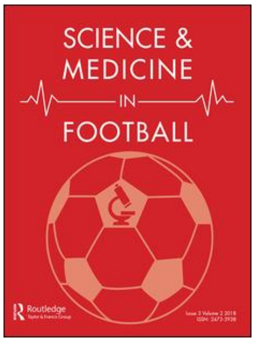

Science and Medicine in Football

ISSN: 2473-3938 (Print) 2473-4446 (Online) Journal homepage: https://www.tandfonline.com/loi/rsmf20

The influence of training load on postural control and countermovement jump responses in rugby union

Jordan C. Troester, Jason G. Jasmin & Rob Duffield

SCIENCE AND MEDICINE IN FOOTBALL
https://doi.org/10.1080/24733938.2019.1598621

Routledge
Taylor & Francis Group

The influence of training load on postural control and countermovement jump responses in rugby union

Jordan C. Troester [a,b], Jason G. Jasmin[a,b] and Rob Duffield [b]

[a]High-Performance Department, NSW Waratahs Rugby, Moore Park, NSW, Australia; [b]Sport and Exercise Discipline Group, University of Technology Sydney, Moore Park, NSW, Australia

ABSTRACT

Purpose: This study investigated responses of single-leg balance and landing and countermovement jump (CMJ) following rugby union training and the specific components of training load associated with test decrement. **Methods:** Twenty-seven professional rugby union players performed CMJ, single-leg balance and landing tests on a 1000 Hz force plate at the beginning and end of training days. Training load was described by session RPE, Banister's TRIMP, GPS total distance, high-speed running distance (>5.5 m s^{-1}), relative speed and body load. **Results:** CMJ eccentric rate of force development (EccRFD) demonstrated moderate impairment post-training (ES ± 90%CL = −0.79 ± 0.29, MBI = *almost certainly*). CMJ height (−0.21 ± 0.16, *possible*), concentric impulse (ConIMP) (−0.35 ± 0.17, *likely*) and single-leg balance sway velocity on the non-dominant leg (0.30 ± 0.26, *possible*) were also impaired. Regression analyses identified the strongest relationship between sRPE and impaired ConIMP (r = −0.68 ± 21, β = −0.68) whilst other load measures explained 27–50% of the variance in balance and CMJ changes. **Conclusions:** CMJ variables representing altered movement strategy (EccRFD and IMP) may be useful for assessing acute neuromuscular fatigue in rugby union, though single-leg balance sway velocity may be an alternative when maximal tests are impractical.

ARTICLE HISTORY
Accepted 14 March 2019

KEYWORDS
Single-leg balance; single-leg landing; neuromuscular fatigue; sensorimotor control

Introduction

Rugby union is a collision-based team sport that results in substantial physical and perceptual fatigue from running, physical contact and the static efforts of rucks, scrums, and mauls (Duthie et al. 2003). Practitioners commonly utilize countermovement jump (CMJ) tests to identify impairments in force production and altered movement strategy to determine the extent of neuromuscular fatigue (NMF) and guide the planning of subsequent training and recovery (West et al. 2014; Oliver et al. 2015; Shearer et al. 2015). CMJ variables of height, mean power, peak power, and mean force demonstrate good reliability (Roe et al. 2015) and responsiveness (5–8%) following youth and professional rugby union matches (West et al. 2014; Oliver et al. 2015; Shearer et al. 2015; Roe et al. 2016). However, questions regarding the practicality of CMJ tests have arisen due to the maximal effort required and challenges of athlete motivation and compliance (Carling et al. 2018), particularly in collision sports (Clarke et al. 2015). Consequently, tests of postural control (PC) based on balance and landing have been proposed as NMF monitoring tools given the minimal physical cost to athletes (Clarke et al. 2015) and sensitivity to proprioception and sensorimotor control (Pau et al. 2016). Further, understanding the fine motor control elements underpinning coordination and proprioception as related to NMF may help guide the planning of training to reduce injury risk and optimize recovery (Paillard 2012).

Postural control is defined as the ability to maintain the center of mass in relation to the center of pressure and incorporates the synergistic performance of the neuromuscular and sensorimotor systems (Paillard 2012). Static and dynamic tests of PC are often performed on a force plate through the assessment of balance and landing ability, respectively. Single-leg balance performance often is assessed by the center of pressure measures such as sway velocity (SV) (Panjan and Sarabon 2012); whilst single-leg landing tests commonly identify key ground reaction force measures of relative peak force (rPF), relative landing impulse (rIMP) and time to stabilisation (TTS) (Wikstrom et al. 2005). Reliability of these measures is reported across a variety of athletic and non-athletic populations (ICC = 0.65–0.95; CV = 6–13%) as well as specific rugby union populations (ICC = 0.67–0.79; CV = 9–11%) (Birmingham 2000; Wikstrom et al. 2005; Troester et al. 2018).

Previous research also reports impaired PC following fatiguing exercise. In athletic populations, aerobic, anaerobic, and treadmill run to exhaustion protocols produced 15–47% increases in balance measures of SV (Fox et al. 2008; Zech et al. 2012; Steib et al. 2013). Similarly, soccer match and Canadian football game simulation resulted in a 27.5% increase in SV and a 95% increase in sway area, respectively (Brito et al. 2012; Clarke et al. 2015). Single-leg landing performance assessed by TTS demonstrated impairment following intermittent running tests (4–10%), functional movement protocols (11%), and youth soccer matches (28%) (Wikstrom et al. 2004; Steib et al. 2013; Pau et al. 2016). Whilst evidence exists for fatigue-induced PC impairment, further understanding of the relationship to specific magnitudes and types of training loads would enable practitioners to optimize training and recovery to manage player fatigue.

CONTACT Jordan C. Troester jordan.troester@gmail.com Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Driver Ave, Moore Park, NSW, Australia

Therefore, the purpose of this study was to investigate the responsiveness of PC measures of single-leg balance and landing to NMF, alongside traditional CMJ tests, following typical rugby union training days. A secondary aim was to investigate the magnitudes and types of training load that were associated with test decrement. It was hypothesized that single-leg balance and landing tests would exhibit NMF responses relevant to the magnitude of training load.

Methods

Experimental approach to the problem

Measures of NMF were collected on a force plate before and after six separate training days throughout the season due to practical limitations of data collection for all tests in a single day. Two testing dates for each test resulted in pre- and post-training observations for balance (n = 34), landing (n = 35), and CMJ (n = 28), respectively. All testing days followed mid-week rest days and had similar training schedules consisting of three separate sessions; resistance training, specific skills (kicking, passing, scrum, lineout) and team-based skills and conditioning, hereafter referred to as gym, skills, and rugby. Subjective and heart rate (HR) based internal training load measures as well as global positioning satellite (GPS) system based external load were also collected for each field-based session. Changes in PC and CMJ tests and relationship with load measures were examined to further understand the components of training load associated with respective test decrement following rugby union training.

Subjects

Twenty-seven professional rugby union players (11 backs, 16 forwards) from the same Super Rugby team (age: 24 ± 3 y, height: 187 ± 7 cm, body mass: 104 ± 12 kg, Super Rugby games: 18 ± 20) participated in this study. Participants were training in the professional rugby club and had prior familiarity with all data collection methods as part of regular monitoring procedures. Participants were informed of the aims, requirements, and risks associated with the study prior to giving written informed consent. Prior to commencing the study, approval was granted by the University Ethics Committee (UTS HREC REF NO. ETH16-0626).

Procedures

Tests of NMF were undertaken on a 1000 Hz force plate (9260AA6, Kistler Instruments, Winterthur, Switzerland) and analyzed using commercially available software (SpartaTrac, Menlo Park, USA) that provides a select set of measures for use in applied sport settings. Prior to testing, the force plate was calibrated according to manufacturer's specifications. Pre-testing was performed at the beginning of the training day between 8:00 and 10:00am with no prior activity, and post-testing occurred within 30 min of the final training session of the day (team rugby). Gym and skills sessions were performed in the morning and there were 3–4 h of recovery prior to rugby sessions in the afternoon.

Postural control

Single-leg balance and single-leg landing tests were performed in a secluded corner of the team training facility and resulting data was coded for dominant (D) and non-dominant (ND) legs based on preferred kicking leg (Pau et al. 2014). Single-leg balance tests were performed on the hard surface of the force plate with shoes off, eyes closed and hands on hips. Two 20 s trials were performed on each leg. Mean values for total sway velocity (SV) (cm s^{-1}) were calculated based on the displacement of the center of pressure divided by trial length. Single-leg landing tests were performed by dropping from a 30 cm box with shoes off and hands on hips. Trials in which participants removed their hands from hips or touched the opposite leg were discarded. Mean values from three trials on each leg were calculated for relative peak landing force (rPF) (N kg^{-1}), relative landing impulse (rIMP) (N s kg^{-1}), and time to stabilisation (TTS) (s) based on the time required for forces to equalise within 5% of the baseline (Colby et al. 1999). Between day reliability has been previously reported for SV (CV = 9–12%), rPF (CV = 12–14%), rIMP (CV = 7–8%), and TTS (CV = 13–21%) (Troester et al. 2018).

CMJ

Participants performed CMJs according to previously established methods (Nibali et al. 2015). Participants performed a standardised warm-up of dynamic mobility and plyometric exercises (approximately 5 min), followed by three countermovement jumps using arm swing and a self-selected depth. Ten-second rest intervals were provided between each jump, and the mean values from three jumps were calculated. The eccentric rate of force development (EccRFD) (N s^{-1}) was determined from the minimum and maximum forces between the point at which vertical ground reaction forces exceed body mass during the countermovement and the point of minimum displacement. Mean relative concentric force (ConMF) (N kg^{-1}) and relative concentric impulse (ConIMP) (N s kg^{-1}) were calculated for the concentric portion of the jump (point of minimum displacement to take-off). Jump height (cm) was derived from takeoff velocity. Between day reliability has been previously reported for EccRFD (CV = 21.3%), ConPF (CV = 2.7%), ConIMP (CV = 2.7%), and jump height (CV = 3.5%) (Nibali et al. 2015).

Training load

Internal load measures were collected for training sessions using heart rate (HR) and session rating of perceived exertion (sRPE). Participants provided an RPE 15–30 min post-training using the CR-10 scale (Borg 1998) which was then multiplied by session duration (min) resulting in measures of sRPE Training Load (sRPE-TL) in arbitrary units (AU) for gym, skills, and rugby sessions. Additionally, HR was recorded during rugby sessions (Firstbeat, Jyvaskyla, Finland) and Banister's training impulse (bTRIMP) was calculated using individual thresholds determined during maximal fitness testing (Banister 1991). External load measures were collected for skills and rugby sessions using GPS units with integrated triaxial accelerometers (SPI-HPU – 15 Hz GPS, 16 g accelerometer) (GPSports, Canberra, Australia). GPS units were turned on 10 min prior to use to ensure adequate satellite connection, and worn between the shoulder blades in manufacturer provided vests. Data was downloaded and analyzed using Team AMS software

(GPSports, Canberra, Australia). GPS measures of total distance (m) (TD), high-speed running distance (m) (HSR) (>5.5 m s^{-1}), average relative speed (m min^{-1}) (ARS) and Bodyload (AU) (BL) were selected to quantify external training loads.

The result is a battery of training load measures to describe volume and intensity of gym, skills, and rugby sessions across balance landing and CMJ testing days. The sole measure for gym training is sRPE-TL_{Gym}. The skills session is represented by sRPE-TL_{Skills}, TD_{Skills}, HSR_{Skills}, ARS_{Skills}, and BL_{Skills}. The rugby session is described by sRPE-TL_{Rugby}, $bTRIMP_{Rugby}$, TD_{Rugby}, HSR_{Rugby}, ARS_{Rugby} and BL_{Rugby}.

Statistical analyses

Differences in load measures between testing days and pre- to post-training changes in PC and CMJ measures were assessed using custom spreadsheets (Hopkins 2007) to determine effect size (ES), 90% confidence limits (CL), and qualitative inference of practical significance (Hopkins et al. 2009). Where non-uniformity of error were present data were log transformed. The threshold for smallest worthwhile change (SWC) was set at 0.2 x between subject standard deviation (SD), based on Cohen's ES principle. Quantitative chances of increase or decrease were assessed qualitatively as follows: <1%, *almost certainly not*; 1–5%, *very unlikely*; 5–25%, *unlikely*; 25–75%, *possible*; 75–95%, *likely*; 95–99, *very likely*; >99%, *almost certain*. If the chance of increase and decrease were both > 5%, the true effect was assessed as *unclear* (Hopkins et al. 2009). Effect sizes were further evaluated as trivial (0–0.19), small (0.20–0.59), medium (0.60–1.19) and large (1.20 and greater) (Hopkins et al. 2009).

Stepwise multiple-regression analyses were used to investigate the relationship of internal and external load variables to variance (individual percent change) of single-leg balance, single-leg landing, and CMJ variables. Partial correlations and standardised coefficients with 95% CL, and level of significance for training load predictors of performance test variance were reported. Highly correlated predictor variables were removed from the model based on collinearity tolerance statistics whereby values <0.10 indicate unacceptable collinearity. All regression analyses were conducted using SPSS software (SPSS v 23.0, IBM Corp, Chicago, IL). Statistical significance was set at $p \leq 0.05$.

Results

As a summary of results, there were *trivial* differences between testing days for total sRPE-TL and total distance. Balance testing days represented the highest rugby loads, but the lightest gym and skills loads. Landing testing days represented the lowest rugby loads, but the highest gym and skills loads. CMJ testing days represented moderate gym, skills, and rugby loads. Further detail is presented in Table 1.

Balance

Results indicate a *possibly* small increase (6.2%) in sway velocity on the non-dominant leg (SV-ND), indicating impaired performance (Table 2). However, a *likely* trivial change (0.4%) was evident on the dominant leg. Regression analysis (Table 3) revealed that variance in SV-ND (R^2 = .496, $F(5,26)$ = 5.12, p = 0.01) could be explained by sRPE-TL_{Gym}, $bTRIMP_{Rugby}$, HSR_{Skills}, ARS_{Skills}, and TD_{Rugby} (y = 38.97 + .72 sRPE-TL_{Gym} – 1.09 $bTRIMP_{Rugby}$ – .64 HSR_{Skills} + .69 ARS_{Skills} + .92 TD_{Rugby}). The collinearity statistics for this model were acceptable with tolerance levels at 0.31, 0.10, 0.31, 0.31, 0.13 for respective variables.

Landing

A *likely* small decrease (10.4%) of time to stabilisation on the dominant leg (TTS-D) indicates improved performance (Table 2) whilst the decrease of TTS on the non-dominant leg (TTS-ND) was *likely* trivial (1.7%). Furthermore, all other landing variables of rPF and rIMP on either leg were trivial (0.8–2.2%). Regression analyses revealed no significant predictors for changes in landing variables, and as a result are not presented in Table 3.

CMJ

CMJ height demonstrated a *possibly* small decrease (3.6%), EccRFD was *almost certainly* moderately decreased (22.7%), changes in ConMF were *likely* trivial (0.1%), and ConIMP demonstrated a *likely*

Table 1. Mean ± SD for training load measures on single-leg balance, single-leg landing and CMJ training days.

	Balance	Landing	CMJ
sRPE-TL_{Gym} (AU)	231 ± 148	288 ± 164	280 ± 167
sRPE-TL_{Skills} (AU)	198 ± 154	218 ± 129	227 ± 152
$Distance_{Skills}$ (m)	1220 ± 745	1328 ± 707	1269 ± 921
HSR_{Skills} (m)	25 ± 37	30 ± 40	33 ± 65
Relative $Speed_{Skills}$ (m min^{-1})	29 ± 14*#	37 ± 21*	33 ± 16#
$Bodyload_{Skills}$ (AU)	17 ± 14#	21 ± 15	27 ± 22#
sRPE-TL_{Rugby} (AU)	520 ± 214*#	635 ± 168*	550 ± 235#
$bTRIMP_{Rugby}$ (AU)	151 ± 79	154 ± 53	162 ± 62
$Distance_{Rugby}$ (m)	5379 ± 1937*	4411 ± 688*	4647 ± 1103
HSR_{Rugby} (m)	620 ± 423*	289 ± 131*	507 ± 341#
Relative $Speed_{Rugby}$ (m min^{-1})	98 ± 17*#	81 ± 8*^	91 ± 14#^
$Bodyload_{Rugby}$ (AU)	137 ± 57*#	103 ± 37*	106 ± 56#

sRPE-TL = Training Load (RPE x duration); bTRIMP = Banister's Heart Rate based Training Impulse; HSR = High Speed Running distance.
* = inference of likely difference between balance and landing load; # = inference of likely difference between balance and CMJ load; ^ = inference of likely difference between landing and CMJ load.

Table 2. Pre- and post-mean ± SD, effect size (± 90% CL), and qualitative inferences for changes in single-leg balance, single-leg landing, and CMJ performance.

	Pre	Post	ES (± 90% CL)	Qualitative Inference
Balance				
SV – D (cm s^{-1})	8.18 ± 1.56	8.17 ± 1.33	−0.01 ± 0.20	*Likely Trivial*
SV – ND (cm s^{-1})	7.85 ± 1.56	8.33 ± 1.51	0.30 ± 0.26	*Possibly Small*
Landing				
rPF – D (N kg^{-1})	3.37 ± 0.63	3.42 ± 0.51	0.07 ± 0.20	*Likely Trivial*
rPF – ND (N kg^{-1})	3.28 ± 0.56	3.25 ± 0.52	−0.06 ± 0.24	*Likely Trivial*
rIMP – D (N s kg^{-1})	1.36 ± 0.19	1.39 ± 0.17	0.14 ± 0.22	*Possibly Trivial*
rIMP – ND (N s kg^{-1})	1.34 ± 0.17	1.32 ± .18	−0.12 ± 0.22	*Possibly Trivial*
TTS – D (s)	0.46 ± 0.09	0.41 ± 008	−0.51 ± 0.31	*Likely Small*
TTS – ND (s)	0.44 ± 0.10	0.44 ± 0.09	−0.09 ± 0.23	*Likely Trivial*
CMJ				
Jump Height (cm)	47.81 ± 7.46	46.26 ± 7.93	−0.21 ± 0.16	*Possibly Small*
EccRFD (N s^{-1})	6447 ± 1658	5136 ± 1506	−0.79 ± 0.29	*Almost Certainly Moderate*
ConMF (N Kg^{-1})	19.67 ± 1.44	19.69 ± 1.56	0.01 ± 0.19	*Likely Trivial*
ConIMP (N s Kg^{-1})	6.11 ± 0.29	6.01 ± 0.33	−0.35 ± 0.17	*Likely Small*

SV = sway velocity; rPF = relative Peak Force; rIMP = relative Impulse; TTS = Time to Stabilization; EccRFD = Eccentric Rate of Force Development; ConMF = Concentric Mean Force; ConIMP = Concentric Impulse; D = dominant leg; ND = non-dominant leg; ES = Effect size; CL = Confidence limits

Table 3. Partial correlations (± 95% CL), standardized coefficients (β), and level of significance (*p*) for training load predictors of variance (% change) in single-leg balance, and CMJ variables.

	Partial Correlation ± 95% CL	β	*P*
Sway Velocity – ND			
sRPE-TL_{Gym} (AU)	0.49 ± 0.26	0.72	.008*
$bTRIMP_{Rugby}$ (AU)	−0.44 ± 0.28	−1.09	.021*
HSR_{Skills} (m)	−0.47 ± 0.27	−0.64	.017*
Relative $Speed_{Skills}$ (m min^{-1})	0.48 ± 0.27	0.69	.001*
$Distance_{Rugby}$ (m)	0.42 ± 0.28	0.92	.027*
Jump Height			
$Bodyload_{Skills}$ (AU)	0.39 ± 0.32	0.39	.049*
$Bodyload_{Rugby}$ (AU)	−0.55 ± 0.27	−0.61	.004*
EccRFD			
Relative $Speed_{Rugby}$ (m min^{-1})	0.44 ± 0.31	0.60	.024*
$Bodyload_{Rugby}$ (AU)	−0.51 ± 0.29	−0.74	.007*
ConIMP			
sRPE-TL_{Rugby} (AU)	−0.68 ± 0.21	−0.68	.001*

sRPE-TL = Training Load (RPE x duration); bTRIMP = Banister's Heart Rate based Training Impulse; HSR = High Speed Running distance; EccRFD = Eccentric Rate of Force Development; ConIMP = Concentric Impulse; ND = non-dominant leg; CL = confidence limits; * indicates significance ($p < 0.05$)

small decrease (1.7%) (Table 2). Regression analysis (Table 3) revealed that variance in jump height (R^2= .309, $F(2,24)$ = 5.38, p= 0.01) could be explained by BL_{Skills}, and BL_{Rugby} (y = 2.91 + .39 BL_{Skills} − .61 BL_{Rugby}). The collinearity statistics for this model were acceptable with tolerance levels for each variable at 0.8. Likewise, variance in EccRFD (R^2 = .268, $F(2,24)$ = 4.40, p = 0.02) could be explained by ARS_{Rugby} and BL_{Rugby} (y = −75.06 + .60 ARS_{Rugby} − .74 BL_{Rugby}). The collinearity statistics for this model were acceptable with tolerance levels for each variable at .48. Finally, variance in ConIMP (R^2= .462, $F(1,25)$ = 21.47, p= 0.01) could be explained by sRPE-TL_{Rugby} alone (y = 2.29–.68 sRPE-TL_{Rugby}).

Discussion

The purpose of this investigation was to identify the acute response of NMF tests of CMJ, single-leg balance and landing to rugby union training and to identify the components of training load associated with impairment. CMJ EccRFD and ConIMP demonstrated the greatest impairment following rugby training whilst balance measures of SV-ND were impaired more than traditional measures of CMJ height. Of note, *trivial* changes were evident in most single-leg landing measures, though an improvement in TTS on the dominant leg was observed post-training. Despite some extent of uncertainty, load measures of BL_{Rugby} and $sRPE_{Rugby}$ demonstrate the largest association to CMJ impairment and could be considered for TL manipulation to manage player fatigue. CMJ force-time variables of EccRFD and ConIMP that may describe altered CMJ strategy demonstrate the largest impairment following a rugby union training day. However, when maximal testing is inappropriate, single-leg balance sway velocity may be a suitable alternative to traditional CMJ height testing.

Balance

Impaired balance on the non-dominant leg (6.2%) observed in the current investigation supports research demonstrating 5–35% decrements following fatigue-inducing protocols ranging from 2 min anaerobic sprint intervals (Fox et al. 2008) to 90 min soccer matches (Brito et al. 2012). Of note, changes in the current study are lower than the reported variability (CV = 9–12%) (Troester et al. 2018); however, the *possibly* small changes may represent a bias toward impaired performance post-training. Although balance measures represent a static task, ankle musculature is reported as the biomechanical limiting factor to locomotor activities (particularly running and sprinting), given the greater relative effort compared to knee extensor musculature (Kulmala et al. 2016) and represents the weakest link in this kinetic chain. Given the acute post-training responses noted here, single-leg non-dominant measures of balance may present a possible measure of NMF with the added benefit of less physical effort than landing and CMJ tests.

The impairment of SV-ND post training can be best explained (R^2= 0.496) by decreased sRPE-TL_{Gym}, ARS_{Skills} and TD_{Rugby} and increased HSR_{Skills} and $bTRIMP_{Rugby}$. Such loads may represent high-intensity efforts within training, such as tackling, grappling, and ruck involvements that normally result in less distance but high internal strain (ie increased HR) (Dubois et al. 2017). Clarke et al. (2015) demonstrated similar impairment of postural sway and CMJ following intermittent high-intensity efforts of a Canadian Football game simulation, although the relationship to load measures was not an aim of that study. Regardless, the current results suggest that with all other variables being equal, a 1 SD increase in $bTRIMP_{Rugby}$ (79 AU) would yield a 1.09 SD impairment (18%; 1.48 cm s^{-1}) in SV-ND. Accordingly, single-leg balance on the non-dominant leg may be related to fatigue driven by high-intensity efforts represented by increased HSR_{Skills} and $bTRIMP_{Rugby}$.

Landing

Post-training measures of TTS improved on the dominant leg (10.4%), whilst changes on the non-dominant leg were minimal. This contrasts with existing research demonstrating increased TTS, and thus impaired PC following treadmill running (Steib et al. 2013), functional movement protocols (Wikstrom et al. 2004; Brazen et al. 2010), and a 35-min soccer match (Pau et al. 2016). The improved dominant leg TTS could indicate a potentiating effect from training or a post-test practice effect, however, results should be considered in relation to previously reported variability (CV = 21%) on the dominant leg (Troester et al. 2018). Also of note are the differences in load during the landing testing days in which rugby sessions had the highest sRPE-TL, but likely lower HSR and ARS compared to balance and CMJ training days. Regression analysis did not reveal any relationships between load measures and improved landing, suggesting that high sRPE-TL was driven by elements other than the load measures included in this study (which may have impacted central and peripheral mechanisms that affect landing performance).

The trivial changes identified for rPF and rIMP in the current study also contrast existing research. Some authors suggest that rPF increases post-fatigue due to alterations in landing strategy that favor reliance on passive structures (ligaments and joint capsule) rather than musculature for shock absorption (Wikstrom et al. 2004; Brazen et al. 2010). Alternatively, the majority of studies report decreased rPF and rIMP post-fatigue, indicating lag time in muscle contraction that diminishes force absorption and stability (Augustsson et al. 2006; Coventry et al. 2006; Santamaria and Webster 2010; Zadpoor and Nikooyan 2012). The improvement of TTS-D in the current study, alongside mixed findings for rPF and rIMP in the previous research, may suggest some variability in the response of single-leg landing measures to different types of load which make the interpretation of post-fatigue landing performance challenging.

CMJ

CMJ performance demonstrated the largest post-training impairments in EccRFD (ES = −0.79) and ConIMP (ES = −0.35). Current impairments in CMJ height (ES = −0.21; −3.6%) support existing research describing 5–7.5% decreases in jump height following rugby union matches and training (West et al. 2014; Johnston et al. 2016, 2017; Kennedy and Drake 2017). The CMJ measures used in this study represent those available through commercial force plate testing software (SpartaTrac, Menlo Park, CA) and are not commonly reported in the literature. However, Gathercole et al. (2015) observed smaller decreases in RFD (ES = −0.30) and increases in eccentric duration (ES = 0.29). Impairment of EccRFD and ConIMP variables in the current investigation may support conclusions of altered movement strategy in response to NMF (Cormack et al. 2008; Gathercole et al. 2015) and support existing research on the use duration-based GRF variables for identification of NMF in rugby union.

The post-training decreases in CMJ variables can best be explained (R^2= 0.268–0.462) by measures of BL_{Skills}, BL_{Rugby}, ARS_{Rugby}, and $sRPE\text{-}TL_{Rugby}$. Positive correlations with BL_{Skills} and ARS_{Rugby} and negative correlations with BL_{Rugby} and $sRPE\text{-}TL_{Rugby}$ may suggest CMJ impairment is more related to change of direction, contact, and static exertion than absolute running intensity. As an example, standardized coefficients suggest that all other variables being equal, a 1 SD increase in $sRPE\text{-}TL_{Rugby}$ (235 AU) would yield a 0.68 SD impairment in ConIMP (1.7%; 0.1 N s·kg^{-1}). Reduced CMJ height, EccRFD, and ConIMP here support existing research on the response of CMJ and movement strategy to NMF (Cormack et al. 2008; Gathercole et al. 2015) which may result from rugby sessions emphasizing change of direction and static efforts that drive HR despite lower ARS.

Several limitations of the current investigation warrant mentioning. Due to practical limitations, data collection was performed across six different training days resulting in different loads for each day. Though regression analysis accounts for the influence of a range of loading parameters across subjects and testing days, any comparisons should be treated with caution. Secondly, the collinearity of load measures has been dealt with by applying tolerance limits to the regression analysis; however, such measures within a session are often highly interrelated and interpretation of the impact of a change in one measure apart from related changes in other measures may be impractical. Finally, post-testing was performed 15–30 min post-training when evidence of impaired PC exists (Pau et al. 2016) and various levels of recovery may have existed between athletes, though individual fatigue responses are beyond the scope of this investigation.

Conclusions

CMJ measures of EccRFD and ConIMP demonstrated the largest impairment post-training suggesting altered movement strategy. Single-leg balance SV-ND demonstrated greater sensitivity to post-training fatigue than traditional measures of CMJ height. Bodyload, sRPE-TL, and bTRIMP may be the main contributing factors to CMJ and balance impairment. Practitioners may use this information to guide the planning of training and recovery. Whilst CMJ remains a valuable measure of NMF, single-leg balance measures of SV could provide an alternative in situations where maximal jump testing is impractical.

Acknowledgements

Special thanks to the New South Wales Waratahs Rugby Club staff and players for their assistance and participation in the completion of this research. The authors have no conflicts of interest to declare, and no financial funding was obtained for this study.

Disclosure statement

There are no conflicts of interest concerning this paper.

Funding

No external funding was received for this work.

ORCID

Jordan C. Troester http://orcid.org/0000-0003-3843-8959
Rob Duffield http://orcid.org/0000-0002-5641-1314

References

Augustsson J, Thomee R, Linden C, Folkesson M, Tranberg R, Karlsson J. 2006. Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. Scand J Med Sci Sports. 16(2):111–120.

Banister E. 1991. Modeling elite athletic performance. Champaign (IL): Human Kinetics (Physiological Testing of Elite Athletes).

Birmingham TB. 2000. Test-retest reliability of lower extremity functional instability measures. Clin J Sports Med. 10(4):264–268.

Borg G. 1998. Borg's perceived exertion and pain scales, Vol. viii. Champaign (IL, US): Human Kinetics.

Brazen DM, Todd MK, Ambegaonkar JP, Wunderlich R, Peterson C. 2010. The effect of fatigue on landing biomechanics in single-leg drop landings. Clin J Sport Med. 20(4):286–292.

Brito J, Fontes I, Ribeiro F, Raposo A, Krustrup P, Rebelo A. 2012. Postural stability decreases in elite young soccer players after a competitive soccer match. Phys Ther Sport. 13(3):175–179.

Carling C, Lacome M, McCall A, Dupont G, Le Gall F, Simpson B, Buchheit M. 2018. Monitoring of post-match fatigue in professional soccer: welcome to the real world.. Sports Med. 48: 2695

Clarke N, Farthing JP, Lanovaz JL, Krentz JR. 2015. Direct and indirect measurement of neuromuscular fatigue in Canadian football players. Appl J Physiol Nutr Metab. 40(5):464–473.

Colby SM, Hintermeister RA, Torry MR, Steadman JR. 1999. Lower limb stability with ACL impairment. J Orthop Sports Phys Ther. 29(8):444–451, discussion 452–444.

Cormack SJ, Newton RU, McGuigan MR. 2008. Neuromuscular and endocrine responses of elite players to an australian rules football match. Int J Sports Physiol Perform. 3(3):359–374.

Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. 2006. The effect of lower extremity fatigue on shock attenuation during single-leg landing. Clin Biomech. 21(10):1090–1097.

Dubois R, Paillard T, Lyons M, McGrath D, Maurelli O, Prioux J. 2017. Running and metabolic demands of elite rugby union assessed using traditional, metabolic power, and heart rate monitoring methods. J Sports Sci Med. 16(1):84–92.

Duthie G, Pyne D, Hooper S. 2003. Applied physiology and game analysis of rugby union. Sports Med. 33(13):973–991.

Fox ZG, Mihalik JP, Blackburn JT, Battaglini CL, Guskiewicz KM. 2008. Return of postural control to baseline after anaerobic and aerobic exercise protocols. J Athl Train. 43(5):456–463.

Gathercole R, Sporer B, Stellingwerff T, Sleivert G. 2015. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. Int J Sports Physiol Perform. 10(1):84–92.

Hopkins MSW, Batterham AM, Hanin J. 2009. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 41(1):3–13.

Hopkins WG 2007. A spreadsheet to compare means of two groups. sportssci.org/2007/inbrief/.htm#xcl2: SportsScience; [accessed 2018 1/1/2018]. sportssci.org/2007/inbrief/.htm#xcl2.

Johnston MJ, Cook CJ, Drake D, Costley L, Johnston JP, Kilduff LP. 2016. The neuromuscular. Biochemical, and endocrine responses to a single-session vs. double-session training day in elite athletesJ Strength Condition Res. 30 (11):3098–3106.

Johnston MJ, Johnston JP, Cook CJ, Costley L, Kilgallon M, Kilduff LP. 2017. The effect of session order on the physiological, neuromuscular, and endocrine responses to maximal speed and weight training sessions over a 24-h period. J Sci Med Sport. 20(5):502–506.

Kennedy RA, Drake D. 2017. The effect of acute fatigue on countermovement jump performance in rugby union players during preseason. J Sports Med Phys Fitness. 57(10):1261–1266.

Kulmala JP, Korhonen MT, Ruggiero L, Kuitunen S, Suominen H, Heinonen A, Mikkola A, Avela J. 2016. Walking and running require greater effort from the ankle than the knee extensor muscles. Med Sci Sports Exerc. 48(11):2181–2189.

Nibali ML, Tombleson T, Brady PH, Wagner P. 2015. Influence of familiarization and competitive level on the reliability of countermovement vertical jump kinetic and kinematic variables. J Strength Condition Res. 29(10):2827–2835.

Oliver JL, Lloyd RS, Whitney A. 2015. Monitoring of in-season neuromuscular and perceptual fatigue in youth rugby players. Eu J Sports Sci. 15(6):514–522.

Paillard T. 2012. Effects of general and local fatigue on postural control: a review. Neurosci Biobehav Rev. 36(1):162–176.

Panjan A, Sarabon N. 2012. Review of methods for the evaluation of human body balance. Sport Sci Rev. 19(5–6):131–163.

Pau M, Ibba G, Attene G. 2014. Fatigue-induced balance impairment in young soccer players. J Athl Train. 49(4):454–461.

Pau M, Mereu F, Melis M, Leban B, Corona F, Ibba G. 2016. Dynamic balance is impaired after a match in young elite soccer players. Phys Ther Sport. 22:11–15.

Roe G, Darrall-Jones J, Till K, Phibbs P, Read D, Weakley J, Jones B. 2015. Between-day reliability and sensitivity of common fatigue measures in rugby players. Int J Sports Physiol Perform. 11(5):581-6

Roe G, Till K, Darrall-Jones J, Phibbs P, Weakley J, Read D, Jones B. 2016. Changes in markers of fatigue following a competitive match in elite academy rugby union players. South Afr J Sports Med. 28:1–4.

Santamaria LJ, Webster KE. 2010. The effect of fatigue on lower-limb biomechanics during single-limb landings: a systematic review. J Orthop Sports Phys Ther. 40(8):464–473.

Shearer DA, Kilduff LP, Finn C, Jones RM, Bracken RM, Mellalieu SD, Owen N, Crewther BT, Cook CJ. 2015. Measuring recovery in elite rugby players: the brief assessment of mood, endocrine changes, and power. Res Q Exerc Sport. 86(4):379–386.

Steib S, Hentschke C, Welsch G, Pfeifer K, Zech A. 2013. Effects of fatiguing treadmill running on sensorimotor control in athletes with and without functional ankle instability. Clin Biomech. 28(7):790–795.

Troester J, Jasmin J, Duffield R. 2018. Reliability of single-leg balance and landing tests in rugby union; prospect of using postural control to monitor fatigue. J Sports Sci Med. 17:174–180.

West DJ, Finn CV, Cunningham DJ, Shearer DA, Jones MR, Harrington BJ, Crewther BT, Cook CJ, Kilduff LP. 2014. Neuromuscular function, hormonal, and mood responses to a professional rugby union match. J Strength Condition Res. 28(1):194–200.

Wikstrom EA, Powers ME, Tillman MD. 2004. Dynamic stabilization time after isokinetic and functional fatigue. J Athl Train. 39(3):247–253.

Wikstrom EA, Tillman MD, Smith AN, Borsa PA. 2005. A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index. J Athl Train. 40(4):305–309.

Zadpoor AA, Nikooyan AA. 2012. The effects of lower extremity muscle fatigue on the vertical ground reaction force: a meta-analysis. Proc Inst Mech Eng H. 226(8):579–588.

Zech A, Steib S, Hentschke C, Eckhardt H, Pfeifer K. 2012. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. J Strength Condition Res. 26(4):1162–1168.