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Research article

Training Load, Heart Rate Variability, Direct Current Potential and Elite Long Jump Performance Prior and during the 2016 Olympic Games

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Abstract
The primary objective of this investigation was to investigate the relationships between training load (TL), heart rate variability (HRV) and direct current potential (DC) with elite long jump performance prior to and during the 2016 Olympics Games. Sessional ratings of perceived exertion (sRPE), training duration, HRV and DC were collected from four elite athletes (26.4 ± 1.4 years, height 1.83 ± 0.05 m, weight 68.9 ± 5.0 kg) for a 16-week period in qualification for and competition at the 2016 Olympic Games. Acute and chronic TL, training stress balance and differential load were calculated with three different smoothing methods. These TL measures along with HRV and DC were examined for their relationship to intra-athlete performance using repeated measure correlations and linear mixed models. Successful compared to unsuccessful intra-athlete performances were characterised by a higher chronic TL ($p < 0.01$, $f^2 = 0.31$) but only when TL was exponentially smoothed. There were also negative correlations between HRV and performance ($r = -0.55$, $p < 0.01$) and HRV was significantly lower for more successful performances ($p < 0.01$, $f^2 = 0.19$). Exponentially smoothed chronic TL was significantly higher and HRV was significantly lower for successful intra-athlete performances prior and during the 2016 Olympics Games in an elite group of long jump athletes. Monitoring sRPE and HRV measures and manipulating TL prior to competition seems worthwhile for elite long jump athletes.

Key words: Monitoring, tapering, periodization

Introduction

Athletics competitions are comprised of different events including the long jump. As horizontal speed is highly correlated with long jump distance (r = 0.70-0.95) (Hay, 1993), training plans in the long jump are often very similar to sprinting (e.g., mainly comprised of acceleration, maximal velocity, resisted and assisted sprints, and resistance training) (Haugen et al., 2019) with actual technical jumping work normally being only ~10-15% of elite long jumper's programs (lead author's unpublished observations and communications with international level coaches). However, there is little research on the training practices and training load (TL) monitoring of Olympic level long jump athletes, especially when compared to elite endurance and team sports (McLaren et al., 2018; Mujika, 2017).

There are a number of different measures that can be used to monitor TL in athletics. These measures typically assess either internal (i.e., the athlete's psychophysiological response to training) or external TL (i.e., the actual work performed in training) (Impellizzeri et al., 2019). It is recommended that both these constructs are applied, and their relationships monitored to optimize the athlete's training (Coyne et al., 2018; Impellizzeri et al., 2019). However, there is no consensus on the most appropriate methods for measuring external TL in athletics with the majority of research in this area focusing on internal TL or non-TL outcome measures (e.g., sprinting tests, counter movement jump) to monitor adaptations to training (Cristina-Souza et al., 2019; Haugen et al., 2019; Jimenez-Reyes et al., 2016; Suzuki et al., 2006). From this research, the most common internal TL measure was session ratings of perceived exertion (sRPE) which are also recommended as a primary TL intensity measure in team sports and used widely in endurance sports (Drew and Finch, 2016; McLaren et al., 2018; Mujika, 2017). There appears to be a relationship between sRPE-TL (the product of sRPE and session duration) (Foster et al., 2021) and performance in the sprints (Suzuki et al., 2006) where sRPE-TL using Bannister's model predicted performance in an elite Japanese 400-m sprinter. In regards to monitoring tools that can be used with sRPE-TL, the acute-to-chronic workload ratio (Hulin et al., 2014) has been the most popular in many coaching circles, although there seems to be significant statistical concerns with its use (Impellizzeri et al., 2020). Alternatives to the acute-to-chronic workload ratio include the training stress balance (TSB) metric (Allen and Coggan, 2010), which is represented by the chronic minus the acute TL, and differential load (Lazarus et al., 2017), which is an exponential smoothing of week-to-week rate of change in TL. Both of these measures have become more common in TL monitoring research. For instance, in one recent investigation on elite weightlifting (which, like the long jump, is a similar high neuromuscular demand sport) prior to a 2016 Olympic qualification competition, the volatility of sRPE-TL TSB was significantly lower for successful performances compared to unsuccessful performances (Coyne et al., 2020b).

Another item of interest when monitoring TL is the debate over the most appropriate smoothing method for TL data (Coyne et al., 2018; Williams et al., 2016). It has been

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suggested that simple moving averages (SMA) do not account for variations in how athletes accumulate TL or accurately represent the physiological gain or decay of "fitness" and "fatigue" (Menaspà, 2017; Williams et al., 2016). Due to these concerns, exponentially weighted moving averages (EWMA) have been proposed to be a superior alternative (Menaspà, 2017; Williams et al., 2016). However, like SMA, EWMA also has some conceptual issues with the set time constants typically used being problematic if athletes have individual "fitness" and "fatigue" gain and decay rates (Coyne et al., 2018). To compound this issue, there are also two different EWMA calculation methods predominately presented in the scientific literature (Lazarus et al., 2017; Williams et al., 2016). All these different calculation methods (SMA, EWMA variations) produce different values for the TL data, and there have been conflicting results as to which smoothing method produces TL metrics that have superior relationships to performance (Coyne et al., 2020b; 2021).

It also seems common for practitioners to combine TL monitoring with athlete readiness measures that aid in acute decision-making on an athlete's training (Coyne et al., 2018). Athlete readiness measures are measures that can infer, or are associated with, an athlete's ability to train or perform in competition (Cullen et al., 2020). Two athlete readiness measures that have been studied in elite and college-level athletics have been heart rate variability (HRV) and direct current potential (DC) (Berkoff et al., 2007; Peterson, 2018). HRV is the variability between successive heart beats (RR interval) and is considered an indicator of the autonomic nervous system (Buchheit, 2014). Less researched is DC, which is measured through electrodes placed on the scalp or the forehead and thenar eminence and has been suggested to be an indicator of central nervous system status, is defined as very slow brainwave activity (0-0.5 Hz) and appears to be correlated with electroencephalography measures (Coyne et al., 2020a; Valenzuela et al., 2020). The autonomic and central nervous system status of athletes seems to be worthwhile for athletics coaches to be aware of to inform training (Buchheit, 2014; Peterson, 2018). Although HRV has been more studied in endurance and team sports and may also be more applicable as measures in these sports (Buchheit, 2014), in the studies assessing HRV and DC in athletics, Berkoff et al (Berkoff et al., 2007) found no difference in HRV variables of power- (e.g., sprint, long jump) or aerobic-based (e.g., 1500 m, steeplechase) athletes at the 2004 United States Track and Field Olympic trials. Meanwhile, in another study, Peterson determined that the RR interval square root of the mean squared differences (RMSSD) and DC could predict performance in NCAA Division 1 sprint competitions (Peterson, 2018). This result aligns with current recommendations for RMSSD to be the primary variable for HRV analysis (Buchheit, 2014; Plews et al., 2013). However, practitioners should be aware that there may not be a positive relationship between RMSSD and competition performance in elite athletes, which is different and even opposite to national or well-trained athletes (Plews et al., 2013; 2017). Regarding DC, the authors were unable to find any recommendations for monitoring this measure in athletes despite recent publications examining DC's measurement characteristics (Coyne et al., 2020a; Valenzuela et al., 2020).

In light of the scant research on elite long jump TL monitoring and the inability to identify the effects of training without precise quantification of TL (Mujika, 2017); further investigation in this area is justified. Therefore, the first purpose of this study was to provide descriptive data of sRPE-TL, HRV, and DC from an elite cohort of long jump athletes prior and during Olympic competition. The second purpose of this study was to investigate correlations between TL, HRV and DC with competition performance and determine if differences exist in these measures for intra-athlete successful and unsuccessful performances. Based on previous research examining sRPE-TL and competition performance (Coyne et al., 2020b; Coyne et al., 2021; Suzuki et al., 2006), we hypothesized that there would be positive correlations between sRPE-TL and intra-athlete performance and significant differences in sRPE-TL values between intra-athlete successful and unsuccessful performances. Due to the debate over the different TL smoothing methods, the final purpose of this study was to examine the three main smoothing methods used in previous literature to add to the evidence base for practitioners.

Methods

Experimental Approach to the Problem

This investigation was a retrospective observational study. The sRPE-TL, HRV and DC data were collected from the athletes for 16-weeks prior to and during the 2016 Olympic Games. This data collection period was based on athlete availability. Repeated measure correlations between the different measures were examined as well as their relationship with performance. Differences in the TL, HRV and DC of successful and unsuccessful performances were also investigated with linear mixed models.

Participants

This study comprised four elite international level athletes from the same national team and in the same training squad. The participants were four male long jumpers (athletes A, B, C and D, age 25 ± 1 year, height 182.5 ± 4.5cm, weight 68.9 ± 5.0kg, long jump personal best 8.22 ± 0.10m). All athletes participated in the 2016 Olympic Games except for athlete D (who was the first alternate for the Olympic squad). This cohort included medallists at the 2015 World Outdoor Championships and 2016 World Indoor Championships. All participants were informed of the benefits and risks of the investigation and all data for this study were collected within the athletes' training environment as part of the national team's requirements of their athletes. The data was released de-identified from the respective National Olympic Committee. Approval for this investigation was granted by the University Human Ethics Committee (Approval #19521) and conforms to the *Code of Ethics of the World Medical Association* (Declaration of Helsinki).

Procedures

Training load data as the product of sRPE (in this paper defined as the rating of perceived exertion for the complete training session by the athlete (Foster et al., 2021)) and session duration (Foster et al., 2001) were collected from both technical (i.e., sprint/jump) and non-technical (i.e., strength/power, corrective or recovery/regeneration) sessions and included competition loads. Alongside the total weekly TL and week-to-week change in TL, the following variables were calculated daily: i) acute TL (7-day average), ii) chronic TL (21-day average); iii) TSB (Allen and Coggan, 2010) and, iv) differential load (Lazarus et al., 2017) using established methods. These variables are presented as SMA, EWMA as per Williams et al. (EWMA-W) (2016) and EWMA as per Lazarus et al. (EWMA-L) (2017). The acute and chronic periods were set at 7- and 21-days. Differential load was also assessed using 7- and 21-day exponential decays. The period length determination was based on the typical training micro-mesocycle combination employed by the head coach in this investigation (Coyne et al., 2018). This was typically a three-week mesocycle with a "moderate, "hard", "easy" loading pattern; although there were differences in how the head coach applied this with the athletes. Microcycles were generally comprised of two training sessions/day alternated with one training session/day for the first 6 days of the microcycle and a complete rest day on the 7th day. On the days that comprised two training sessions/day, commonly athletes would perform technical training (e.g., acceleration, maximal velocity, resisted and assisted sprints; jumping variations, plyometrics) in the morning followed by a mixture of technical training and non-technical strength/power and assistance exercises (e.g., Olympic lifts, squat, deadlift, hamstring exercises) in the afternoon. On the days that comprised one training session/day, this typically had a regenerative focus with lower-level aerobic exercise (e.g., tempo work) combined with mobility and injury prevention exercises. Based on previous research examining sRPE-TL and performance (Coyne et al., 2020b) and elite coaching practice prior to competition in athletics (Ritchie et al., 2017), TSB was assessed as: i) absolute values (i.e., the value on the day of the competition); ii) the value 21-days prior to competition subtracted from the absolute value (CH21); and, iii) the volatility (standard deviation) of values in the last 21 days prior to competition (VOL21).

Heart rate variability and DC were assessed using Omegawave® (Omegawave Oy, Espoo, Finland) which appears to have adequate reliability and sensitivity as a measurement device (Coyne et al., 2020a; Parrado et al., 2010; Valenzuela et al., 2020). As recommended by the manufacturer, athletes self-administered the HRV/DC assessment in a supine position 15-30 minutes after waking and before ingesting food or liquid in the morning before training. The data was then exported from the Omegawave® system for analysis. Respiration rate was not controlled during measures. The HRV variables analysed were a) the natural logarithm of RMSSD (LnRMSSD), b) LnRMSSD averaged over 7-days (Ln rMSSD-7), c) the coefficient of variation of LnRMSSD-7 (LnRMSSD-7%CV) and d) the ratio between LnRMSSD and R-R intervals over 7-days (LnRMSSD:RR-7) (Plews et al., 2013; 2017). The LnRMSSD:RR values have been presented as multiplicative of 10^{-3} for ease of interpretation (Plews et al., 2017). DC was assessed as a) the value on each day and b) averaged over 7-days (DC-7) to theoretically reduce noise similar to the rationale with HRV (Buchheit, 2014). It was at the athlete's discretion if they recorded their HRV/DC measurements on prescribed rest days and if the athletes were not able to achieve 3 HRV/DC recordings over a rolling 7-day period, these data points were removed from analysis (Plews et al., 2017). In this study, this HRV/DC data removal represented 14% of the total training data points.

The percentage of training burdened by injury/illness compared to total training time was also considered (Coyne et al., 2020b). This percentage was based on any injury or illness that affected an athlete's training (e.g., a hamstring injury may have limited maximal speed training) or required medical intervention (Coyne et al., 2021). If athletes were absent from training, sRPE-TL was recorded as zero to enable continuous calculations. Lastly, each individual performance was assigned a score according to World Athletics' ranking rules which accounts for result, wind, level of competition, placing and allows for comparison between events. More details on how these scores are calculated can be found in at https://www.worldathletics.org/world-ranking-rules/track-field-events. Individual performances were then converted into z-scores for each athlete (i.e., intra-, not inter-, athlete performance z-scores). After the repeated measure correlations, performances were allocated into either a successful (better than average or z-score >0.2) or unsuccessful group (worse than average performances or z-score <-0.2) (Coyne et al., 2020b; 2021).

Statistical Analysis

Statistical analyses were performed using statistical software (R statistics packages: *lmerTest, rmcorr, and performance;* https://www.r-project.org) or purposefully designed Excel spreadsheets (Microsoft Corporation, Washington, U.S.). All data were analysed as mean ± standard deviation (SD). The alpha level for significance for all tests was defined as $p \leq 0.05$. Repeated measure correlation analyses (Bakdash and Marusich, 2019) with 95% confidence intervals were used to determine the relationship both between the TL, HRV and DC measures with intra-athlete performance. These correlations were interpreted as per the recommendations of Hopkins et al (Hopkins et al., 2009). *R-z* transformations were also applied to establish if there were significant differences in correlations of sRPE-TL calculated with the three different moving averages with performance. The individual correlations between LnRMSSD and RR interval for each athlete were also calculated (Plews et al., 2013). Linear mixed models with the athlete as the random intercept were then used to assess differences in sRPE-TL, HRV and DC variables as dependent variables between successful and unsuccessful intra-athlete performances (Coyne et al., 2021). All models were checked for a) linearity, b) residual independence, and c) residual normality. Effect sizes of differences from the models (marginal f^2) (Aiken and West, 1991) were then calculated and interpreted as trivial (<0.02), small (0.02-0.14), moderate (0.15-0.34) and large

(>0.35) (Cohen, 1992).

Results

A total of 463 training sessions and 31 competitions (athlete A = 8, B = 6, C = 7, D = 7) from the 16-week investigation period were included in this analysis. There were 2 performances excluded from the competition total where no legal jump was recorded. The time series of Chronic TL, TSB and LnRMSSD-7 along with intra-athlete performance z-scores for athletes A-D are presented in Figure 1. The average total sRPE-TL per session was 341 ± 357 AU. The average weekly total sRPE-TL was 1633 ± 692 AU before competition and 2400 ± 1060 AU three weeks prior to competition; representing a 32% decrease in total weekly TL. Technical training (e.g., technical sprinting, jumping and derivatives) comprised 55.9 ± 43.9% of sRPE-TL compared to non-technical training (e.g., strength, corrective, rehabilitation or aerobic exercise). The percentage of training burdened by some form of injury or illness throughout the investigation for each athlete was A = 79%, B = 38%, C = 69%, and D = 35%.

The repeated measure correlations between the sRPE-TL variables and intra-athlete performance z-scores with *r-z* transformations comparing the different smoothing methods are presented in Table 1. There was no significant correlation between training burdened by injury or illness in the last 21 days prior to competition and performance in this investigation (r = 0.15 [-0.23, 0.49], p = 0.42). The repeated measure correlations between HRV/DC variables and intra-athlete performance z-scores are presented in Table 2. The correlations between LnRMSSD and the RR interval for each athlete are displayed in Figure 2.

The sRPE-TL overall values (i.e., across the 16-week investigation period) and differences between successful and unsuccessful performance groups are presented in Table 3. There was not a significant difference and trivial effect size in the training burdened by injury or illness in the last 21 days prior to competition between successful and unsuccessful performance groups (56.4 ± 33.4% vs. 44.6 ± 31.1%, p = 0.41, f^2 = 0.02). The HRV and DC overall values and differences between successful and unsuccessful performance groups are presented in Table 4.

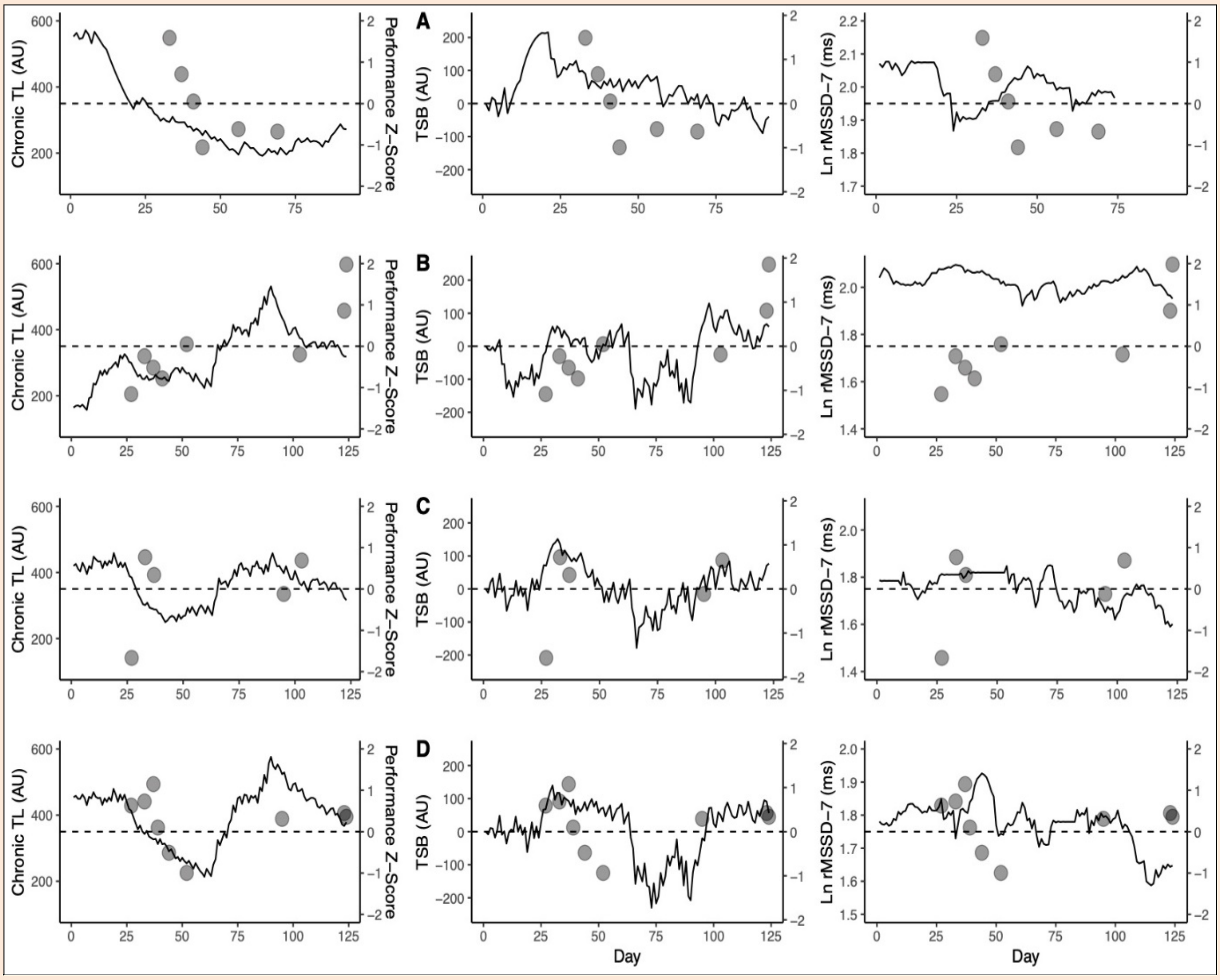

Figure 1. A time series of chronic training load, training stress balance, heart rate variability and performances (as z-scores) for four elite international long jump athletes prior and during the 2016 Olympic Games. The chronic training load, training stress balance and heart rate variability time series are indicated by the solid line whereas the performances (as z-scores) are indicated by the circular points. *TL – training load, TSB – training stress balance, AU – arbitrary units, LnRMSSD-7 - natural logarithm of the square of the mean sum of the squared differences between R-R intervals averaged over 7 days, ms – milliseconds.*

Table 1. Repeated measures correlations between different training load variables with competitive performance for four elite international long jump athletes in a 16-week period that included the qualification for and competition at the 2016 Olympic Games.

	SMA		EWMA-W			EWMA-L			
	r [95% CI]	p	r [95% CI]	p	SM r-z p	r [95% CI]	p	SM r-z p	EWMA-W r-z p
sRPE Training Load Variables									
Total week TL	0.06 [-0.35, 0.46]	0.74	-	-	-	-	-	-	-
Week-to-week TL change	-0.13 [-0.51, 0.29]	0.53	-	-	-	-	-	-	-
Acute TL	0.06 [-0.35, 0.46]	0.74	0.09 [-0.32, 0.47]	0.67	0.95	0.11 [-0.31, 0.49]	0.61	0.90	0.95
Chronic TL	0.15 [-0.27, 0.52]	0.46	0.16 [-0.26, 0.53]	0.44	0.97	0.29 [-0.13, 0.62]	0.16	0.64	0.66
TSB	0.08 [-0.34, 0.47]	0.71	0.20 [-0.22, 0.56]	0.32	0.68	0.25 [-0.17, 0.59]	0.22	0.56	0.86
TSB VOL21	-0.27 [-0.85, 0.61]	0.48	0.19 [-0.23, 0.55]	0.35	0.39	0.15 [-0.27, 0.52]	0.47	0.43	0.88
TSB CH21	0.23 [-0.63, 0.84]	0.55	0.06 [-0.35, 0.45]	0.76	0.75	0.11 [-0.31, 0.49]	0.60	0.82	0.85
DIFF 7-day	-	-	-0.21 [-0.56, 0.22]	0.32	-	-0.15 [-0.52, 0.27]	0.46	-	0.86
DIFF 21-day	-	-	-0.15 [-0.52, 0.27]	0.46	-	-0.19 [-0.55, 0.24]	0.36	-	0.92

SMA – simple moving average, EWMA-W – exponentially weighted moving averages as per Williams et al. (2016), EWMA-L - exponentially weighted moving averages as per Lazarus et al. (2017), TL – training load, TSB – training stress balance, DIFF – differential load, VOL21 - the volatility (standard deviation) of values in the last 21 days prior to competition , CH21 - the value 21 days prior to competition subtracted from the value on the day of the competition, r – correlation coefficient; CI – confidence interval.

Table 2. Repeated measures correlations between different heart rate variability and direct current potential variables with competitive performance for four elite international long jump athletes in a 16-week period that included the qualification for and competition at the 2016 Olympic Games.

	r [95% CI]	p
LnRMSSD	-0.46 [-0.76, -0.01]	0.03*
LnRMSSD %CV	0.41 [0.00, 0.71]	0.05*
R-R interval	-0.17 [-0.58, 0.31]	0.46
LnRMSSD:RR	-0.28 [-0.65, 0.21]	0.23
LnRMSSD-7	-0.55 [-0.79, -0.17]	<0.01**
LnRMSSD:RR-7	-0.01 [-0.43, 0.42]	0.97
DC	0.09 [-0.40, 0.55]	0.69
DC-7	0.26 [-0.22, 0.64]	0.26

LnRMSSD - natural logarithm of the square of the mean sum of the squared differences between R-R intervals, LnRMSSD %CV - LnRMSSD coefficient of variation, LnRMSSD:RR - LnRMSSD to R-R interval ratio, LnRMSSD-7 – LnRMSSD averaged over 7 days, LnRMSSD:RR-7 - LnRMSSD:RR averaged over 7 days, DC – direct current potential, DC-7 – direct current potential averaged over 7 days, r – correlation coefficient; CI – confidence interval, * - p <0.05.

Table 3. The overall average values and values for successful and unsuccessful performances in different training load variables for four elite international long jump athletes in a 16-week period that included the qualification for and competition at the 2016 Olympic Games.

		OVERALL	SUCCESSFUL PERFORMANCES	UNSUCCESSFUL PERFORMANCES	p	f^2	Effect size
	Total week TL	2369 ± 1120	1766 ± 894	1369 ± 432	0.20	0.08	Small
	Week-to-week TL change	-50.5 ± 1144	-508 ± 875	-315 ± 676	0.56	0.02	Small
SMA	**Acute TL**	338 ± 160	252 ± 127	196 ± 61.8	0.19	0.08	Small
	Chronic TL	334 ± 117	332 ± 107	268 ± 79.6	0.19	0.06	Small
	TSB	6.11 ±128	80.0 ± 86.8	72.5 ± 58.0	0.75	0.00	Trivial
	TSB VOL21	93.4 ± 40.8	80.5 ± 25.3	53.9 ± 9.21	0.13	0.37	Large
	TSB CH21	-19.2 ± 194	15.5 ± 167	-50.0 ± 172	0.60	0.04	Small
EWMA-W	**Acute TL**	341 ± 159	242 ± 85.2	191 ± 55.8	0.11	0.12	Small
	Chronic TL	346 ± 116	304 ± 91.5	236 ± 61.2	0.07	0.14	Small
	TSB	5.08 ±128	61.2 ± 36.6	45.3 ± 26.0	0.39	0.03	Small
	TSB VOL21	66.0 ± 24.4	63.4 ± 17.8	52.0 ± 18.2	0.14	0.16	Moderate
	TSB CH21	1.04 ± 118	32.3 ± 127	43.6 ± 86.6	0.34	0.01	Trivial
	DIFF 7-day	-69.8 ± 811	-364 ± 626	-259 ± 511	0.68	0.01	Trivial
	DIFF 21-day	-107 ± 563	-319 ± 416	-246 ± 210	0.62	0.01	Trivial
EWMA-L	**Acute TL**	343 ± 134	273 ± 95.6	215 ± 60.3	0.11	0.11	Small
	Chronic TL	350 ± 93.0	348 ± 64.8	267 ± 53.6	<0.01**	0.31	Moderate
	TSB	7.29 ± 77.4	75.2 ± 37.5	52.2 ± 33.5	0.21	0.07	Small
	TSB VOL21	47.9 ± 22.0	45.4 ± 15.7	39.1 ± 17.9	0.33	0.04	Small
	TSB CH21	4.72 ± 109	54.5 ± 94.7	43.5 ± 79.3	0.91	0.00	Trivial
	DIFF 7-day	-86.8 ± 652	-321 ± 522	-256 ± 330	0.79	0.00	Trivial
	DIFF 21-day	-155 ± 521	-333 ± 430	-256 ± 209	0.37	0.02	Small

SMA – simple moving average, EWMA-W – exponentially weighted moving averages as per Williams et al. (2016), EWMA-L - exponentially weighted moving averages as per Lazarus et al. (2017), TL – training load, TSB – training stress balance, DIFF – differential load, VOL21 - the volatility (standard deviation) of values in the last 21 days prior to competition, CH21 - the value 21 days prior to competition subtracted from the value on the day of the competition. * - p<0.05, f^2 – Cohen's marginal effect size.

Table 4. The overall average values and values for successful and unsuccessful performances in different heart rate variability and direct current potential variables for four elite international long jump athletes in a 16-week period that included the qualification for and competition at the 2016 Olympic Games.

	OVERALL	*SUCCESSFUL PERFORMANCES*	*UNSUCCESSFUL PERFORMANCES*	*p*	*f²*	*Effect size*
LnRMSSD	1.83 ± 0.22	1.80 ± 0.26	1.99 ± 0.12	0.06	0.20	Moderate
LnRMSSD %CV	8.04 ± 4.80	9.38 ± 6.60	4.71 ± 3.37	0.11	0.08	Small
RR	1000 ± 167	1034 ± 92.7	1091 ± 116	0.32	0.05	Small
LnRMSSD:RR ($x10^{-3}$)	1.86 ± 0.24	1.75 ± 0.25	1.83 ± 0.12	0.37	0.05	Small
LnRMSSD-7	1.84 ± 0.16	1.81 ± 0.13	1.99 ± 0.13	<0.01**	0.19	Moderate
LnRMSSD:RR-7 ($x10^{-3}$)	1.86 ± 0.16	1.81 ± 0.06	1.77 ± 0.13	0.59	0.01	Trivial
DC	11.8 ± 15.1	19.3 ± 9.03	19.5 ± 10.7	0.71	0.01	Trivial
DC-7	11.3 ± 11.2	15.4 ± 7.48	16.9 ± 7.51	0.48	0.01	Trivial

LnRMSSD - natural logarithm of the square of the mean sum of the squared differences between R-R intervals, LnRMSSD %CV - LnRMSSD coefficient of variation, LnRMSSD:RR - LnRMSSD to R-R interval ratio, LnRMSSD-7 – LnRMSSD averaged over 7 days, LnRMSSD:RR-7 - LnRMSSD:RR averaged over 7 days, DC – direct current potential, DC-7 – direct current potential averaged over 7 days, * - $p<0.05$, f^2 – Cohen's marginal effect size.

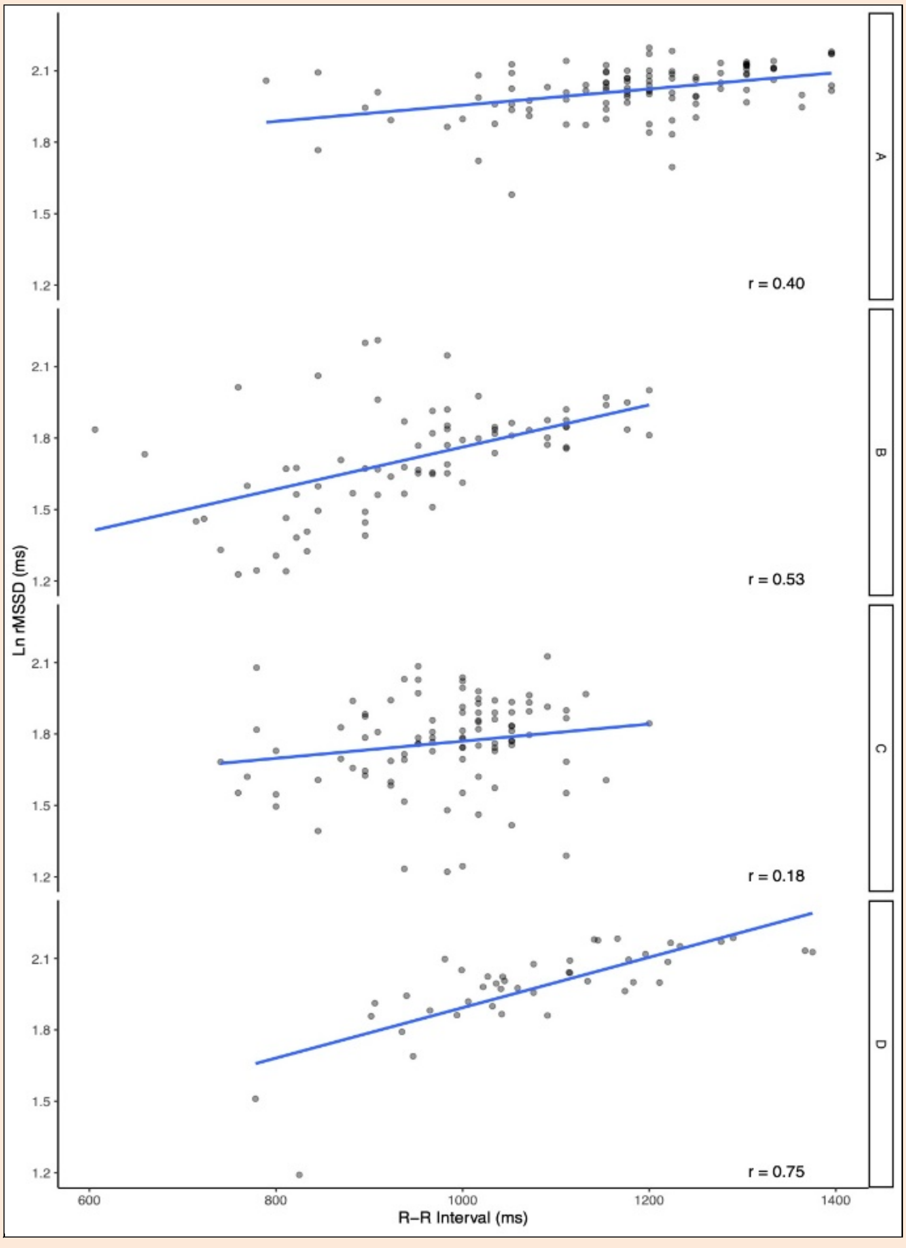

Figure 2. The relationship between the natural logarithm of the square of the mean sum of the squared differences between R-R intervals (LnRMSSD) and R-R interval length in four elite international long jump athletes prior and during the 2016 Olympic Games. *LnRMSSD - natural logarithm of the square of the mean sum of the squared differences between R-R intervals, ms – milliseconds.*

Discussion

This seems to be the first investigation to detail and compare values of sRPE-TL, HRV and DC in elite long jump athletes and also the first investigation to compare these measures with competition performance at and in qualification for an Olympic Games. Considering the first purpose of this study, practitioners may be able to use this investigation's average weekly sRPE-TL three weeks prior to competition (~2400 AU), at competition (~1600 AU), the relative change between the two (~30% reduction in TL), along with the TSB and TSB CH21 to help design training programs and tapers for long jump competitions.

The second purpose of this study was to investigate the relationships between the sRPE-TL, HRV and DC measures used in this investigation and competition performance as well as differences in these measures between successful and unsuccessful performances. All correlations between sRPE-TL and performance were trivial or small. A higher chronic TL when calculated using EWMA-L was also the only significant difference between successful and unsuccessful groups in sRPE-TL with a moderate effect size ($p < 0.01$, $f^2 = 0.31$); which supports our second hypothesis. When further comparing the smoothing methods across chronic TL, there was also a small effect size between successful and non-successful performances when smoothed with EWMA-W ($p = 0.07$, $f^2 = 0.14$) and with a SMA ($p = 0.19$, $f^2 = 0.06$). These results are of interest and having adequate levels of chronic TL in a taper may be important to maintain any required physiological qualities developed in training (e.g., sprinting speed) for competition. This result also seems to reinforce the suggestion that any change in TL metrics like TSB should always be interpreted in relation to the chronic TL of an athlete (Gabbett, 2018). It is also somewhat interesting that in this study successful performances' TSB tended to be higher than unsuccessful performances across all smoothing calculation methods. Although there were only small effect sizes in these differences between successful and unsuccessful performances, increasing TSB before competition would seem desirable for coaches and athletes. However, although external TL reductions common to tapers in athletics (Ritchie et al., 2017) should naturally increase TSB, it is worthwhile for practitioners to consider that when using sRPE measures, TSB will also be influenced by the athlete's perception of any training. As such, we hypothesize that also reducing cognitive work (e.g., less technique modifications or video analysis of sprinting technique) and modifying coaching feedback (e.g., more frequent positive reinforcement) closer to competition, which are common practice in elite athletics coaches (Ritchie et al., 2017), may further augment external TL decreases during the taper period for an athlete.

Regarding HRV/DC and their relationship to performance, a lower HRV (LnRMSSD-7) was significantly correlated with performance ($r = -0.55$, $p < 0.01$) and was also significantly lower for the successful performance group with moderate effect size ($p < 0.01$, $f^2 = 0.19$). This is similar to previous reports from Plews et al. (2013; 2017). As there were trivial differences between performance groups in LnRMSSD:RR-7 and little evidence for trivial correlations between LnRMSSD and RR interval in the athletes (which Plews et al. 2017) has suggested may explain a negative relationship between HRV and performance), we hypothesize that there is an increased requirement of sympathetic "fight or flight" activity, indicated by lower HRV, necessary for successful performance by elite athletes in major competitions. Further, we suggest these changes in HRV prior to competition are also likely not training related and may be a natural function of an elite athlete's autonomic nervous system as they prepare for major competitions, where outcomes have significant consequences on their future life. This hypothesis may be supported by recent research in female soccer that found HRV was significantly reduced before more important matches, due to nervousness and anxiety, compared with less important matches (Ayuso-Moreno et al., 2020). It would seem important for practitioners to use context around an athlete's TL changes and competition schedule to be able to distinguish when decreases in RMSSD may be indicative of an elite athlete being in the final stages of a competition taper versus autonomic over-reaching or over-training during a preparation training period. In contrast to HRV, there were no significant correlations or differences between successful and unsuccessful performances with any of the DC variables. However, given the results of previous research on DC (Peterson, 2018; Valenzuela et al., 2020), more research is warranted on DC as a marker of readiness in athletes and its ability to indicate the central nervous system status of an individual.

The final purpose of this investigation was to add to the evidence base for practitioners wanting to determine the optimal method to smooth TL data with. Based upon an the results of this study EWMA smoothing of sRPE-TL may have been more sensitive to performance in this group of athletes and adds to the support for this calculation method. It may also be worthwhile considering whether exponentially smoothing physiological athlete readiness measures like HRV and DC to more heavily weight the most recent daily measures may be more beneficial than using SMA (which is the current method) for future research.

There are a number of potential limitations with this study. The first is the usefulness of monitoring HRV for the long jump is debatable as heart rate measures may not accurately reflect athlete adaptations in high neuromuscular sports (Buchheit, 2014). This may also have impacted the utility of sRPE in this investigation considering its conceptual basis is derived from agreement with heart rate (Borg, 1998). There is also some evidence that orthostatic HRV measures (supine to standing) may be more suited to team sport performance than supine HRV measures, which were used in this investigation (Ravé and Fortrat, 2016). However, it is unknown if this is similar in high neuromuscular demand sports like long jump, the time demands are also much greater with orthostatic tests (Ravé and Fortrat, 2016) (which is a feasibility concern when dealing with Olympic-level athletes) and orthostatic measures were not consistent with the manufacturer recommendations for the measurement device used in this investigation (Omegawave®). Another potential limitation related to the use of Omegawave® in this investigation is this device does not measure electroencephalography, which is the reference standard for quantifying DC (Valenzuela et al., 2020), however an electroencephalography device is much less practical for regular use with athletes. Despite these factors, there were significant differences in HRV and sRPE-TL variables between successful and unsuccessful performances in this investigation. The second potential limitation was all athletes followed a training program designed by the same coach and although this standardised TL to some degree (e.g., athletes had different training durations at times and rated sessions differently based on their experience in said sessions), other coaches may use different training and taper methods that would give different responses prior to competition (Ritchie et al., 2017). Further, a third limitation is the use of total session duration as a volume factor in sRPE-TL calculations, which may be misleading considering the intermittent high-intensity nature of elite long jump training. Although preferred over alternate volume measures like distance in this study, we would suggest external TL measures (e.g., global positioning system and accelerometry data) should be used to complement sRPE-TL in the future on studies involving long jumpers. The last potential limitation is the low number of athletes in the investigation. However almost all research on this calibre of athlete (i.e., Olympians) in an individual sport will have this issue (Plews et al., 2017) and given the number of repeated performance measures per athlete in this study, this should be considered as a strength of the investigation when compared to previous research.

Conclusion

Practitioners may be able to use the descriptive TL values including the comparison between average and competition weekly TL and TSB to help prepare elite long jump athletes for competition. Due to the differing correlations between TL, HRV and DC measures, practitioners should employ valid TL and athlete readiness measures to gain better understandings of an athlete's response to training and readiness to perform. Deliberately modifying training to have adequate levels of chronic TL and increase TSB based on sRPE before competition seems worthwhile for improving performance. Practitioners should also be aware of a potentially negative relationship between HRV and competition performance in elite athletes (which may be different to recreational or well-trained athletes) with this possibly being a natural function of an elite athlete preparing for a major competition. Lastly, it may be more appropriate to use EWMA to smooth sRPE-TL data.

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Key points

- It seems worthwhile for practitioners to purposefully modify training to have adequate levels of chronic training load and increase training stress balance in elite long jump athletes.
- There may be negative relationship between heart rate variability and competition performance in elite athletes.
- Exponentially weighted moving averages may be more appropriate than simple moving averages to smooth training load data.

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