1}$).[11]

Collisions experienced were determined via accelerometer and gyroscope data provided in 'G' force. For a collision to be registered, the athlete maintained a non-vertical position classified as either; leaning forward by more than 60 degrees, leaning backwards by more than 30 degrees or leaning left or right by more than 45 degrees for one second. Combined G-force was calculated as the average acceleration on each directional axis. Each collision was coded into one of five classification zones according to their severity, these being: light (2-3 G), moderate (3-4.5 G), heavy (4.5-6 G), very heavy (6-8 G) and severe (>8 G). Maximal accelerations and decelerations, classified as greater than 2.79 $m \cdot s^{-2}$, and RHIE bouts, defined as three or more maximal accelerations, high velocity sprints (>5 $m \cdot s^{-2}$) or contact efforts with less than 21 s recovery between efforts,[15] were also recorded.

Creatine Kinase (CK) activity

CK concentration was determined from 30 µL of capillarized, whole blood. Samples were obtained from a fingertip using a spring-loaded disposable lancet. Blood was then analysed using a colorimetric assay procedure (Reflotron, Type 4, Boehringer, Mannheim, Germany). All samples were taken at the same time (09:00 – 11:00) to reduce the effects of diurnal variation.

Repeated plyometric push-up (RPP)

Participants started in a press up position, with their hands placed on the floor 70 cm apart. Participants then rapidly flexed their elbows to approximately 90 degrees before maximally exploding off the floor, clapping their hands together, and landing with their arms fully extended. This was repeated three times within quick succession using an Optojump timing system (Optojump, Microgate, Microgate S.r.l., Bolzano, Italy). Flight time for each push up was recorded, and the total flight time was used for comparison. After completing one sub-maximal plyometric push up as a warm up, participants performed two maximal RPP efforts, with one minute recovery after the warm up, and in-between each effort. Flight time for each push up was recorded, and the total flight time was used for comparison. The coefficient of variation (CV%) for this measurement with the same group of players was 5.5%.

Counter-movement jump (CMJ)

Participants began standing upright in a shoulder width stance, with their hands placed on their hips. They rapidly flexed their knees to approximately 90 degrees, before jumping to maximal height. Flight time was recorded based on the recommendations of Cormack and colleagues.[16] Similar to the RPP protocol, participants completed one sub-maximal practice jump as a warm up, then after one minute, performed two maximal CMJ, with one minute of rest between each jump. The longest flight time was used for analysis. All CMJs were recorded using a timing mat system (Just Jump System, Probotics, Inc., Huntsville, AL). Reliability for this measurement demonstrated a CV% of 2.7%.

Perceived muscle soreness

Players provided a rating of perceived muscle soreness using a seven point Likert scale ranging from 0 (extreme soreness) to 6 (no soreness). All players completed this measurement on their own to ensure no influence from other players or members of staff. Despite being subjective, this measurement allows for complex psycho-physiological stresses to be monitored, all of which are associated with poor recovery.[17] Research employing similar scales has demonstrated a good level of reliability (Cronbach's alpha coefficient = 0.9).[18]

Statistical Analysis

Differences in match demands between positions were determined using multiple one-way analyses of variance (ANOVAs). Sphericity was assessed via Mauchly's test, with any violations accounted for via the Greenhouse-Geisser statistic. Independent *t*-tests were used to follow up any significant effects. Changes in muscle damage markers were analysed using repeated measures ANOVAs and paired sample *t*-tests were used to follow up any significant effects. Effect sizes and magnitude based inferences, as previously suggested by Twist and Highton,[17] were calculated for GPS variables and fatigue markers at 12 and 36 h post-match. Threshold probabilities for a considerable effect based on the 90% confidence intervals were: >0.5% most unlikely, 0.5-5% very unlikely, 5-25% unlikely, 25-75% possibly, 75-95% likely, 95-99.5% very likely, > 99.5% most likely. The magnitude of the observed change was determined as the within-participant standard deviation multiplied by 0.2, 0.5 and 0.8 for a small, moderate and large effect, respectively.[19] Effects with confidence limits across a likely small positive or negative change were classified as unclear.[20] Pearson's product-moment correlation (r), the coefficient of determination (R^2) and the 95% confidence interval (95% CI) was used to assess the relationship between match demands and recovery post-match. Where appropriate the alpha level was set at $p < 0.05$.

Results

Match-demands

Positional comparisons for match-demands are presented in Tables 2 and 3. ANOVA revealed no significant interaction between position and relative distance covered in each speed zone ($F = 0.840$, $p > 0.05$). Forwards experienced significantly more light collisions ($t = 2.75$, $p < 0.05$) and total collisions ($t = 2.19$, $p < 0.05$) than backs. Magnitude-based inferences indicated *likely* positional effects for cruising and high-intensity running distance relative to duration of match-play, high-intensity accelerations, total efforts performed over 18 $km \cdot h^{-1}$, light, moderate and total collisions experienced and total RHIE bouts.

Table 2 and 3 near here

Recovery

Changes in CK concentration over time are presented in Figure 1. ANOVA revealed significant differences in CK concentration over each time point ($F = 13.2$, $p < 0.05$). CK concentration was significantly increased at 12 h ($t = -9.451$, $p < 0.05$), and 36 h ($t = -8.207$, $p < 0.05$), returning to baseline at 60 h post-match. These increases were *most likely large* at 12 and 36 h post-match (Table 4).

Figure 1 and Table 4 near here

CMJ flight time significantly decreased ($F = 5.781$, $p < 0.05$) at 12 h ($t = 4.108$, $p < 0.05$) and 36 h post-match ($t = 2.872$, $p < 0.05$) in comparison to baseline (Figure 2). The magnitude of change at these time points was *very likely large* (Table 4). Total flight time during RPP is displayed in Figure 3. ANOVA failed to show significant differences in flight time during the RPP at 12 and 36 h post-match compared to baseline ($F = 2.684$, $p > 0.05$). However, effect sizes demonstrated *possibly small* and *likely moderate* decrements in RPP at 12 and 36 h, respectively. Significant increases in perceived muscle soreness were observed at 12 h ($t = 4.974$, $p < 0.05$) and 36 h ($t = 3.286$, $p < 0.05$) post-match (Table 4).

Figure 2 and Figure 3 near here

Relationship between match demands and recovery

Correlations between selected match demands and markers of fatigue at 12 h are presented in Table 5 and 6. All correlations for CMJ flight time were $r < 0.3$ and therefore have not been reported within the study.

Table 5 and Table 6 near here

Discussion

To our knowledge, this is the first study to examine the relationship between the movement demands of elite rugby league match-play and post-match neuromuscular, perceptual and biochemical markers of EIMD. The key findings of this study were reductions in upper body neuromuscular function and elevations in CK concentration and muscle soreness were associated with duration of match-play, distance covered during high-intensity running (>18 $km \cdot h^{-1}$), total collisions and RHIE bouts performed during the matches analysed.

The absolute distances covered at high-intensity during matches was greater for backs (481.4 ± 262.1 m) compared to forwards (306.5 ± 194.3 m), a difference that also remained when high intensity running was expressed relative to playing time (6.6 ± 2.6 *cf.* 5.1 ± 1.6 $m \cdot min^{-1}$). Such findings reaffirm those reported previously.[21,22] The observed differences in the number of maximal accelerations performed by backs in comparison to forwards (9.1 *cf.* 4.7) might be explained by the shorter sprint distances (6 – 10 m) typical of hit-up forwards.[23] However, no such differences were found for the number of maximal decelerations performed during match-play between positions (8.4 ± 4.6 cf. 9.6 ± 5.7) and could be due to rapid changes of direction to return to the defensive-line particularly when the opposing team gains possession of the ball.

Similar to previous reports,[6,21,23] forwards experienced a greater number of total collisions than backs (54.1 ± 37.0 *cf.* 31.1 ± 13.1). Whilst McLellan et al.[13] reported noticeably higher collisions (795 to 858) during rugby league match-play, the use of an alternative GPS device incorporating different algorithms for a collision to be registered, reaffirms that comparisons of match characteristics between GPS models should not be made.[24] RHIE bouts occurred regularly throughout the game between both positions, indicating repeated sprints incorporating physical collisions are essential to fully prepare players for competition, particularly given their association with higher standard rugby league teams.[25] Collectively, the data provides evidence to confirm the movement patterns observed within the current study are typical of rugby league match-play.

In accordance with previous research[2,13] the largest increases in CK concentration were observed at 12 h post-match, with values remaining elevated for at least 36 h. Increases in circulating CK suggest match-play resulted in disruption to the structural integrity of skeletal tissue, causing an increase in cell permeability.[26] Combined with contemporaneously large decrements in CMJ flight time, small to moderate decrements in RPP and large increases in muscle soreness (as indicated by a lower score) at 12 and 36 h post-match, these data reaffirm muscle damage occurred in the 36 h period after a rugby league match.[1,4,6] Coaches of elite rugby league players should be cognisant that both upper and lower body muscular function are reduced for at least 36 h after a competitive match. Furthermore, increases in perceived muscle soreness are also likely to alter an athlete’s sense of effort, causing them to down-regulate their exercise capacity.[27] These findings have clear implications for the programming of training and recovery strategies in the days after a match.

The novel aspect of the study assessed the relationship between match demands and markers of muscle damage after elite rugby league match-play. Significant correlations were observed between total distance (r = 0.86), match duration (r = 0.9) and CK concentration. A longer period of time on the field would explain the greater total distance covered, both of which lead to an increase in circulating CK that is indicative of tissue damage. Strong associations were also observed between absolute (r = 0.76) and relative distance (r = 0.49) covered over 18 $km \cdot h^{-1}$ and increases in CK concentration. These data support previous research demonstrating small to moderate correlations between high-intensity distance covered and CK activity after rugby union matches.[14] Given that high intensity running incorporates high-force, high-velocity eccentric contractions, which can induce muscle damage,[10] it is proposed that players who engage in more of these actions will experience a greater magnitude of tissue damage. The total number of high intensity accelerations and decelerations performed were moderately correlated (r = 0.44 and r = 0.48, respectively) with CK concentration. Whilst little research exists on the relationship between the number of accelerations performed during match-play and markers of muscle damage Nedelec et al.[28] reported a significant relationship between decrements in CMJ and the number of hard changes in direction performed during a soccer match. The mechanical loading, caused by rapid accelerations and decelerations could have caused a lengthening and ‘popping’ of the sarcomeres ultimately leading to a loss of calcium ion homeostasis and a decrease in force production.[29]

Total collisions experienced were significantly correlated with decrements in RPP (*r* = -0.48), increases in CK concentration (*r* = 0.67) and muscle soreness (*r* = -0.68). These results are consistent with others who have observed associations between CK concentration and collisions experienced in rugby league.[6,14] Typically, heavier collisions were associated with greater decrements in RPP and increases in CK concentration and muscle soreness, highlighting the importance of quantifying the severity of collisions to implement appropriate recovery strategies after a match. A novel finding of the study was that decrements in upper body neuromuscular function were associated with total collisions experienced. Whilst no other study has assessed this relationship, McLellan & Lovell[4] found heavy impacts were significantly correlated to decrements in CMJ performance at 24 h after a match. Similarly, Twist et al.[6] found correlations between total contacts during match-play and tissue damage after a match in forwards. Collectively, these data support the notion that players who experience a higher number of collisions during match-play experience a greater magnitude of muscle damage, and the associated loss of muscle strength post-match.

The total amount of RHIE bouts was also significantly correlated with decrements in RPP (*r* = -0.49), increases in CK concentration (*r* = 0.73) and muscle soreness (*r* = -0.66). Thus, tissue damage caused by blunt force trauma from physical collisions interspersed with high intensity eccentrically biased actions might affect muscle soreness and muscle damage to a greater extent than that caused by repeated eccentric actions alone. Indeed, Johnston & Gabbett[30] reported a higher internal load for repeated sprints performed in conjunction with tackling (167 $b \cdot min^{-1}$), compared to a repeated sprint performed without (154 $b \cdot min^{-1}$). This high physiological cost could limit ATP availability, decreasing the action of the calcium adenosine triphosphatase (ATPase), compromising the removal of calcium.[31] Furthermore, an increase in hydrogen ions, resulting from high rates of glycolysis has been implicated in the loss of calcium homeostasis, associated with EIMD.[32] Given the association between RHIE bouts performed and muscle damage, reporting RHIE bouts might provide a more comprehensive understanding of player recovery after a match.

Despite very large reductions in CMJ performance after match-play, these changes were not strongly correlated with match demands. These data are in contrast to previous studies reporting relationships between match demands and post-match decreases in CMJ performance.[4,28] That we observed no relationship between changes in jump performance and movement demands might be partly explained by a weak association between vertical jumping and horizontal running performance.[33] Previous studies reporting stronger associations between running demands and changes in CMJ performance have also used a portable force platform, to quantify jump performance.[4,28] These apparatus provide a more comprehensive understanding of neuromuscular fatigue by allowing measures of muscle force and power [17] that might possess a greater capability to detect a potential relationship between jump performance and match demands.

Practical Implications

The decrements observed in both RPP and CMJ confirm that measurements of upper and lower body neuromuscular fatigue are necessary in the days after a rugby league match. For the first time, we have shown that individual player measurements of duration, distance covered over 18 $km \cdot h^{-1}$, the total number of collisions experienced and RHIE bouts performed during a match are indicative of the magnitude of muscle damage experienced by an individual player in the days that follow. Given the routine assessment of movement demands using GPS in both training and matches, we propose that coaches might want to use these data to forward plan so that training quality and recovery in the days after is not compromised. The strong association between increases in perceived muscle soreness and collisions experienced during match-play also reaffirms the use of this psychometric tool to monitor recovery status in rugby league players.

Conclusion

In conclusion, the movement patterns observed within the current study were typical of elite rugby league match-play and resulted in evidence of muscle damage that lasted for up to 36 h after a match. Reductions in upper body neuromuscular function and increases in CK concentration and perceived muscle soreness were associated with playing duration, high-intensity running and the number of collisions experienced. Accordingly, subsequent recovery for one player might vary from another based on individual match demands. Although lower limb neuromuscular function was compromised after a match, no significant correlations between decrements in CMJ performance and specific match demands were observed. These findings extend the use of GPS in training sessions and competitive matches to provide an advanced indication of individual player recovery and preparedness to train.

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References

1. Mclean BD, Coutts AJ, Kelly V, McGuigan MR, Cormack SJ. Neuromuscular, endocrine and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int J Sports Physiol Perform.* 2010;5:367-383.

2. McLellan CP, Lovell DI, Gass GC. Creatine kinase and endocrine responses of elite players pre, during and post rugby league match play, *J Strength Cond Res.* 2010;24:2908-2919.

3. Johnston RD, Gibson NV, Twist C, Gabbett TJ, MacNav SA, MacFarlane NG. Physiological responses to an intensified period of rugby league competition. *J Strength Cond Res.* 2013;27:643-654.

4. McLellan CP, Lovell DI. Neuromuscular responses to impact and collision during elite rugby league match play. *J Strength Cond Res.* 2012;26:1431-1440.

5. Duffield R, Murphy A, Snape A, Minett G, Skein M. Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. *J Sci Med Sport.* 2012;15:238-243.

6. Twist C, Waldron M, Highton J, Burt D, Daniels M. Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *J Sport Sci.* 2012;30:359-367.

7. Gabbett TJ, Jenkins DG, Abernethy B. (2011). Physical collisions and injury in professional rugby league match-play. *J Sci Med Sport*. 2011;14:210-215.

8. Sirotic AC, Knowles H, Catterick C, Coutts AJ. Positional match demands of professional rugby league competition. *J Strength Cond Res.* 2011;25:3076-3087.

9. Waldron M, Twist C, Highton J, Worsfold P, Daniels M. Movement and physiological match demands of elite rugby league using portable global positioning systems, *J Sport Sci.* 2011;29:1223-1230.

10. Howatson G, Milak A. Exercise-induced muscle damage following a bout of sport specific repeated sprints. *J Strength Cond Res.* 2009;23:2419-2424.

11. Austin DJ, Kelly S. Professional rugby league positional match-play analysis through the use of global positioning system. *J Strength Cond Res.* 2014;28:187-193.

12. Kempton T, Sirotic AC, Coutts AJ. Between match variation in professional rugby league competition. *J Sci Med Sport,* 2013;17:404-407.

13. McLellan CP, Lovell DI, Gass GC. Biochemical and endocrine responses to impact and collision during elite rugby league match play. *J Strength Cond Res.* 2011;25:1553-1562.

14. Jones MR, West DJ, Harrington BJ, Cook CJ, Bracken RM, Shearer DA, Kilduff LP. Match play performance characteristics that predict post-match creatine kinase responses in professional rugby union players. *BMC Sport Sci, Med Rehab*. 2014;6:38-44.

15. Gabbett TJ, Mulvey MJ. Time-motion analysis of small-sided training games and competition in elite women soccer players. *J Strength Cond Res.* 2008;22:543-552.

16. Cormack SJ, Newton RU, McGuigan MR, Doyle TL. Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform.* 2008;3:131-144.

17. Twist C, Highton J. Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perform.* 2013;8:467-474.

18. De Vries Michielsen HJ, Van Heck, GL. Assessment of fatigue among working people: A comparison of six questionnaires. *Occup Environ Med.* 2003;60:i10-i15.

19. Cohen J. *Statistical power analysis for the behavioural sciences*. Hillsdale, NJ: Lawrence Erlbaum associates; 1988.

20. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sport medicine and exercise science. *Med Sci Sports Exerc.* 2009;41:3-12.

21. Gabbett TJ, Jenkins DG, Abernethy B. Physical demands of professional rugby league training and competition using microtechnology. *J Sci Med Sport.* 2012;15:80-86.

22. McLellan CP, Lovell DI, Gass GC. Performance analysis of elite rugby league match play using global positioning system. *J Strength Cond Res.* 2011;25:1703-1710.

23. Gabbett TJ. Influence of playing standard on the physical demands of professional rugby league. *J Sports Sci.* 2013;31:1125-1138.

24. Johnston RJ, Watsford ML, Kelly SJ, Pine MJ, Spurrs RW. Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *J Strength Cond Res.* 2014;28:1649-1655.

25. Gabbett TJ. Influence of the opposing team on the physical demands of elite rugby league match play. *J Strength Cond Res.* 2013:27:1629-1635.

26. Cheung K, Hume PA, Maxwell L. Delayed onset muscle soreness - treatment strategies and performance factors. *Sports Med*. 2003;33:145-164.

27. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol.* 2009;106:857-864.

28. Nedelec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. The influence of soccer playing actions on the recovery kinetics after a soccer match. *J Strength Cond Res.* 2014;28:1517-1523.

29. Zhou Y, Li Y, Wan R. Evaluation of exercise-induced muscle damage by surface electromyography. *J Electromyogr Kinesiol.* 2011;21:356-362.

30. Johnston RD, Gabbett TJ. Repeated-sprint and effort ability in rugby league players. *J Strength Cond Res.* 2011;25:2789-2795.

31. Tee JC, Bosch AN, Lambert MI. Metabolic consequences of exercise-induced muscle damage. *Sports Med.* 2007;37:827-836.

32. Kendall B, Eston R. Exercise-induced muscle damage and the potential protective role of estrogen. *Sports Med.* 2002;32:103-123.

33. Dobbs CW, Gill ND, Smart DJ, McGuigan MR. Relationship between vertical and horizontal jump variables and muscular performance in athletes. *J Strength Cond Res.* 2015;29:661-671.

Tables

Table 1. An example of typical training and recovery strategies performed before and after a match day.

	Day 1 pre-match	Match day	Day 1 post-match	Day 2 post-match	Day 3 post-match
Morning	Testing Captains run session 20-30 min	Rest	Testing Recovery session 30 min	Testing Rest	Testing Resistance training 30–40 min
Afternoon	Rest	Pre-match warm up 20 – 30 min Match 80 min	Rest	Rest	Team training (skills) 40–60 min

Testing: comprised blood samples for assessing CK, neuromuscular measurements (CMJ, RPP) and perceptual muscle soreness.
Captains run session: attack and defence patterns and game structure.
Recovery session: 20 minutes of low intensity exercise followed by 10 minutes of massage
Resistance training: typical exercises include squat variations, bench press, shoulder press, horizontal pull, power clean and push/pull variations.
Team training (skills): attack and defensive patterns and general skills.
Rest: No structured training, players encouraged to rest.

Table 2. Positional comparison of distance covered, duration, accelerations and decelerations performed during rugby league match-play.

	Forwards (*n* = 17)	**Backs (*n* = 11)**	**Mean diff ± 90% confidence interval**	**Qualitative interpretation**
Playing duration (min)	55:14 ± 21:26	67:10 ± 25:18	11:56 ± 16:42	Unclear
Total distance (m)	4675 ± 1678	5640 ± 2191	964.8 ± 1409.1	Unclear
$m\cdot min^{-1}$	81.9 ± 7.3	83.2 ± 10.1	1.4 ± 6.4	Unclear
Walking/jogging (m)	3584.1 ± 1254.1	4322.5 ± 1705.3	738.5 ± 1089	Unclear
$m\cdot min^{-1}$	65.0 ± 7.1	64.1 ± 6.5	-0.9 ± 4.7	Unclear
Cruising distance (m)	393.1 ± 121.9	384.5 ± 181.5	-8.7 ± 113.9	Unclear
$m\cdot min^{-1}$	7.3 ± 1.5	5.9 ± 2.2	-1.5 ± 1.4	Likely, moderate ↓
Striding distance (m)	376.8 ± 152.1	451.5 ± 230.2	74.6 ± 144.0	Unclear
$m\cdot min^{-1}$	6.9 ± 1.3	6.5 ± 2.0	-0.3 ± 1.3	Unclear
HI running (m)	306.5 ± 194.3	481.4 ± 262.1	174.9 ± 167.7	Likely, moderate ↑
$m\cdot min^{-1}$	5.1 ± 1.6	6.6 ± 2.6	1.5 ± 1.6	Likely, moderate ↑
Total efforts over 18 $km\cdot h^{-1}$	21.4 ± 13.0	31.9 ± 16.6	10.6 ± 10.7	Likely, moderate ↑
HI accelerations (n)	4.7 ± 3.0	9.1 ± 6.4	4.4 ± 3.8	Likely, large ↑
HI decelerations (n)	8.4 ± 4.6	9.6 ± 5.7	1.2 ± 3.7	Unclear

Table 3. Positional comparison of collisions and repeated high-intensity effort bouts during rugby league match-play.

	Forwards (*n* = 17)	**Backs (*n* = 11)**	**Mean diff ± 90% confidence interval**	**Qualitative interpretation**
Collisions (n):				
Light (2-3 G)	24.2 ± 16.0	11.5 ± 7.1	-12.6 ± 7.9	Very likely, large ↓
Moderate (3-4.5 G)	21.3 ± 13.2	13.9 ± 4.5	-7.4 ± 6.2	Likely, moderate ↓
Heavy (4.5-6 G)	6.1 ± 6.0	4.1 ± 3.0	-2.0 ± 3.0	Unclear
Very heavy (6-8 G)	1.8 ± 2.7	1.1 ± 1.4	-0.7 ± 1.4	Unclear
Severe (8-15 G)	0.7 ± 1.9	0.5 ± 0.7	-0.3 ± 0.9	Unclear
Total	54.1 ± 37.0	31.1 ± 13.1	-23.0 ± 17.4	Likely, moderate ↓
RHIE bouts (n)	14.4 ± 10.4	10.0 ± 4.8	-4.4 ± 5.1	Likely, small ↓

Table 4. Magnitude based inferences for fatigue markers at 12 h and 36 h post-match in comparison to baseline.

	Baseline to 12 h		**Baseline to 36 h**	
	Mean diff ± 90% confidence interval	**Qualitative interpretation**	**Mean diff ± 90% confidence interval**	**Qualitative interpretation**
RPP (s)	-0.04 ± 0.1	Possibly, small ↓	-0.07 ± 0.1	Likely, moderate ↓
CMJ (s)	-0.02 ± 0.0	Very likely, large ↓	-0.02 ± 0.0	Very likely, large ↓
CK ($U.L^{1}$)	808.0 ± 169.3	Most likely, large ↑	525.0 ± 136.4	Most likely, large ↑
Muscle soreness	-1.1 ± 0.5	Most likely, large ↓	-0.8 ± 0.5	Very likely, large ↓

Table 5. Correlations between running based match demands and fatigue markers at 12 h post-match.

Match demands	Fatigue markers					
	RPP			CK		
	r	95% CI	R^2	r	95% CI	R^2
Playing Duration (min)	-0.39	-0.74 to 0.05	0.15	0.9*	0.77 to 0.96	0.81
Total distance (m)	-0.43	-0.77 to 0.01	0.18	0.86*	0.7 to 0.95	0.74
HI running (m)	-0.41	-0.72 to 0.02	0.17	0.76*	0.51 to 0.91	0.58
HI ($m \cdot min^{-1}$)	-0.31	-0.65 to 0.05	0.1	0.49*	0.12 to 0.84	0.24
Efforts over 18 $km \cdot h^{-1}$ (n)	-0.38	-0.71 to 0.4	0.14	0.76*	0.49 to 0.91	0.58
HI accels (n)	0.19	-0.25 to 0.66	0.04	0.44	-0.06 to 0.84	0.19
HI decels (n)	-0.23	-0.68 to 0.28	0.05	0.48*	-0.02 to 0.85	0.23

* Significant correlation ($p<0.05$).

Table 6. Correlations between collision match demands and fatigue markers at 12 h post-match.

Match demands	**Fatigue markers**								
	RPP			**CK**			**Muscle soreness**		
	r	95% CI	R^2	r	95% CI	R^2	r	95% CI	R^2
Collisions:									
Light	-0.43	-0.74 to 0.16	0.18	0.68*	0.36 to 0.84	0.46	-0.66*	-0.89 to 0.09	0.44
Moderate	-0.54*	-0.75 to -0.24	0.29	0.73*	0.45 to 0.88	0.53	-0.66*	-0.86 to -0.01	0.44
Heavy	-0.38	-0.68 to 0.15	0.14	0.72*	0.4 to 0.91	0.52	-0.74*	-0.89 to -0.46	0.55
Very heavy	-0.4	-0.69 to 0.37	0.16	0.58*	0.47 to 0.83	0.34	-0.56	-0.82 to -0.03	0.31
Severe	-0.33	-0.74 to 0.14	0.1	0.43	0.04 to 0.79	0.18	-0.56*	-0.73 to -0.4	0.31
Total collisions (n)	-0.48*	-0.74 to 0.02	0.23	0.67*	0.42 to 0.85	0.31 0.45	-0.68*	-0.87 to -0.1	0.76
Total RHIE bouts (n)	-0.49*	-0.77 to 0.05	0.26 0.24	0.73*	0.51 to 0.87	0.53	-0.66*	-0.89 to 0.21	0.44

* Significant correlation (p<0.05).

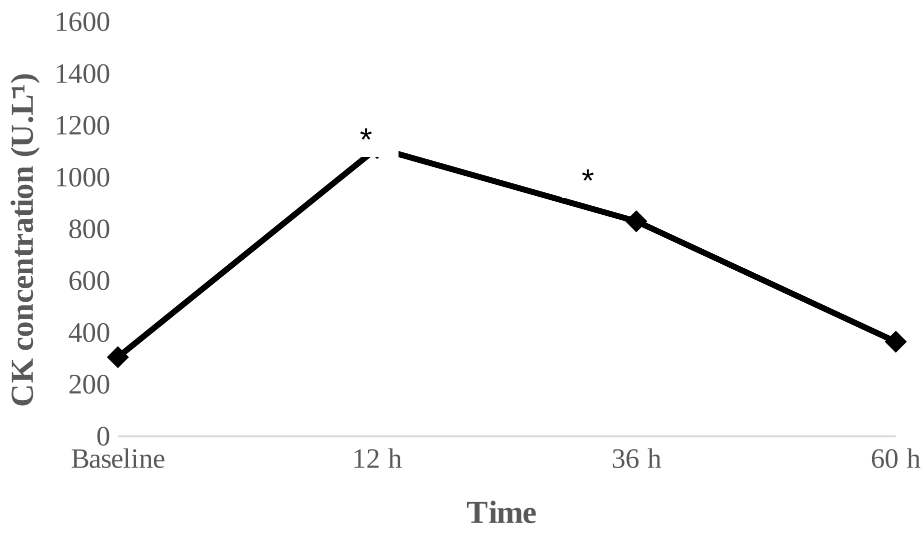

Figure 1. Changes in CK concentration after elite rugby league match-play.

* Significantly different from baseline values.

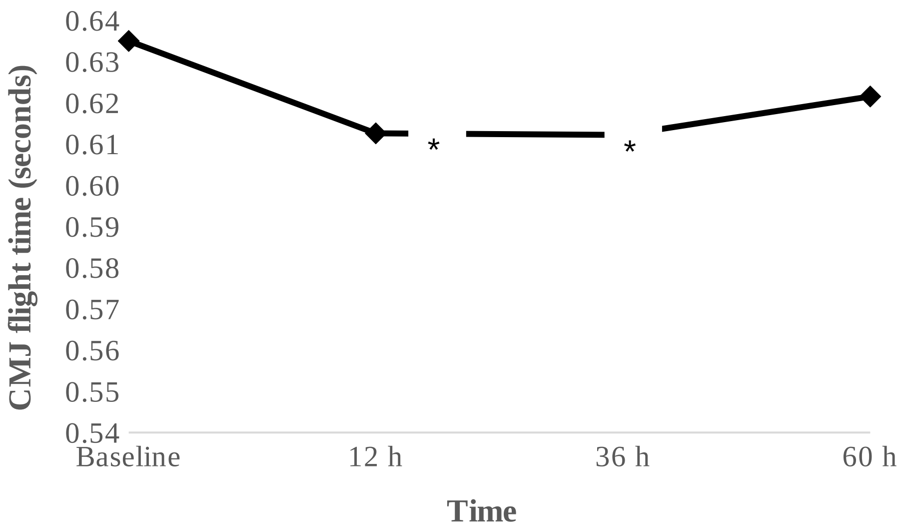

Figure 2. Changes in CMJ flight time following elite rugby league match-play.

* Significantly different from baseline values.

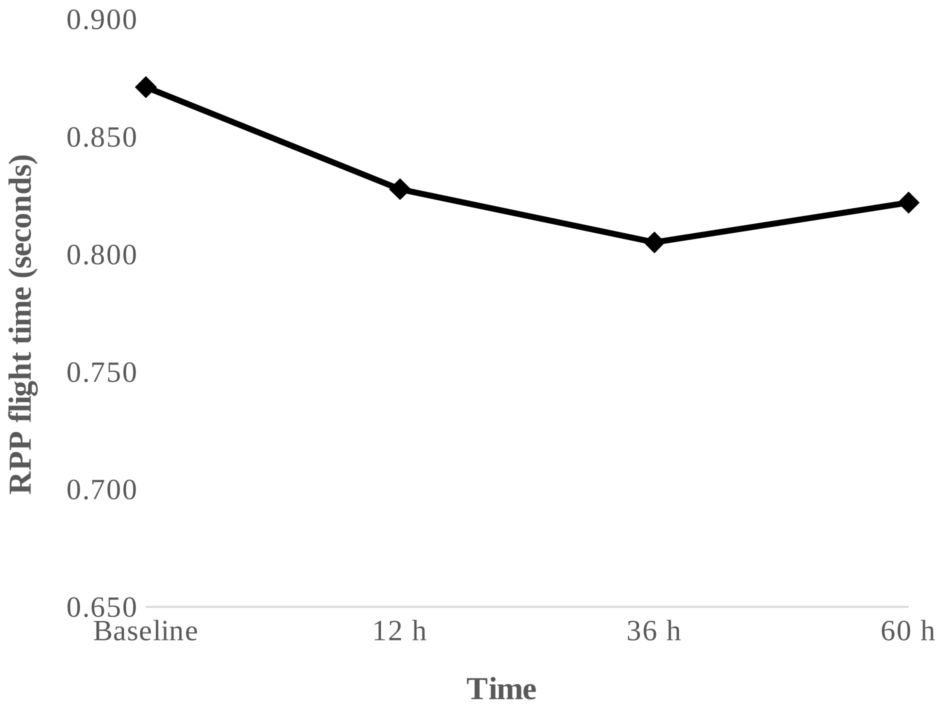

Figure 3. Changes in total flight time and contact time during a RPP following elite rugby league match-play.