European Journal of Sport Science, 2019
Vol. 19, No. 10, 1312–1319, https://doi.org/10.1080/17461391.2019.1606941

ORIGINAL ARTICLE

Monitoring residual 36 h post-match neuromuscular fatigue in rugby union; a role for postural control?

JORDAN C. TROESTER [1,2] & ROB DUFFIELD[1]

[1] *Sport and Exercise Discipline Group, University of Technology Sydney, Moore Park, Australia &* [2] *High Performance Department, NSW Waratahs Rugby, Sydney, Australia*

Abstract
The present study investigated single-leg balance and landing measures, respectively, at the beginning of a weekly micro-cycle 36 h after a match compared to 48 h rest without any match load. Twenty-seven professional rugby union players performed balance and landing tests on a 1000 Hz force plate across three in-season micro-cycles either with or without match loads in the prior 36 h. Participants were further sub-divided into higher and lower match load groups to investigate changes in balance and landing variables. Differences between rested and 36 h post-match single-leg balance sway velocity were *trivial* in all cases, except for the higher-load group on the dominant leg, which were *possibly* impaired 36 h post-match (ES ± 90% CL = 0.68 ± 0.66). Differences between rested and 36 h post-match single-leg landing measures of relative impulse on the non-dominant leg were *possibly* lower (0.36 ± 0.34), with *possible* impairment observed on both legs in the higher load group 36 h post-match (0.39 ± 0.33; 0.49 ± 0.42). Differences in landing measures of peak force and time to stabilisation were mainly *trivial* (ES < 0.20). Postural control measures at 36 h post-match are comparable to a rested state; though impairment of sway velocity on the dominant leg and landing impulse may indicate residual neuromuscular fatigue resulting from increased match exposure.

Keywords: *Single-leg balance, single-leg landing, athlete monitoring, readiness to train*

Highlights

- Whilst most PC measures are expected to be within rested levels 36 h post-match, SV balance measures and IMP landing measures demonstrate the potential for *possibly* small impairments to remain.
- Thresholds for meaningful change based on previous reliability results may be used to identify individuals still experiencing large impairment of PC resulting from NMF 36 h post-match.
- PC tests require minimal physical effort and motivation and may prove useful for informing readiness to train at the beginning of a micro-cycle following a match.

Introduction

Rugby union is a high-intensity collision-based sport that results in significant musculoskeletal and physiological stress (Dubois et al., 2017). The between-match micro-cycle within a competitive rugby season presents coaches with the challenge of balancing match loads, recovery, and the necessary technical, tactical, and physical preparation for the upcoming match (Cross, Williams, Trewartha, Kemp, & Stokes, 2016; Lindsay et al., 2015; West et al., 2014). Hence, methods to guide training load prescription, or understand player readiness to train, at the start of a weekly training micro-cycle are often important tools for coaches and practitioners. Consequently, a host of measures, including psychological wellbeing, endocrine profiles and speed / power tests are suggested within high-performance sport to inform an athletes' readiness to train (Taylor, Chapman, Cronin, Newton, & Gill, 2012). While each tool provides insight into specific aspects of recovery, measures of neuromuscular fatigue (NMF) are of particular interest due to their objective assessment of force production (Boyas & Guevel, 2011). This fundamental force capacity underlies many mechanisms of performance and injury and is of prime focus in the post-match recovery context (Quarrie et al., 2017; Taylor et al., 2012).

Correspondence: Jordan C. Troester, Sport and Exercise Discipline Group, University of Technology Sydney, Driver Ave, Moore Park, NSW, Australia. E-mail: jordan.troester@gmail.com

Countermovement jump (CMJ) tests are commonly used in applied sport settings to assess NMF, with measures of height, mean power, and peak power demonstrating significant decreases (5–8%) immediately following youth and professional rugby union matches, and returning to pre-match levels between 48–60 h (Oliver, Lloyd, & Whitney, 2015; Roe et al., 2016; Shearer et al., 2015; West et al., 2014). Alteration of movement efficiency within CMJ using the flight time to contraction time ratio (FT:CT) has further indicated NMF immediately following and up to 24 h post-AFL and rugby league matches (Cormack, Newton, & McGuigan, 2008; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010). While CMJ is a valuable tool for monitoring NMF, practical application during the 48 h post-match window may be limited by the challenge of consistently obtaining maximal jump data from players recovering from the match (Taylor et al., 2012; Wehbe, Gabett, Dwyer, McLellan, & Coad, 2015). As a result, less physically demanding balance and stability tests of postural control (PC) have been proposed to assess NMF and infer readiness to train post-match (Clarke, Farthing, Lanovaz, & Krentz, 2015; Pau et al., 2016).

Postural control is the coordinated use of the neuromuscular and sensorimotor systems to stabilise the centre of mass over the base of support (Paillard, 2012). Previous investigations have established the between day variability (CV = 9–12%) of single-leg balance tests on a force plate with eyes closed in professional rugby union players (Troester, Jasmin, & Duffield, 2018). Meanwhile, impairment of balance measures has been demonstrated immediately following Canadian football game simulation (63%) (Clarke et al., 2015) youth (12–20%) (Brito et al., 2012) and elite (11–25%) soccer matches (Zemkova & Hamar, 2009). Between day variability for single-leg landing measures range from CV = 7–23% in professional rugby union players (Troester et al., 2018) with previous results indicating impairments in time to stabilisation of single-leg landings immediately following youth soccer match loads (24%) (Pau et al., 2016) and functional fatigue protocols (31–41%) (Brazen, Todd, Ambegaonkar, Wunderlich, & Peterson, 2010). When considering readiness to train at the beginning of an ensuing micro-cycle (~36 h post-match), PC tests may provide insight into general NMF, reduced muscle activation, and reduced proprioception that contribute to alterations in muscle stiffness and joint stability (Steib, Hentschke, Welsch, Pfeifer, & Zech, 2013; Wikstrom, Powers, & Tillman, 2004). In turn, such mechanistic changes may affect performance and increase risk of injury when exposed to ensuing training sessions (Trojian & McKeag, 2006; Zemkova, 2014). Previous evidence suggests acute recovery of PC measures from 15 min up to 48 h depending on the magnitude, intensity, and type of prior load (Clarke et al., 2015; Fox, Mihalik, Blackburn, Battaglini, & Guskiewicz, 2008; Pau et al., 2016). However, no research has investigated PC responses within the context of quantifying residual NMF at the beginning of the ensuing training week following either rest or a match.

Therefore, the primary purpose of this study was to evaluate the efficacy of PC tests for monitoring NMF by investigating single-leg balance and landing measures at the beginning of the training micro-cycle (when monitoring tools are practically used) following professional rugby union match loads (36 h post) compared to following 48 h of rest (bye week with no match load). A secondary purpose was to identify differences in the PC measure responses between higher and lower match load groups. It was hypothesised that single-leg balance and landing measures would still be impaired at 36 h post-match, and that impairment would be greater in the higher load group compared to lower load group.

Methods

Experimental approach to the problem

Single-leg balance and landing performance was tested on a force plate on the first day of a training micro-cycle following a bye with 48 hours rest and on the first day of a subsequent micro-cycle 36 h post-match. This approach reflects the aims of this study by testing the practical use of PC measures for monitoring NMF and readiness to train post-match compared to rested within the context of an in-season schedule. Data collection coincided with three periods throughout the season following a bye and data were pooled resulting in 61 balance and 55 landing comparisons. Training schedules and loads were consistent for all weeks prior to testing with 3 team rugby sessions, 3 gym sessions and 1 position-specific skills session. To further infer the effect of match loads on PC measures, data were sub-divided into higher match load (top 20 samples based on game minutes) and lower match load (bottom 20) groups.

Subjects

Twenty-seven male professional rugby union players (10 backs, 17 forwards, age: 26 ± 3 y, height: 189 ± 6 cm, mass: 106 ± 14 Kg, Super Rugby experience: 46 ± 22 games) participated in this study. All participants were free from injury and had prior familiarity with data collection methods as part of regular club monitoring procedures. This study was approved by the University Ethics Committee (UTS HREC

REF NO. ETH16-0626), and all participants were informed of the possible risks of involvement and provided informed consent.

Procedures

Single-leg balance and landing tests were performed on the hard surface of a force plate (9260AA6, Kistler Instruments, Winterthur, Switzerland) with a sampling rate of 1000 Hz, and data was processed using commercially available software (SpartaTrac, Menlo Park, USA). Data was further coded for dominant (D) and non-dominant (ND) legs based on preferred kicking leg. All tests were performed in a secluded corner of the team training facility wearing no shoes and normal team training uniform. Data collection occurred during the medical screening window between 8:00–10:00am on the first training day of the week with no prior activity. Post-match data were collected following home games and thus excluding the potential effects of travel. All testing was performed according to previously reported methods (Troester et al., 2018), and participants had extensive prior familiarity with procedures having completed them at least 10 times as a part of normal monitoring at the club.

Postural control. Single-leg balance measures were collected while participants performed 20s trials with eyes closed and hands on hips. Two trials were performed on each leg in alternating fashion, starting with the right leg. Trials in which the participant removed their hands from hips, touched the opposite foot off the force plate, or lost balance were discarded and repeated. Resulting data for mean sway velocity ($cm{\cdot}s^{-1}$) was calculated based on total displacement of the centre of pressure (COP) divided by the duration of the trial. The mean of two trials resulted in measures of sway velocity (SV) for each leg. For single-leg landing tests, participants started at a point 1 m from the centre of the force plate and were instructed to jump as high as possible off two legs and stick and hold the landing on one leg. Three trials were performed in alternating fashion on each leg, starting with the right. If the landing foot moved after contact or the opposite foot touched down, trails were discarded. Measures were obtained for relative peak landing force ($N{\cdot}Kg^{-1}$), relative landing impulse ($N{\cdot}s{\cdot}Kg^{-1}$) across 200 ms post-contact (Madigan & Pidcoe, 2003), and time to stabilisation (s) as measured by the time required for force to equalise within 5% of baseline (Colby, Hintermeister, Torry, & Steadman, 1999). The mean of three trials on each leg resulted in measures of peak force (PF), impulse (IMP), and time to stabilisation (TTS) for each leg. Among the many PC measures supported in the literature, SV (representing static balance) and PF, IMP, and TTS (representing dynamic landing) were used in this study based on the measures available within the commercially available testing software (SpartaTrac, Menlo Park, USA) widely used in applied sport settings. The reliability of procedures and measures within the context of professional rugby union players performing tests at the beginning of subsequent training weeks following rest has been previously reported for balance measures of SV (ICC = .67-.79; CV = 9–12%), and landing measures of PF (ICC = .58-.71; CV = 12–14%), IMP (ICC = .64-.68; CV = 7–8%), and TTS (ICC = .28-.60; CV = 13–21%) (Troester et al., 2018).

Training and match load. Sessions rating of perceived exertion (sRPE) was collected using a CR–10 scale 15–30 min post-training/match and multiplied by session duration to quantify internal load (AU) (Foster et al., 2001). External load measures were collected using global positioning system (GPS) units (SPI-HPU, GPSports, Canberra, AU) sampling at 15 Hz. Units were worn between the scapulae in custom fitted pockets within the game jerseys. Measures used for analysis included total distance (m), high speed running (>5.5 $m{\cdot}s^{-1}$) distance (m), and total accelerations and decelerations (>2.5 $m{\cdot}s^{-1}{\cdot}s^{-1}$). Further, match involvement data was collected using the official match statistics provided by OPTA sports and available through Fair Play (Fair Play Pty Ltd, Jindalee, Australia) and included game minutes, carries, tackles, and total rucks.

Statistical analysis

Paired analysis of rested and 36 h post-match balance and landing measures were undertaken with data log transformed to reduce non-uniformity bias. Because reliability has been previously established for these specific measures, population, and testing conditions (Troester et al., 2018) custom spreadsheets (Hopkins, 2017) were used to calculate magnitude-based inferences using percent difference in the mean and 90% confidence limits (CL) where the coefficient of variation was set as thresholds for smallest meaningful change: SV-ND = 12%, SV-D = 9%, PF-ND = 14%, PF-D = 12%, IMP-ND = 8%, IMP-D = 7%, TTS-ND = 13%, TTS-D = 21%. Quantitative chances of increase or decrease were assessed qualitatively as follows: <1%, most likely not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99, very likely; >99%, most likely. If the chance of increase and decrease were both > 5%, the true effect was assessed as unclear (Hopkins, Marshall, Batterham, & Hanin, 2009). Effect sizes were further evaluated as trivial (0–0.19), small (0.2–0.59), moderate (0.6–1.19) and large (1.2 and greater) (Hopkins et al., 2009).

Results

Training and match load

Mean weekly training loads ranged from 2194 ± 393 to 2326 ± 625 AU with 12,266 ± 2945 to 14,663 ± 5115 m total distance and 978 ± 464 to 1087 ± 555 m high speed running distance. Differences in training load between weeks were *likely* trivial. For all participants, mean match loads resulted in 4363 ± 2131 m total distance, 201 ± 183 m high speed running distance, 28.4 ± 20.2 total accelerations and decelerations, 67 ± 30 min of game duration, 4.5 ± 3.4 carries, 6.8 ± 5.5 tackles, and 9.8 ± 7.7 ruck involvements. The higher load groups consisted of 11 backs and 9 forwards for balance and 12 backs and 8 forwards for landing whilst the lower load groups consisted of 9 backs and 11 forwards for balance and 10 backs and 10 forwards for landing. Differences between higher and lower match load groups are presented in Table 1; with *most likely* large differences between groups (60–75%) for all measures.

Balance

Differences between SV at the start of the weekly micro cycle in a rested or 36 h post-match state were *trivial* for the entire group (Table 2) based on a threshold of change of 12% for SV-ND and 9% for SV-D. In the higher and lower load groups, rested to 36 h post-match differences were *trivial* in all cases except SV-D, where a *possibly* moderate (ES = 0.68 ± 0.66; 6.9 ± 6.7%) impairment was evident in the higher load group (Figure 1).

Landing

Rested compared to 36 h post-match differences in single-leg landing measures for the entire group were *trivial* in all cases based on %CV threshold for change except for IMP on the D leg which resulted

Table 1. Comparison of match loads between higher and lower match load groups.

	Group	Mean ± SD	% Difference ± 90% CL	ES ± 90% CL	Qualitative descriptor
Game duration (min)	Higher	98 ± 3	−71.53 ± 5.41	−37.28 ± 5.61	*most likely*
	Lower	31 ± 14			
Distance (m)	Higher	6551 ± 637	−74.05 ± 4.82	−13.46 ± 1.84	*most likely*
	Lower	1888 ± 968			
High speed distance (m)	Higher	292 ± 191	−75.37 ± 10.07	−1.98 ± 0.56	*most likely*
	Lower	78 ± 61			
Accel + Decel (count)	Higher	44 ± 18	−75.48 ± 7.29	−3.04 ± 0.63	*most likely*
	Lower	12.0 ± 7.5			
Carries (count)	Higher	7.5 ± 3.5	−63.20 ± 13.63	−1.54 ± 0.56	*most likely*
	Lower	2.1 ± 1.8			
Tackles (count)	Higher	9.3 ± 6.8	−60.60 ± 18.59	−1.40 ± 0.68	*most likely*
	Lower	3.0 ± 2.9			
Total Rucks (count)	Higher	13.6 ± 9.2	−68.75 ± 15.29	−1.58 ± 0.64	*most likely*
	Lower	4.8 ± 4.1			

Table 2. Rested and 36 h post-match balance and landing performance.

	Rested mean ± SD	36 h post-match mean ± SD	% difference ± 90% CL	ES ± 90% CL	Change threshold (%CV)	Qualitative descriptor
Balance						
SV-ND ($cm{\cdot}s^{-1}$)	8.27 ± 1.57	8.39 ± 1.50	1.5 ± 5.7%	0.08 ± 0.29	12%	*most likely trivial*
SV-D ($cm{\cdot}s^{-1}$)	8.65 ± 1.28	8.64 ± 1.29	−0.1 ± 4.5%	−0.01 ± 0.30	9%	*most likely trivial*
Landing						
PF-ND ($N{\cdot}Kg^{-1}$)	4.46 ± 1.06	4.43 ± 1.09	−0.8 ± 7.6%	−0.03 ± 0.31	14%	*very likely trivial*
PF-D ($N{\cdot}Kg^{-1}$)	4.77 ± 1.02	4.60 ± 1.01	−3.6 ± 6.7%	−0.17 ± 0.32	12%	*very likely trivial*
IMP-ND ($N{\cdot}s{\cdot}Kg^{-1}$)	2.08 ± 0.30	2.04 ± 0.34	−2.2 ± 5.1%	−0.14 ± 0.34	8%	*very likely trivial*
IMP-D ($N{\cdot}s{\cdot}Kg^{-1}$)	2.15 ± 0.32	2.04 ± 0.34	−7.3 ± 5.0%	−0.36 ± 0.34	7%	*possibly negative*
TTS-ND (s)	0.65 ± 0.14	0.68 ± 0.20	2.8 ± 8.1%	0.13 ± 0.38	13%	*very likely trivial*
TTS-D (s)	0.63 ± 0.12	0.65 ± 0.15	3.1 ± 6.8%	0.16 ± 0.34	21%	*most likely trivial*

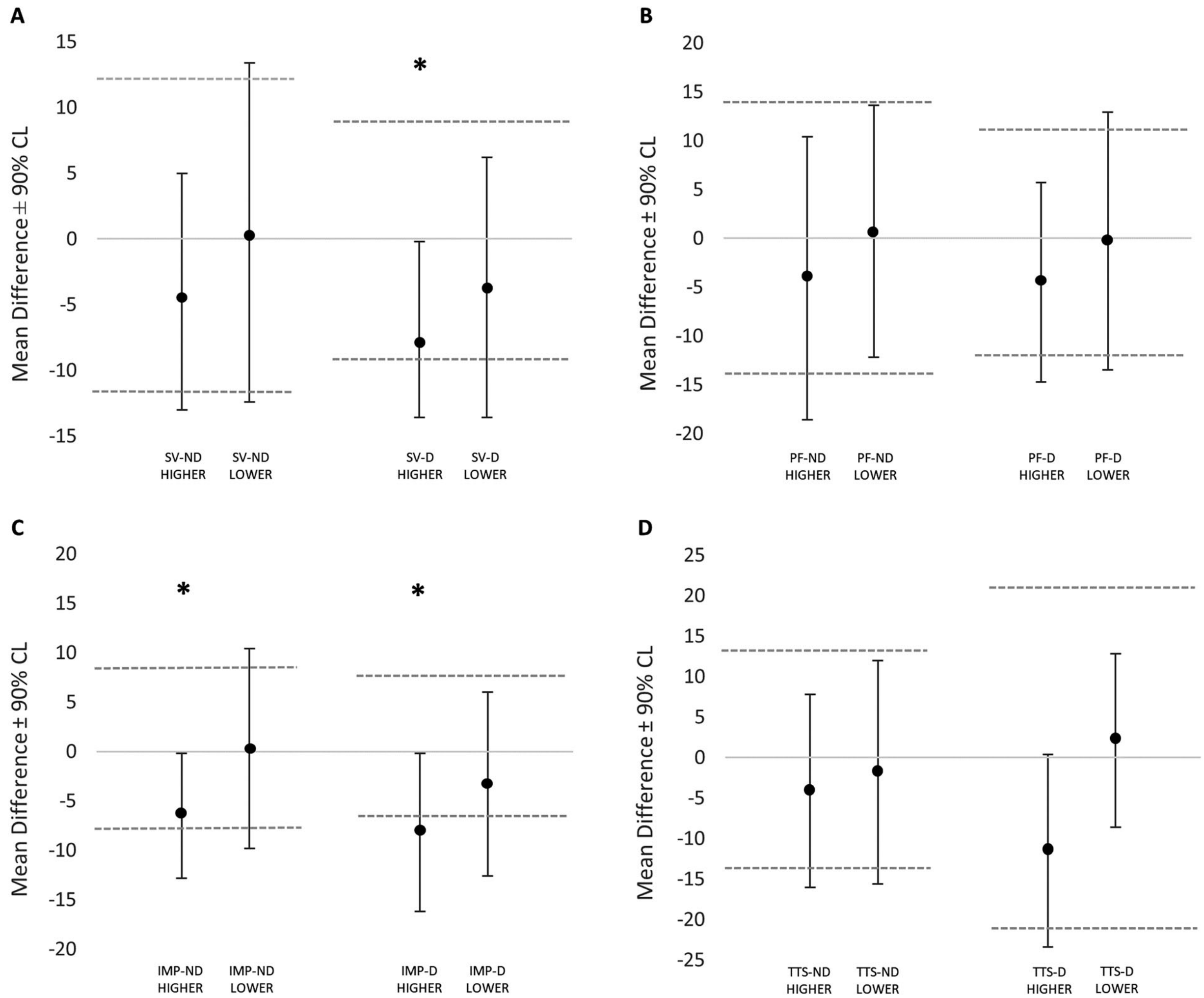

Figure 1. Mean difference (%) ± 90% CL between rested and 36h post-match measures of (A) sway velocity, (B) peak force, (C) impulse and (D) time to stabilisation on non-dominant (ND) and dominant (D) legs for higher and lower match load groups. Notes: Dashed line indicates %CV threshold for smallest meaningful change. Asterisk (*) denotes possible differences.

in *possibly* small (ES = −0.36 ± 0.34; −5.3 ± 5.0%) decreases (Table 2). When post-match data was classified as higher and lower match load groups, *possibly* small decreases were observed for IMP-ND (ES = −0.39 ± 0.33; −6.5 ± 6.3%) and IMP-D (ES = −0.49 ± 0.42; −8.2 ± 8.0%) in the higher match load group (Figure 1). Notably for TTS, *likely* trivial changes were observed for the entire group and for higher and lower load groups, and between group differences were *unclear*.

Discussion

The aim of the present study was to determine differences between single-leg balance and landing measures at the beginning of a weekly micro-cycle 36 h post-match or following 48 h rest without match loads. In turn, such analyses would inform the potential use of PC measures for monitoring residual NMF and thus infer readiness to train. Consequently, measures were mostly *trivial* between rested and 36 h post-match, though *possibly* small decreases in IMP and moderate impairment in SV-D were reported in the higher load group. These observations at 36 h post-match suggest most PC measures have returned to normal, though some impairments in SV and IMP remain evident following higher match loads.

The current investigation revealed *trivial* differences 36 h post-match in SV based on previously established thresholds for meaningful change (9–12%); a result likely due to the extended duration following the match until testing allowing recovery of balance measures. Previous research has demonstrated the responsiveness of balance measures immediately post-exercise in a fatigue state, with impairments of sway area in tandem stance of 63% following Canadian football game simulation

(Clarke et al., 2015) and 12–20% impairments in SV (with eyes open) following soccer match loads (Brito et al., 2012). While such immediate fatigue-induced balance disturbances are observed, the current results support the expectation that balance performance may be recovered within 36–48 h (Clarke et al., 2015). However, 36 h post-match SV in the higher match load group reported here showed *possibly* moderate impairment on the dominant leg and a *possibly* small effect between higher and lower load groups. Consequently, individual responsiveness and time-course for balance recovery may be specific to the magnitude, type, and intensity of load (Fox et al., 2008; Romero-Franco, Martinez-Lopez, Hita-Contreras, Lomas-Vega, & Martinez-Amat, 2015). Thus, residual NMF and disturbance of balance performance may still be present at 36 h post-match in individuals experiencing higher match loads and in turn, balance measures may be a minimally demanding method to inform this presence.

In the current study, differences between rested and 36 h post-match PF were *likely trivial* based on specific change thresholds of 12–14% and highlight that PF may be recovered by 36 h post-match. While previous research suggests recovery of PF during single-leg landings within 3 min of fatigue-inducing knee extensions in healthy males (Augustsson et al., 2006), there are no reports of the time-course for recovery following longer fatigue-inducing or sport-specific protocols representing the demands of rugby union match play. Furthermore, there is conflicting evidence for the response of PF to fatiguing exercise, with reports of increased PF resulting from decreased joint range of motion and reliance on passive structures for stiffness (James, Scheuermann, & Smith, 2010) or decreased PF due to altered landing strategies relying on larger muscles of the hip for force absorption (Coventry, O'Connor, Hart, Earl, & Ebersole, 2006). Regardless, the mainly *trivial* differences in conjunction with evidence of potentially contrasting responses of PF to fatigue, suggest that PF may not be useful to inform the presence of NMF or infer readiness to train in the 36–48 h post-match.

Current results report *possibly* small decreases in IMP-D and then IMP on both legs in the higher load group as based on specific thresholds for meaningful change (7–8%). This may suggest the clearest trend towards 36 h post-match impairment in the landing measures investigated in this study. However, no previous research provides evidence for the time-course for recovery of impulse measures from a single-leg landing task to contextualise this finding. Impulse is a measure of the area under the force-time curve (N·s) and represents change in momentum or force absorption during landing (Madigan & Pidcoe, 2003). Since changes in PF were *likely trivial*, the *possible* decreases in IMP in the current investigation support previous reports of altered landing strategy with shorter time to peak force resulting in lower impulse (James et al., 2010; Zadpoor & Nikooyan, 2012). This strategy could indicate NMF resulting in increased landing stiffness and reliance on connective tissues rather than the absorption of force through eccentric muscular contraction (Coventry et al., 2006). While speculative, this explanation coincides with reports of altered movement strategy in CMJ related to NMF following AFL matches and intensified periods of rugby union training (Cormack, Mooney, Morgan, & McGuigan, 2013; Gathercole, Sporer, & Stellingwerff, 2015). Given the *possibly* lower values 36 h post-match (especially in the higher load group) compared to rested states, IMP provides the most pronounced and longest lasting response of the landing measures investigated in this study. As a result, IMP may be useful for identifying altered landing strategy indicative of NMF and could be used to inform readiness to train at the beginning of a micro-cycle following a match.

Results of the current investigation indicate *likely trivial* increases (1.8–11.5%) in TTS at 36 h post-match which do not align with the reports of increased TTS during single-leg landing tasks on a force plate immediately following treadmill running (9%), functional protocols (31–41%), and soccer match loads (11–28%) (Brazen et al., 2010; Pau et al., 2016; Steib et al., 2013; Wikstrom et al., 2004). Current results could be explained by the monitoring timeline (36 h post-match) when TTS values may have returned to within rested levels (Augustsson et al., 2006); however, no research clearly establishes the expected time-course for recovery of TTS. Further, this study used a high threshold for meaningful change (CV = 13–21%) based on previous between-day reliability results (Troester et al., 2018) requiring large and lasting changes for identification of impairment to be made. As such, TTS appears to have low signal to noise ratio and lacks evidence to suggest its use for identifying NMF at the start of a weekly training micro-cycle.

The findings of the current investigation should be considered in context of the advantages and limitations of the study design. For example, this study used commercially available force plate software that made data collection simple and time-effective, despite a limited selection of previously reported PC variables. Further, the landing protocol specifically utilised a self-selected maximal jump height which may be most applicable to elite athletes, though variation in jump height between rested and

36 h post-match testing windows may affect landing measures. Finally, the comparison of PC measures following two days rest to those obtained 36 h post-match using specific thresholds for change based on prior reliability data informs the specific application of such tests for monitoring NMF and readiness to train at the beginning of a post-match micro-cycle, however acute and chronic loading factors may affect NMF and the response and time-course for recovery of PC measures remains unclear.

In conclusion, this study aimed to evaluate the efficacy of PC tests for monitoring NMF by comparing measures at the beginning of the training micro-cycle (when monitoring tools are practically used) following 48 h rest with no match loads and 36 h post-match at the beginning of the subsequent micro-cycle. Most PC measures were comparable with rested measures and within normal limits of variability by 36 h post-match, with only landing impulse displaying a *possible* decrease. However, the higher load group demonstrated impaired SV-D and IMP on both legs. Hence, recovery of PC is dependent on the magnitude of match load; and thus alterations in proprioception, sensorimotor control and landing strategy related to residual NMF may still exist 36 h after higher load rugby union matches. SV and IMP measures may be useful for identifying individuals with larger than expected impairment 36 h post-match which may contra-indicate neuromuscular recovery and inform the readiness to train process.

Acknowledgements

The authors would like to thank the athletes who participated in this study. No funding was obtained for the present study, and results do not constitute endorsement of any product by the authors.

ORCID

Jordan C. Troester http://orcid.org/0000-0003-3843-8959

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. *Scandanavian Journal of Medicine and Science in Sports*, *16*(2), 111–120. doi:10.1111/j.1600-0838.2005.00446.x. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/16533349

Boyas, S., & Guevel, A. (2011). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of Physical Rehabilitation Medicine*, *54*(2), 88–108. doi:10.1016/j.rehab.2011.01.001. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/21376692

Brazen, D. M., Todd, M. K., Ambegaonkar, J. P., Wunderlich, R., & Peterson, C. (2010). The effect of fatigue on landing biomechanics in single-leg drop landings. *Clinical Journal of Sports Medicine*, *20*(4), 286–292. doi:10.1097/JSM.0b013e3181e8f7dc. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/20606514

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. *Physical Therapy in Sport*, *13*(3), 175–179. doi:10.1016/j.ptsp.2011.07.004. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/22814452

Clarke, N., Farthing, J. P., Lanovaz, J. L., & Krentz, J. R. (2015). Direct and indirect measurement of neuromuscular fatigue in Canadian football players. *Applied Journal of Physiology, Nutrition, and Metabolism*, *40*(5), 464–473. doi:10.1139/apnm-2014-0465. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/25894521

Colby, S. M., Hintermeister, R. A., Torry, M. R., & Steadman, J. R. (1999). Lower limb stability with ACL impairment. *Journal of Orthopaedic and Sports Physical Therapy*, *29*(8), 444–451, discussion 452–444. doi:10.2519/jospt.1999.29.8.444 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10444734

Cormack, S. J., Mooney, M. G., Morgan, W., & McGuigan, M. R. (2013). Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *International Journal of Sports Physiology and Performance*, *8*(4), 373–378. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/23170747

Cormack, S. J., Newton, R. U., & McGuigan, M. R. (2008). Neuromuscular and endocrine responses of elite players to an Australian rules football match. *International Journal of Sports Physiology and Performance*, *3*(3), 359–374. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19211947

Coventry, E., O'Connor, K. M., Hart, B. A., Earl, J. E., & Ebersole, K. T. (2006). The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clinical Biomechanics*, *21*(10), 1090–1097. doi:10.1016/j.clinbiomech.2006.07.004. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/16949185

Cross, M. J., Williams, S., Trewartha, G., Kemp, S. P., & Stokes, K. A. (2016). The influence of in-season training loads on injury risk in professional rugby union. *International Journal of Sports Physiology and Performance*, *11*(3), 350–355. doi:10.1123/ijspp.2015-0187. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/26309331

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. *Journal of Sports Science and Medicine*, *16*(1), 84–92. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28344455

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., … Dodge, C. (2001). A new approach to monitoring exercise training. *Journal of Strength and Conditioning Research*, *15*(1), 109–115. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/11708692

Fox, Z. G., Mihalik, J. P., Blackburn, J. T., Battaglini, C. L., & Guskiewicz, K. M. (2008). Return of postural control to baseline after anaerobic and aerobic exercise protocols. *Journal of Athletic Training*, *43*(5), 456–463. doi:10.4085/1062-6050-43.5.456. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/18833307

Gathercole, R., Sporer, B., & Stellingwerff, T. (2015). Countermovement jump performance with increased training loads in elite female rugby athletes. *International Journal of Sports*

Medicine, *36*(9), 722–728. doi:10.1055/s-0035-1547262. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/25831403

Hopkins, W. G. (2017). Spreadsheets for analysis of controlled trials, crossovers and time series. *SportScience*, *21*, 1–4.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41* (1), 3–13. doi:10.1249/MSS.0b013e31818cb278 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/19092709

James, C. R., Scheuermann, B. W., & Smith, M. P. (2010). Effects of two neuromuscular fatigue protocols on landing performance. *Journal of Electromyography in Kinesiology*, *20*(4), 667–675. doi:10.1016/j.jelekin.2009.10.007. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/20006522

Lindsay, A., Lewis, J. G., Scarrott, C., Gill, N., Gieseg, S. P., & Draper, N. (2015). Assessing the effectiveness of selected biomarkers in the acute and cumulative physiological stress response in professional rugby union through non-invasive assessment. *International Journal of Sports Medicine*, *36*(6), 446–454. doi:10.1055/s-0034-1398528. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25760150

Madigan, M. L., & Pidcoe, P. E. (2003). Changes in landing biomechanics during a fatiguing landing activity. *Journal of Electromyography in Kinesiology*, *13*(5), 491–498. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/12932423

McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R., & Cormack, S. J. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *International Journal of Sports Physiology and Performance*, *5*(3), 367–383. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20861526

Oliver, J. L., Lloyd, R. S., & Whitney, A. (2015). Monitoring of in-season neuromuscular and perceptual fatigue in youth rugby players. *European Journal of Sports Science*, *15*(6), 514–522. doi:10.1080/17461391.2015.1063700. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/26366619

Paillard, T. (2012). Effects of general and local fatigue on postural control: A review. *Neuroscience and Biobehavioral Reviews*, *36*(1), 162–176. doi:10.1016/j.neubiorev.2011.05.009. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/21645543

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. *Physical Therapy in Sport*, *22*, 11–15. doi:10.1016/j.ptsp.2016.05.008. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/27579802

Quarrie, K. L., Raftery, M., Blackie, J., Cook, C. J., Fuller, C. W., Gabbett, T. J., … Tucker, R. (2017). Managing player load in professional rugby union: a review of current knowledge and practices. *British Journal of Sports Medicine*, *51*(5), 421–427. doi:10.1136/bjsports-2016-096191. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/27506436

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 African Journal of Sports Medicine*, *28*, 1–4. Retrieved from http://www.scielo.org.za/scielo.php?script = sci_arttext&pid = S1015-51632016000100002&nrm = iso

Romero-Franco, N., Martinez-Lopez, E. J., Hita-Contreras, F., Lomas-Vega, R., & Martinez-Amat, A. (2015). Effects of an anaerobic lactic training session on the postural stability of athletes. *Journal of Sports Medicine and Physical Fitness*, *55*(6), 578–586. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/24844625

Shearer, D. A., Kilduff, L. P., Finn, C., Jones, R. M., Bracken, R. M., Mellalieu, S. D., … Cook, C. J. (2015). Measuring recovery in elite rugby players: The brief assessment of mood, endocrine changes, and power. *Research Quarterly for Exercise and Sport*, *86*(4), 379–386. doi:10.1080/02701367.2015.1066927. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/26288253

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. *Clinical Biomechanics*, *28*(7), 790–795. doi:10.1016/j.clinbiomech.2013.07.009. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/23932774

Taylor, K. L., Chapman, D. W., Cronin, J. B., Newton, M. J., & Gill, N. (2012). Fatigue monitoring in high performance sport: a survey of current trends. *Journal of Australian Strength and Conditioning*, *20*(1), 12–23.

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. *Journal of Sports Science and Medicine*, *17*, 174–180.

Trojian, T. H., & McKeag, D. B. (2006). Single leg balance test to identify risk of ankle sprains. *British Journal of Sports Medicine*, *40*(7), 610–613, discussion 613. doi:10.1136/bjsm.2005.024356. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/16687483

Wehbe, G., Gabett, T. J., Dwyer, D., McLellan, C., & Coad, S. (2015). Monitoring neuromuscular fatigue in team-sport athletes using a cycle-ergometer test. *International Journal of Sports Physiology and Performance*, *10*(3), 292–297. doi:10.1123/ijspp.2014-0217. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25115142

West, D. J., Finn, C. V., Cunningham, D. J., Shearer, D. A., Jones, M. R., Harrington, B. J., … Kilduff, L. P. (2014). Neuromuscular function, hormonal, and mood responses to a professional rugby union match. *Journal of Strength and Conditioning Research*, *28*(1), 194–200. doi:10.1519/JSC.0b013e318291b726 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/23539085

Wikstrom, E. A., Powers, M. E., & Tillman, M. D. (2004). Dynamic stabilization time after isokinetic and functional fatigue. *Journal of Athletic Training*, *39*(3), 247–253. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15496994

Zadpoor, A. A., & Nikooyan, A. A. (2012). The effects of lower extremity muscle fatigue on the vertical ground reaction force: a meta-analysis. *Proceedings of the Institution of Mechanical Engineers, Part H*, *226*(8), 579–588. doi:10.1177/0954411912447021. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/23057231

Zemkova, E. (2014). Sport-specific balance. *Sports Medicine*, *44*(5), 579–590. doi:10.1007/s40279-013-0130-1. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/24293269

Zemkova, E., & Hamar, D. (2009). Effect of soccer match induced fatigue on neuromuscular performance. *Kinesiology*, *41*(2), 195–202.