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Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football

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ABSTRACT: Optimal strategies for recovery following training and competition in elite athletes presents ongoing debate. The effects of cold-water immersion (CWI) compared to passive recovery (PR) though a triad of performance measures after fatiguing exercise within a normal micro-cycle, during mid-competitive training cycle, in elite male footballers were investigated. Twenty-four elite footballers (age 20.58 ± 2.55 years; height 179.9 ± 5.6 cm; weight 75.7 ± 7.5 kg; body fat 6.2 ± 1.7%) were randomly assigned to CWI or PR following a fatiguing training session. Objective measures included eccentric hamstring strength, isometric adductor strength, hamstring flexibility and skin surface temperature (T_{sk}). Subjective measures included overall wellbeing. Data were collected at match day+3, immediately post-training, immediately post-intervention and 24 hrs post-intervention. Physiological, biomechanical and psychological measures displayed significant main effects for timepoint for eccentric hamstring strength, T_{sk}, overall wellbeing, sleep, fatigue, stress and group for eccentric hamstring strength, T_{sk} and sleep (groups combined). Group responses identified significant effects for timepoint for CWI and PR, for eccentric hamstring strength peak force, sleep, fatigue, and muscle soreness for CWI. Significant differences were displayed for eccentric hamstring strength (immediately post-intervention and immediately post-training) for peak force and between CWI and PR eccentric hamstring strength immediately post-intervention. Linear regression for individual analysis demonstrated greater recovery in peak torque and force for CWI. CWI may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite football settings. Multiple measures and individual analysis of recovery responses provides sports medicine and performance practitioners with direction on the application of modified approaches to recovery strategies, within mid-competitive season training cycles.

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INTRODUCTION

Football requires multi-directional activity where players are exposed to high eccentric muscle loads, commonly associated with injury [1, 2]. Deleterious effects of fatigue post-match have been shown to continue for up to 47 hrs, with, albeit individual minimal recovery exhibited between 24–48 hrs in elite populations [3]. Accordingly, the importance of optimum recovery strategies that allow positive adaptation to competition, maximise performance and reduce the probability of injury [4] is emphasised. The fitness fatigue model [5] and general adaptation syndrome [6] both highlight the importance of recovery before the next competition exposure. Insufficient recovery within this period can heighten injury risk and/or reduce positive training effects [4]. Multifaceted in nature, recovery is a restorative process comprising of physiological and psychological elements, relative to time [7]. Regenerative (physical) and psychological recovery strategies with subcategories of modalities [7] and multifactorial approaches are frequently applied in contemporary elite football settings [8].

Cold-water immersion (CWI) is a common recovery modality used within elite sport to reduce symptoms of post-exercise fatigue [9–12]. Temperatures of CWI often represent between 10–15°C and exposure durations of between 10–15 minutes [13]. Importantly, consideration must be given to the rationale for its application [13]. Debate exists within literature with regards to the benefits of immediate post training CWI [14, 15]. Studies suggests deleterious or negative effects of cooling such as CWI may mitigate adaptive responses gained through resistance training particularly [11]. Therefore, types of training may be a factor to consider in achieving the desired response to cooling.

Commonly in elite sports environments varying measures are utilised to inform decision-making on a player's readiness to train/play. The combination of subjective and objective measures is more likely to determine fatigue status in team-sport athletes, with single measures insufficient in explaining fatigue status [16]. The literature examining the acute effects of CWI does not consider these measures and focusses heavily on physiological measures that can be affected by several factors. Decision-making around optimal recovery choice and application in a practical environment should consider numerous factors including physiological, biomechanical and psychological effects. Varying measures are utilised within football environments, that help effectively monitor and quantify player readiness to train [17]. These are often determined by the club budget and staff resources within the performance department. Some performance metrics alongside psychometric data are previously quantified [18], however the literature fails to synthesise multiple metrics that represent contemporary performance markers relevant to elite sport.

Generally, reductions in perceived symptoms of delayed onset muscle soreness (DOMS) in sport are positively reported following the application of various cryotherapy modalities [18, 19], highlighting the support of cryotherapeutic applications to enhance physiological recovery. Literature suggests CWI is superior to passive recovery (PR), in relation to reducing muscle soreness [20]. Consensus fails to agree on optimal implementations of recovery strategies with several variables influencing the best approach. Investigation into the effects of CWI on functional performance are still warranted [21] particularly in elite populations. Evidently, research into optimum periodisation of cooling applications such as CWI to understand dose-response are important [9], simultaneous to investigations that compare CWI to PR in applied sport settings to inform contemporary practice. The aim of the current study was to explore the effects of CWI post fatiguing exercise on multiple performance parameters in elite footballers, compared to PR during mid-competitive season.

MATERIALS AND METHODS

The study was approved by the host university ethical committee. The professional football club permitted the dissemination of anonymous data for publication. Twenty-four healthy, elite male footballers took part (age: 20.58 ± 2.55 years; height: 179.9 ± 5.6 cm; weight: 75.7 ± 7.5 kg) providing written consent. Participants were defined as elite in the current study through professional full-time footballer status, competing at national or international level and met recommendations for defining elite athletes [22]. All quantification measures that players were exposed to in the present study were regular measures taken within the club to monitor readiness to train and play. Participants were excluded if they had a history of lower limb injury/surgery or known neurological compromise to cold. Players were accustomed to all biomechanical measures which are representative of regular parameters of performance measures taken at the club throughout the season.

Testing Protocol

Testing protocol took place at the club's training facility corresponding with pre-determined weekly training schedules collected mid-competitive season. Players were familiar with all tests performed, wore normal training attire, refrained from caffeine intake, food, or exercise outside of normal schedules prior to testing. Ambient

TABLE 1. Testing protocol.

		Weekly Post Match Day Training Schedule			
		Match Day +1	**Match Day +2**	**Match Day +3 Scheduled Training**	**Match Day +4 Scheduled Training**
Time Point (1–4)		No data collected	No data collected	1. Pre-Training 2. Immediately Post Training 3. Immediately Post Intervention	4. 24 Hours Post Intervention
GROUP	**Group 1 CWI**	No data collected	No data collected	Baseline measures taken (Pre-training)* GPS Immediately post training data collected* Immediately post CWI data collected*	24 hours post CWI intervention data collection prior to scheduled training*
	Group 2 PR	No data collected	No data collected	Baseline measures taken (Pre-training) * GPS Immediately post training data collected* Immediately post PR data collected*	24 hours post PR intervention data collection prior to scheduled training*

*Data collection across all timepoints consisted of; Performance measures = Eccentric Hamstring Strength, Isometric Adductor Strength, Hamstring Flexibility. Psychological = Wellbeing Questionnaire (McLean et al, 2010). Physiological = Skin Surface Temperature (T_{sk}) (hamstring and adductors). GPS = Monitoring of training load during scheduled training session.

temperature was monitored to identify fluctuations in room temperature (21.0 ± 0.8°C).

Objective measures included; eccentric hamstring strength, isometric adductor strength, skin surface temperature (T_{sk}), hamstring flexibility and perception of wellbeing [23, 24]. Baseline data was collected on match day+3 pre-training, players then completed the training session. Subsequent measures were taken immediately post-training, immediately post-intervention and 24 hrs post-intervention (24 hrs PI). Training was quantified utilising time-motion analysis (Global Positioning System (GPS), Catapult ClearSky, Vector S7, Australia) measuring relative mechanical load (PlayerLoad™; Catapult Innovations, Australia) and distance to ensure standardisation of fatigue levels. Following training, players were randomised to Group 1 (CWI) or Group 2 (PR). Group 1 received an 11-minute exposure to CWI (RecoveryTub Solo), and target temperature of 10°C [25] and CWI temperature ranges reported in the literature [13], immersed up to sternum level. A digital multimeter (Voltacraft MT52, Wollerau, Switzerland) monitored water temperature to ensure maintenance of the targeted temperature, with ice added to maintain consistency [26]. Following CWI, immersed body parts were towel dried and dry shorts provided [27]. Group 2 (PR) lay still in a semi-recumbent position on a plinth for the same 11-minute period. Measures taken at 24 hrs-PI were completed at the same time as baseline to account for circadian variation (Table 1).

Physiological Measure (T_{sk})

T_{sk} using Infrared Thermal Imaging (ThermoVision A40M, FLIR, Danderyd, Sweden) and analysis (Thermacam Researcher V2.8, FLIR) followed Thermographic Imaging in Sports and Exercise Medicine (TISEM) guidelines [28]. The camera was situated 134 cm from the ground perpendicular to the limb [29] with 0.97–0.98 emissivity settings. Images for adductors and hamstrings bilaterally provided unilateral limb data for each region of interest combined to provide an average (Table 2). Region of interest were determined by placement of thermally inert markers, providing a framework for T_{sk} analysis [30] (hamstrings; adductors). Images of adductors were taken with the player laying supine on a plinth placing their lower limb into an externally rotated and flexed hip position, moving into prone to capture the hamstring region. Three images were taken per region of interest per timepoint for analysis. Posterior thigh markers were applied superiorly one-third from the ischial tuberosity to the lateral epicondyle of the femur and inferiorly two-thirds from the lateral epicondyle of the femur to ischial tuberosity. Central posterior thigh was determined by measure of thigh circumference, 50% between ischial tuberosity and lateral epicondyle of the femur thigh marker. Markers to define the adductor region for T_{sk} analysis were placed one third of the way superiorly from the medial epicondyle of the femur and one third inferiorly from the ASIS, with thigh circumference applied in a similar fashion to posterior thigh markers. Inert markers were placed 10% medially and laterally and from the centre of the thigh to complete each region of interest.

Biomechanical Measures (eccentric hamstring strength, isometric adductor strength, hamstring flexibility)

Bilateral eccentric hamstring strength was quantified using the Nordbord® and performed following a previous protocol [31]. Knee position was recorded for each player to standardise position at each timepoint. During the movement players were encouraged to execute maximal effort through verbal instruction by gradually leaning forward, resisting the movement at the slowest speed performing one set of three maximal repetitions [31, 32]. Hands were crossed over the chest with hips remaining in a neutral position [31]. Analyses of peak force and torque (PkF/PkT) measures from all repetitions were recorded per timepoint.

Isometric adductor strength was measured via a Biofeedback Cuff (Donjoy Chattanooga Stabilizer). Before each maximal effort, the biofeedback cuff was pre-inflated to 10 mm Hg and placed between the femoral condyles. Players were instructed to squeeze as hard as possible on each effort with a 15-second rest between each trial, and one-minute rest between each 45° hip flexion test position [33] with three trials performed per timepoint. If any of the following occurred during testing; head lifted off the plinth, hands moved away from the chest, slippage of the pressure cuff, pushing through heels or feet, trials were considered invalid and repeated [33].

Hamstring flexibility was quantified via the sit and reach test (Apollo Sit & Reach Box). Players positioned themselves in a seated position with feet against the testing box, knees in full extension. Players placed one hand over the other flexing forward as far as possible sliding their fingers along the measuring board on the box [34]. One measure was taken per timepoint.

Psychological Measures

A self-reported psychometric questionnaire sensitive to the fluctuations of daily training load [16, 24] quantified fatigue, sleep quality, general muscle soreness, stress levels and mood on a five-point scale [23, 24], 5 being the most positive score and 1 the least, in increments of 1, with one score reported per category per timepoint [23]. Perceived fatigue monitored with this scale has been related to total distance covered at high intensity in elite football populations [24].

Statistical Analysis

Data are presented as mean ± SD and 95% confidence limits. Statistical significance was set at $p = \leq 0.05$. Statistical analysis was performed using SPSS (V26, SPSS Inc, Chicago, IL). A univariate repeated-measures general linear model quantified main effects for all measures across all timepoints for both groups. Significant main effects were explored using post-hoc analysis with a Bonferonni and Wilcoxon signed-rank test correction. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardized and standardised residuals were utilised to assess error of variance associated with the residuals. Assumptions associated with the statistical model were assessed to ensure model adequacy. Mauchly's test of sphericity were completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01–0.059), moderate (0.06–0.137), or large (> 0.138). Individual response for each metric were assessed utilising a linear regression model to determine recovery responses between timepoint immediately-post training to immediately-post intervention; and immediately-post intervention to 24 hrs PI. Proportion of variance (R^2), the linear relationship between the measures at listed timepoints (r) and significance of these relationships were identified for each metric.

RESULTS

Mean ± SD training load quantified through GPS was comparable between groups (CWI = 67.4 ± 6.1 m; PR = 70.5 ± 7.1 m), with total distance of 5862.4 ± 1297.6 m and HSRD of 111.83 ± 53.2 m. No significant differences were identified between training load for either group across all metrics or anthropometric data ($p \geq 0.05$). All measures and percentage changes compared to baseline are presented in Table 2.

Overall Analysis

Overall analysis for physiological, biomechanical and psychological measures reported significant main effects for time and group, for Adductor T_{sk} (Timepoint: $F = 102.0$, $p < 0.001$, $\eta^2 = 0.810$; Group: $F = 101.5$, $p = 0.001$, $\eta^2 = 0.585$), Hamstring T_{sk} (Timepoint: $F = 916.0$, $p < 0.001$, $\eta^2 = 0.947$; Group: $F = 1171.5$, $p < 0.001$, $\eta^2 = 0.942$), PkT (Timepoint: $F = 2.41$, $p < 0.05$, $\eta^2 = 0.48$; Group: $F = 25.43$, $p < 0.001$, $\eta^2 = 0.150$; Side: $F = 9.84$, $p < 0.05$, $\eta^2 = 0.64$), and PkF (Timepoint: $F = 2.41$, $p < 0.05$, $\eta^2 = 0.05$; Group: $F = 25.43$, $p < 0.001$, $\eta^2 = 0.15$; Side: $F = 9.84$, $p < 0.001$, $\eta^2 = 0.64$).

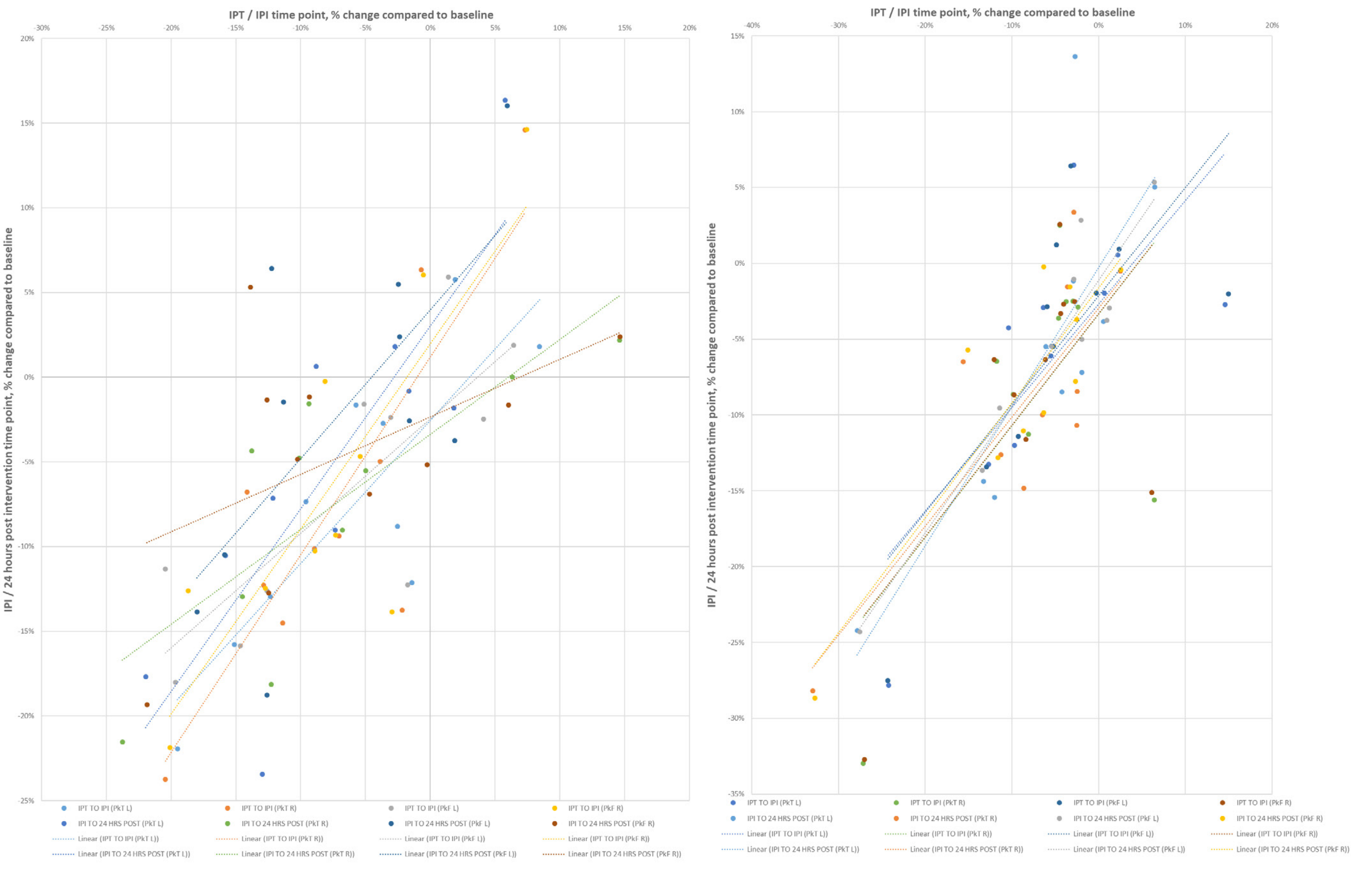

FIG. 1. Linear regression demonstrating % change for eccentric hamstring strength (PkT and PkF), left and right limbs between immediately-post training to immediately-post intervention and immediately-post intervention to 24 hrs PI for CWI group and PR group. (IPI=Immediately Post Intervention; IPT=Immediately Post Training; L=Left Limb; R=Right Limb).

TABLE 2. Physiological, biomechanical and psychological scores for all groups across all timepoints (mean ± SD) with significance, R, and R^2 values for CWI and PR following linear regression analysis.

		Performance Parameter	Time point				Measure	Timepoint	
			Baseline	Immediately Post Training	Immediate-ly Post Intervention	24HrsPI		Immediately Post Training to Immediately Post Intervention	Immediately Post Intervention to 24HrsPI
GROUP	CWI	**Eccentric Hamstring Strength (PkF) (N)**	LEFT LEG = 382.3 ± 51.3	359.9 ± 37.1 (-6.01%)	359.2 ± 51.1 (-6.04%)	357.9 ± 42.9 (-6.4%)	Eccentric Hamstring Strength PkF (R)	*P < 0.001; R = 0.6368; R² = 0.4055*	*P < 0.001; R = 0.8785; R² = 0.7718*
GROUP	CWI	**Eccentric Hamstring Strength (PkF) (N)**	RIGHT LEG = 417.4 ± 68.0	384.6 ± 61.7 (-7.9%)	382.7 ± 79.2 (-8.31%)	383.3 ± 72.4 (-8.16%)	Eccentric Hamstring Strength PkF (L)	*P < 0.001; R = 0.7514; R² = 0.5646*	*P < 0.001; R = 0.9473; R² = 0.8973*
GROUP	CWI	**Accumulative Eccentric Hamstring Strength (PkF) (left and right limb combined)**	399.9 ± 68.0	372.3 ± 49.4 (-6.9%)	371.0 ± 68.0 (-7.2%)	370.6 ± 57.7 (-7.3%)			
GROUP	CWI	**Eccentric Hamstring Strength (PkT) (N)**	LEFT LEG = 168.2 ± 27.4	156.9 ± 18.7 (-6.7%)	156.4 ± 24.1 (-7.0%)	155.7 ± 17.1 (-7.4%)	Eccentric Hamstring Strength PkT (R)	*P < 0.001; R = 0.6365; R² = 0.4051*	*P < 0.001; R = 0.8152; R² = 0.6645*
GROUP	CWI	**Eccentric Hamstring Strength (PkT) (N)**	RIGHT LEG = 181.3 ± 30.9	168.0 ± 29.6 (-7.3%)	166.7 ± 35.6 (-8.0%)	166.6 ± 14.8 (-8.1%)	Eccentric Hamstring Strength PkT (L)	*P < 0.001; R = 0.7432; R² = 0.5524*	*P < 0.001; R = 0.8086; R² = 0.6539*
GROUP	CWI	**Accumulative Eccentric Hamstring Strength (PkT) (left and right limb combined)**	174.3 ± 29.1	162.5 ± 24.2 (-6.8%)	161.6 ± 29.9 (-7.3%)	161.2 ± 25.3 (-7.5%)			
GROUP	CWI	**Isometric Adductor Strength (mm Hg)**	115 ± 13.0	113 ± 16.3	115 ± 9.4	121 ± 15.6	Isometric Adductor Strength	*P = 0.004; R = 0.4772; R² = 0.2277*	*P = 0.024; R = 0.5027; R² = 0.2527*
GROUP	CWI	**Hamstring Flexibility (cm)**	20.0 ± 8.0	20.0 ± 8.0	20.0 ± 8.0	20.0 ± 7.0	Hamstring Flexibility	*P < 0.001; R = 0.8014; R² = 0.6423*	*P < 0.001; R = 0.3738; R² = 0.1397*
GROUP	CWI	**Wellbeing Score (Overall)**	3.7 ± 0.4	3.4 ± 0.5**	3.7 ± 0.3**	3.6 ± 0.2***	Wellbeing Score (Overall)	*P = 0.743; R = -0.4797; R² = 0.0159*	*P = 0.659; R = 0.1298; R² = 0.0168*
GROUP	CWI	**T_{sk} Adductors* (°C)**	31.4 ± 0.8	30.1 ± 1.1	16.9 ± 1.1****	30.5 ± 1.0	T_{sk} (Adductors)	*P = 0.594; R = -0.4526; R² = 0.2049*	*P = 0.557; R = 0.3278; R² = 0.1075*
GROUP	CWI	**T_{sk} Hamstrings* (°C)**	31.9 ± 0.3	29.9 ± 0.8	17.6 ± 1.4****	31.1 ± 0.2	T_{sk} (Hamstrings)	*P = 0.852; R = -0.7283; R² = 0.5304*	*P = 0.476; R = 0.5335; R² = 0.2846*
GROUP	PR	**Eccentric Hamstring Strength (PkF) (N)**	LEFT LEG = 343.1 ± 35.2	319.5 ± 38.1* (-6.8%)	318.3 ± 32.3* (-7.2%)	334.6 ± 37.5* (-2.5%)	Eccentric Hamstring Strength PkF (R)	*P < 0.001; R = 0.8412; R² = 0.7076*	*P = 0.03; 1R = 0.5047; R² = 0.2547*
GROUP	PR	**Eccentric Hamstring Strength (PkF) (N)**	RIGHT LEG = 382.4 ± 30.2	351.6 ± 28.1* (-8.0%)	349.4 ± 43.9* (-6.5%)	364.4 ± 32.3* (-4.7%)	Eccentric Hamstring Strength PkF (L)	*P = 0.002; R = 0.8094; R² = 0.6551*	*P = 0.013; R = 0.6880; R² = 0.4734*
GROUP	PR	**Accumulative Eccentric Hamstring Strength (PkF) (left and right limb)**	362.8 ± 32.7	335.6 ± 33.1 (-7.5%)	333.8 ± 38.1 (-7.9%)	349.5 ± 35.0 (-4.0%)			
GROUP	PR	**Eccentric Hamstring Strength (PkT) (N)**	LEFT LEG = 145.6 ± 24.1	136.3 ± 22.8* (-6.4%)	133.5 ± 20.0* (-8.3%)	136.3 ± 17.7* (-6.4%)	Eccentric Hamstring Strength PkT (R)	*P = 0.001; R = 0.8461; R² = 0.7159*	*P = 0.002; R = 0.7833; R² = 0.6136*
GROUP	PR	**Eccentric Hamstring Strength (PkT) (N)**	RIGHT LEG = 161.6 ± 21.9	148.5 ± 15.2* (-8.1%)	138.7 ± 17.9* (-14.2%)	148.2 ± 14.8* (-8.3%)	Eccentric Hamstring Strength PkT (L)	*P < 0.001; R = 0.8311; R² = 0.6908*	*P < 0.001; R = 0.8244; R² = 0.6796*

TABLE 2. Continue

Performance Parameter	Time point				Measure	Timepoint	
	Baseline	Immediately Post Training	Immediate-ly Post Intervention	24HrsPI		Immediately Post Training to Immediately Post Intervention	Immediately Post Intervention to 24HrsPI
Accumulative Eccentric Hamstring Strength PkT) (left and right limb)	153.6 ± 23.0	142.4 ± 19.0* (-7.3%)	141.0 ± 19.0* (-8.2%)	142.3 ± 16.2* (-7.3%)			
Isometric Adductor Strength (mm Hg)	121.9 ± 16.1	117.3 ± 14.1	118.7 ± 16.6	122.6 ± 7.9	Isometric Adductor Strength	$P < 0.001$; $R = 0.8909$; $R^2 = 0.7937$	$P = 0.097$; $R = 0.326$; $R^2 = 0.1063$
Hamstring Flexibility (cm)	18.0 ± 7.0	18.0 ± 6.0	19.0 ± 6.0	20.0 ± 6.0	Hamstring Flexibility	$P < 0.001$; $R = 0.8899$; $R^2 = 0.7919$	$P < 0.001$; $R = 0.7207$; $R^2 = 0.5194$
Wellbeing Score (Overall)	3.7 ± 0.4	3.2 ± 0.5**	3.3 ± 0.6**	3.8 ± 0.4***§	Wellbeing Score (Overall)	$P = 0.299$; $R = -0.0457$; $R^2 = 0.0021$	$P = 0.435$; $R = 0.7786$; $R^2 = 0.6062$
T_{sk} Adductors* (°C)	31.2 ± 1.0	30.6 ± 0.8	31.4 ± 0.8	31.7 ± 0.7	T_{sk} (Adductors)	$P = 0.47$; $R = -0.684$; $R^2 = 0.4673$	$P = 0.191$; $R = 0.645$; $R^2 = 0.4157$
T_{sk} Hamstrings* (°C)	32.3 ± 0.3	31.0 ± 0.2	32.0 ± 0.2	31.2 ± 0.3	T_{sk} (Hamstrings)	$P = 0.003$; $R = 0.8909$; $R^2 = 0.7937$	$P = 0.184$; $R = 0.326$; $R^2 = 0.1063$
Wellbeing Score Groups Combined	3.7 ± 0.4	3.2 ± 0.5**	3.3 ± 0.6**	3.8 ± 0.4***§			

PkF = Peak Force, PkT = Peak Torque, (%) = Percentage difference compared to baseline scores for Eccentric Hamstring Strength for PkT and PkF, unilateral and bilateral limb data. * = Significant difference compared to baseline time point. ** = Significant difference in overall wellbeing scores compared to baseline scores. *** = Significant difference in overall wellbeing scores compared to post-training scores. § = Significant difference in overall wellbeing score compared to post intervention score. T_{sk} for adductors and hamstrings represent bilateral limb measures combined (mean ± SD). ****Significance at $p < 0.001$.

Biomechanical Measures (eccentric hamstring strength, isometric adductor strength, hamstring flexibility)

Isometric adductor strength and hamstring flexibility measures reported no significant effects of group (Isometric adductor strength: $F = 1.471$, $p > 0.05$, $\eta^2 = 0.020$; hamstring flexibility: $F = 0.785$, $p > 0.05$, $\eta^2 = 0.11$) or timepoint (Isometric adductor strength: $F = 0.708$, $p > 0.05$, $\eta^2 = 0.029$; hamstring flexibility: $F = 0.31$, $p > 0.05$, $\eta^2 = 0.49$).

Psychological Measures

Perceptual recovery displayed significant effects of time for sleep, fatigue and stress (Sleep: $F = 10.00$, $p < 0.001$, $\eta^2 = 0.43$; Fatigue: $F = 6.42$, $p < 0.001$, $n2 = 0.33$; Stress: $F = 3.03$, $p < 0.05$, $\eta^2 = 1.86$), with sleep displaying a significant effect of group ($F = 10.00$, $p = 0.003$, $\eta^2 = 0.20$). No significant effects for time or group were identified for muscle soreness or mood (Muscle soreness: Time: $F = 2.34$, $p = 0.08$, $\eta^2 = 0.150$: Group: $F = 0.98$, $p = 0.33$, $\eta^2 = 0.24$; Mood: Time: $F = 0.417$, $p = 0.74$, $\eta^2 = 0.03$: Group: $F = 4.00$, $p = 0.52$, $\eta^2 = 0.91$). No significant effects for group were identified for fatigue or stress (Fatigue: $F = 0.000$, $p = 1.00$, $\eta^2 = 0.00$; Stress: $F = 1.47$, $p = 0.23$, $\eta^2 = 0.04$).

Significant interactions were displayed between group *x* timepoint for T_{sk}, sleep, fatigue and stress (Sleep: $F = 10.0$, $p < 0.001$, $\eta^2 = 0.43$; Fatigue: $F = 5.19$, $p = 0.004$, $\eta^2 = 0.28$; Stress: $F = 5.24$, $p = 0.04$, $\eta^2 = 0.282$). No other significant interactions were identified between group/timepoint/side for metrics taken ($p > 0.05$). Collapsing of biomechanical and psychological data displayed significant effects for timepoint for CWI for fatigue, muscle soreness, sleep and PkF (Fatigue: $F = 7.25$, $p = 0.002$, $\eta^2 = 0.521$; Muscle soreness: $F = 2.69$, $p = 0.02$, $\eta^2 = 0.512$; Sleep: $F = 7.45$, $p = 0.002$, $\eta^2 = 0.565$; PkF: $F = 3.74$, $p < 0.05$, $\eta^2 = 0.049$). No other significant differences were detected between timepoints for all other metrics. For PR, significant effects for timepoint were reported for fatigue, sleep, stress, PkF and PkT (Fatigue: $F = 5.135$, $p = 0.009$, $\eta^2 = 0.435$; Sleep: $F = 10.00$, $p < 0.001$, $\eta^2 = 0.600$; Stress: $F = 5.287$, $p = 0.008$, $\eta^2 = 0.442$; PkF: $F = 10.66$, $p < 0.05$, $\eta^2 = 0.087$; PkT: $F = 1.636$, $p < 0.05$, $\eta^2 = 0.064$), but not for muscle soreness, mood, isometric adductor strength or hamstring flexibility (Muscle soreness: $F = 2.098$, $p = 0.113$, $\eta^2 = 0.239$; Mood: $F = 0.143$, $p = 0.933$, $\eta^2 = 0.021$; Isometric adductor strength: $F = 0.291$, $p > 0.05$, $\eta^2 = 0.024$; hamstring flexibility $= 0.50$, $p > 0.05$, $\eta^2 = 0.004$). Significant effects for

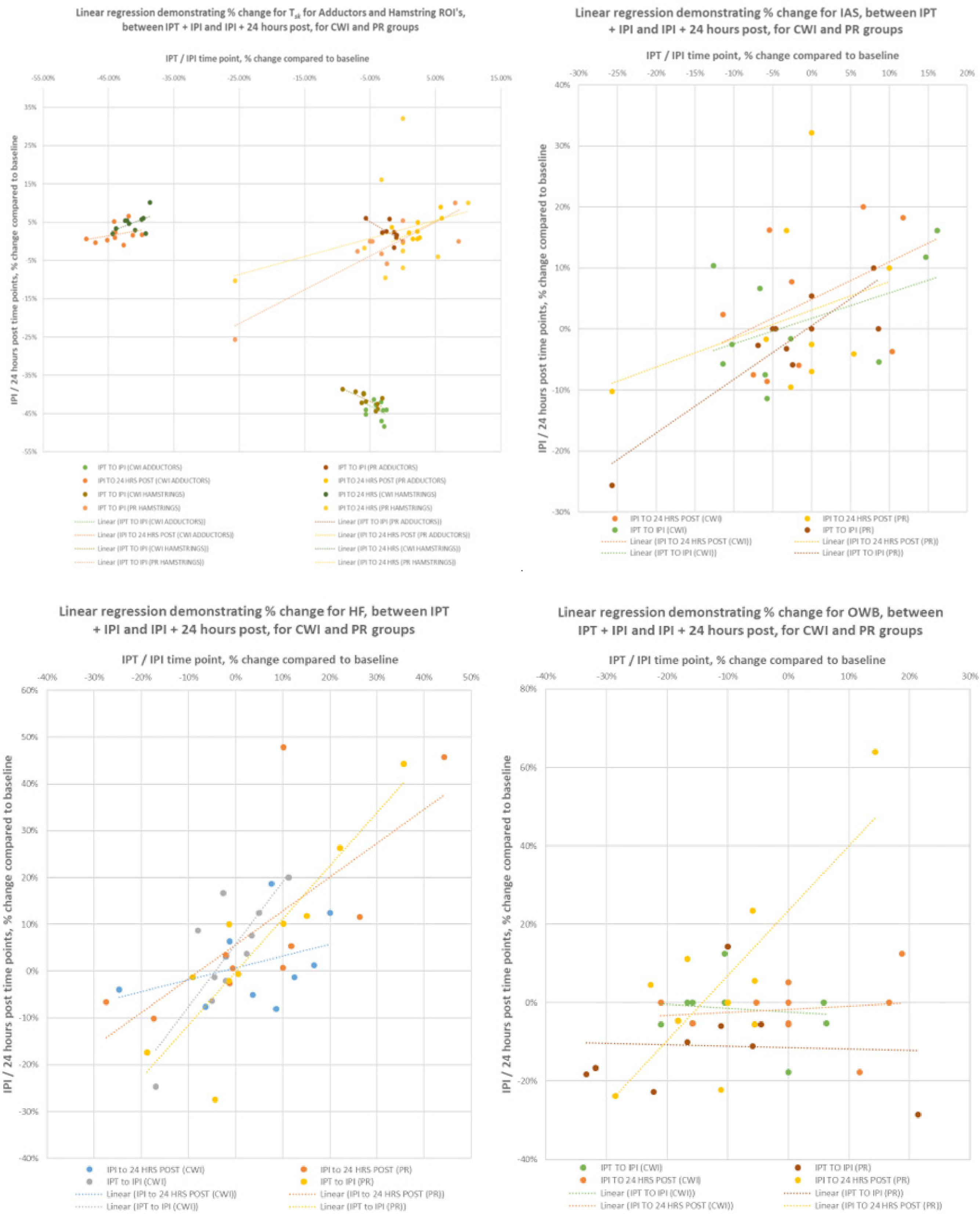

FIG. 2. Linear regression demonstrating % change for isometric adductor strength, hamstring flexibility, overall wellbeing scores and Tsk between immediately-post training to immediately-post intervention, and immediately-post intervention to 24 hrs PI, for CWI and PR groups. (IPI=Immediately Post Intervention; IPT=Immediately Post Training; OWB=Overall Wellbeing).

PkT and PkF for side (PkT: $F = 8.880, p = 0.004, \eta^2 = 0.110$; PkF: $F = 17.84, p < 0.001, \eta^2 = 0.199$) were reported. No significant interactions were identified for either group between timepoint or side ($p > 0.05$).

Collapse of the data into CWI and PR displayed significant T_{sk} reductions for hamstring and adductor regions following CWI between immediately-post intervention, immediately-post training and baseline ($p \leq 0.001$). No significant differences were displayed across hamstring or adductor regions of interest when comparing all timepoints for PR ($p \geq 0.05$). No significant differences between any timepoints for PkT, Isometric adductor strength or hamstring flexibility ($p \geq 0.05$) for either group were reported. For PR, significant differences were displayed between baseline and immediately-post training ($p = 0.023$) and intervention ($p = 0.03$) timepoints for PkF. A significant difference was reported when comparing CWI to PR at immediately-post intervention ($p \leq 0.001$). No significant changes in T_{sk} were reported for any other timepoint between groups.

Linear regression modelling for individual responses to training are displayed for eccentric hamstring strength (PkT, PkF) (Figure 1), and isometric adductor strength, hamstring flexibility, overall wellbeing scores and T_{sk} (Figure 2). Significance, R and R^2 values are represented in Table 2.

DISCUSSION

The aim of the study was to investigate the effects of CWI compared to PR on readiness to train measures, within an elite population of male footballers following a football specific fatiguing training session during mid-competitive season. Previously only a handful of components that quantify readiness to train are examined, limiting interpretation and the ability to draw agreement on optimal recovery methods, effect of immediate application or implementation of them in an elite performance environment. Through a triad of markers commonly employed within an elite sport setting the present study quantified biomechanical, physiological and psychological factors with analysis of the overall data displaying significant main effects for timepoints for eccentric hamstring strength, T_{sk}, overall wellbeing, sleep, fatigue and stress. Further significant main effects of group were identified for eccentric hamstring strength, T_{sk} and sleep. Individual group response identified significant effects for timepoint in both groups for PkF, sleep and fatigue, with CWI displaying significant effects of muscle soreness. No effects were identified for isometric adductor strength or hamstring flexibility. Interestingly, significant differences were displayed for eccentric hamstring strength (PkF) at immediately-post training and immediately-post intervention, with significant differences displayed between CWI and PR eccentric hamstring strength at immediately-post intervention. It is important to note these findings were based on group averages. Therefore, additional linear regression modelling of% change to baseline scores were completed. Important considerations in relation to individual analysis and magnitude of linear regression for each measure demonstrated greater recovery in PkF, PkT, for CWI and changes in isometric adductor strength and hamstring flexibility for PR between immediately-post training to 24 hrs PI. For effective transfer of knowledge into practice this style of analysis was important to illustrate individual response. Findings have implications on decision-making utilising CWI as a recovery strategy, individualisation of approach and ideal periodisation of this modality compared to PR in an elite football setting.

Significant reductions in T_{sk} occurred after CWI exposure, although not meeting therapeutic range (10–15°C) considered in literature to induce several physiological effects [35]. CWI was standardised in respect to current dose recommendations and target water temperatures [13, 25, 36]. Average T_{sk} for hamstrings (16.9 ± 1.8°C) and adductors (17.61 ± .4°C) respectively are in line with previous CWI exposures of similar duration and modality temperatures [37]. Overall analysis indicated reductions in T_{sk} appeared to influence biomechanical recovery outputs with trends in eccentric hamstring strength demonstrating larger continued declines caused by fatigue following PR compared to CWI. When considering individual response, linear regression analysis displayed greater recovery for timepoints immediately-post intervention-24 hrs PI for eccentric hamstring strength metrics for CWI exposure (CWI: $r = 0.81–0.95$; PR: $r = 0.50–0.82$). Percentage change between timepoints compared to baseline data represented in Figure 2. More positive influences on eccentric hamstring strength with a consistently stronger individual response noted for CWI compared to individual analysis for PR where metrics for eccentric hamstring strength responded in a haphazard fashion.

It is reported that cooling negatively affects strength output [29]. The current study presented contrasting findings in relation to strength measures, highlighting contemporary issues for decision-making within performance departments. CWI group reduces further detrimental declines in eccentric hamstring strength following a football specific training session [3], with CWI exposure displaying higher strength output compared to PR, up to 24 hrs PI. Contrastingly isometric adductor strength and hamstring flexibility function for both groups displayed no significant change, indicating no effect of CWI exposure on these parameters. Although, analysis of the data trends associated with these measures is interesting. CWI exposure resulted in a rapid return to baseline post intervention, however this was not displayed for PR. Further analysis of individual response between timepoints immediately-post intervention-24 hrs PI supported this with further improvements detected following CWI (CWI: $r = 0.50$; PR: $r = 0.30$). Reduced decrements to isometric adductor strength following fatigue reveals a positive response to CWI seen in previous literature [38], albeit in different muscle groups. Findings in relation to strength parameters highlighted in this body of work can be associated with the physiological mechanisms caused by cooling [38, 39], although these mechanisms are speculative within the limitations of the current study as simultaneous indices of muscular inflammation were not attained.

Although it may be assumed that attainment of lower T_{sk} may instigate better outcomes in recovery responses, Vieira et al [26] reported that warmer CWI temperatures (15°C) produced superior benefits in performance recovery compared to cooler CWI (5°C) temperatures despite lower T_{sk} reported in the group exposed to 5°C CWI. Therefore, the recommendations to meet T_{sk} ranges of between 10–15°C may appear more fitting for acute injury management rather than recovery, as the detrimental effects of fatigue on specific biomechanical measures (eccentric hamstring strength) were ameliorated through CWI in the current study, despite this. Though it is acknowledged that CWI is best avoided immediately following resistance training [13], current findings agree with the suggestion by Ihsan et al [13] that there is a place for CWI in recovery following other types of training. This may be during mid-competitive season where fixture congestion applies enhanced pressure on players during training both physically and mentally. Importantly the contrasting findings with regards quantifying strength output highlight the importance of relating measures to the functional demands placed on the athlete when performing.

Variance within the physical outputs of athletes could be associated with the players perception of their current physical status post fatigue exposure or physical stress of the test. Psychological overall wellbeing scores suggested accumulative scores of the five categories were maintained for CWI, whereas following PR, scores worsened significantly at the same timepoint. Interestingly at 24 hrs PI overall wellbeing scores significantly improved following PR above baseline, comparatively following CWI a decline to below baseline was displayed. The effectiveness of CWI to improve perceptual recovery is well documented [38], and current results agree in terms of an immediate increase in overall wellbeing scores post CWI response. The inability however to maintain or return overall wellbeing scores at 24 hrs PI following CWI is interesting and may reflect that although a 'halt' on the effects of further biomechanical fatigue (eccentric hamstring strength) was achieved, perhaps one exposure of CWI fails to impact wellbeing continuously to the point of measurement at 24 hrs PI. It would be wise to consider that detrimental functional deficits of eccentric hamstring strength are reported to last up to 40–47 hrs post-fatigue [3], and at this timepoint eccentric hamstring strength had not returned to baseline measures in the current study, therefore impacting overall wellbeing scores. This may explain CWI overall wellbeing results, but not PR responses. Improvements in overall wellbeing scores at 24 hrs PI for PR may be associated with the increase noted in biomechanical measures of hamstring flexibility. Psychological response mechanisms to CWI may be dependent on dose i.e. number of exposures or representative of a placebo effect. Through linear regression analysis greater change for PR between timepoints immediately-post intervention-24 hrs PI for overall wellbeing was reported (CWI: $r = 0.13$; PR: $r = 0.78$) (Table 2). Collectively, observation of eccentric hamstring strength, isometric adductor strength, hamstring flexibility and overall wellbeing results suggest that group analysis may not optimally identify nor account for individual responses, which consequently indicate some measures are more advantageous to the practitioner than others in terms expediency. It may be inappropriate to employ a standardised approach of recovery strategies across a whole squad based on these directives.

To facilitate optimal recovery strategies, a single battery of tests is not yet recognised in practice that would best inform optimal individualised approaches for readiness to train/play. We agree that the method of applying multiple performance measures to quantify fatigue and intervention response is a resourceful approach providing an inclusive picture of the effects of recovery modalities across one cohort. Current findings advocate the application of multiple components of testing aligning to the recommendations in other literature [17]. This approach better expedites the understanding around optimal strategies to improve readiness for training/play. That said, not all tests best represent 'readiness to train' and consideration needs to be given to the choice of performance measure most beneficial to provide applied data that supports the ability to modify tailored recovery strategies in elite performance settings. Variables that impact dose-response in terms of multiple exposures, duration of cooling and temperature of CWI should be evaluated within practical settings, utilising appropriate fatigue monitoring measures with the intention to develop decision-making of sports medicine and performance practitioners for injury risk reduction and recovery strategies.

Some evidence is supportive in the application of cooling such as CWI, to enhance performance post-competitive fixture fatigue [12, 14], conversely agreement over the appropriate window to expose players to this modality is debateable. In many elite performance settings decision-making tools based around fitness-fatigue models whereby an ideal relationship between training and performance is developed [40] instigates a recovery phase which may include exposure to such modalities as CWI. It is important to note that participants were exposed to football specific training and quantified in the current study, not resistance training, highlighting the potential for different outcomes in performance response following CWI. Collectively findings may dictate when CWI is applied but insufficient evidence is available that considers periodisation around such schedules or variables that affect decision-making of this kind. In contemplation of the current results, whereby positive effects on some biomechanical parameters were seen after exposure to CWI (eccentric hamstring strength) and others after PR (hamstring flexibility), and type of training, future research may consider investigating the combination of both CWI followed by a window of PR, or multiple exposures of both interventions sequentially to develop optimal periodisation of CWI. This supports our earlier recommendations based on the current findings, of tailoring recovery strategies to the individual requirements of the player to optimise subsequent performances.

Whilst current findings provide insight for sports medicine and performance practitioners as to the effects of within-season exposure to CWI following fatiguing exercise on multi-measures of performance, there are limitations to this study which the authors recognise. It is impossible to blind players to the conditions (CWI/PR), a common acknowledgement within applied cryotherapy research, although investigators were blinded. Players had used CWI previously although were not accustomed to regular exposure within a scheduled recovery session. A follow up of measures would have been beneficial at up to 48 hrs representative of post-match fatigue effects [3] and to that effect we recommend further applied investigations on the application of CWI in elite sport environments.

CONCLUSIONS

Despite conflicting evidence regarding the effectiveness of CWI and PR, current findings suggest CWI may be useful to ameliorate potential deficits in eccentric hamstring strength that may optimise readiness to train/play in consideration of congested levels of exposure to fatiguing exercise during mid-competitive football seasons. A focus on individual response should be observed in future studies with judgement of cryotherapy effectiveness made through a battery of measures to determine factors that affect choice and periodisation of recovery strategies, applicable to a practical setting with individual athlete approaches in mind. Practitioners should be mindful of which measures best define functional performance and typical stresses which the athlete is exposed with an emphasis of psychological impacts on biomechanical measures. Variable responses to functional performance parameters indicate the need for further investigation of multiple CWI exposures over longer periods to account for the known temporal patterns of fatigue reported for hamstring function in elite football populations. Optimal periodisation of recovery strategies in response to fatigue on an individualised basis requires the implementation of appropriate methods of monitoring and analysis which may positively influence performance and readiness to train/play in elite performance settings.

Key Points Summary:

- Cold water immersion and passive recovery are common recovery modalities used within elite sport to reduce symptoms of post-exercise fatigue.
- Several performance indicators are used in sport to determine readiness to train/play yet the effects of recovery strategies on multi-measures are limited aiding confusion around optimal protocols for cold water immersion or passive recovery.
- Our results suggest cold water immersion may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite football settings.
- We suggest that multi-measures and individual analysis of recovery responses provide sports medicine and performance practitioners with direction on recovery strategies within mid-competitive season training cycles.

Conflict of Interest Declaration

No conflicts of interest.

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