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# Is the Endurance Standardized $ACWR_{HMLD}$ or the Underlying Acute and Chronic Components Related to Injuries?

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**Featured Application: Seasonal analysis of the intensive team training and competition periods for non-contact injuries showed a correlation with pre-season endurance diagnostics, particularly individual lactate thresholds. Individual endurance performance levels should therefore always be taken into account when quantitatively assessing the intensive parts of training and competition periods. The chronic component of the ACWR in conjunction with endurance capacity appears to be a particularly sensitive indicator in the two weeks prior to an injury. Therefore, even during seasonal periods with large load fluctuations, e.g., due to the competition calendar, attention should be paid to constant weekly load management.**

**Abstract:** Acute (AW) and chronic (CW) workload imbalances, including their ratio (ACWR), are largely associated with increased injury risk. However, the inclusion of personal endurance performance (EP) in this calculation as a means of improving accuracy has been neglected in previous studies. The aim of this longitudinal observational study was to evaluate the relevance of the high metabolic load distance ($ACWR_{HMLD}$) to EP in relation to non-contact injuries. Twenty-three German male first division soccer players (age: 24.5 ± 3.5 years; $VO_{2max}$: 53.7 ± 4.9 mL/min/kg; v4: 15.2 ± 0.9 km/h) were analyzed. Eleven players with non-contact injuries were identified and matched with players without any injuries within the same time interval. Players were monitored using GPS and LPS tracking to calculate $ACWR_{HMLD}$ on a daily basis over the course of one competitive season. Relationships between different endurance performance parameters (v2, v4, $v_{LT}$, $VO_{2max}$) and the $ACWR_{HMLD}$, AW, CW were established for statistical analysis. An area under the curve analysis (AUC) was performed. Based on the four weeks preceding the non-contact injuries, the CW, especially for the last two weeks before the injury, proved to be the most suitable parameter to estimate the risk of injury. The highest significant AUC value (0.81, 95% CI: 0.59–1.00) was calculated for the CW (last week before injury) in relation to the $v_{LT}$ (suitable cut-off: 0.04 km; sensitivity: 78%, specificity: 80%). With regard to the injury rate, the $ACWR_{HMLD}$ seems to be the most appropriate method of calculation, especially for CW related to EP ($v_{LT}$). The sole use of ACWR, AW, and CW is not recommended.

**Keywords:** soccer; workload; prevention; training; match

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**Citation:** Marshall, R.P.; Schulze, S.; Droste, J.-N.; Riepenhof, H.; Delank, K.-S.; Kurz, E.; Schwesig, R. Is the Endurance Standardized $ACWR_{HMLD}$ or the Underlying Acute and Chronic Components Related to Injuries? *Appl. Sci.* **2024**, *14*, 9427. https://doi.org/10.3390/app14209427

Received: 11 September 2024
Revised: 9 October 2024
Accepted: 11 October 2024
Published: 16 October 2024



## 1. Introduction

Soccer requires a high number of different skills and demands on a high level comparable with other team sports. Sprints, high-speed running, acceleration, shooting, and jumping performance are just as important as endurance, technical, or tactical skills. For this reason, a detailed and sufficient analysis of load and stress data (training, match) and an effective link between them could be important to improve the match performance and avoid possible non-contact injuries. Technological developments in recent years have provided access to a wide range of performance-related markers. In professional soccer, local positioning system (LPS), global positioning system (GPS), and inertial measurement unit (IMU) technologies are routinely used to quantify workload. LPS and GPS quantify distances covered in different speed zones (e.g., HSRD) or changes in velocity completed (e.g., ACC), while IMU sensors allow the estimation of the mechanical workload during training.

To quantify internal training and match load, the session rate of perceived exertion (sRPE) has been adopted to monitor sustained loads and avoid overtraining [1]. Together with the fitness-fatigue model of physical performance, it can be used to describe an athlete's readiness for sustained exercise. In this context, the acute- (load over the last seven days, fatigue) to-chronic (load over the last 28 days, fitness) workload ratio (ACWR) has been established and is commonly used to manage and adjust the training process [2]. This approach and the associated widespread and used recommendation by Gabbett [3] regarding a suggested range (0.8–1.3) between acute and chronic workload has two major weaknesses. Firstly, this approach does not take into account metric load parameters (e.g., high-speed running distance, HSRD). Secondly, it completely ignores the resilience of the players, which is an even more serious shortcoming. For this reason, this concept has already been questioned by other scientists without, however, offering any new concepts [4]. The need for a more personalized approach has already been highlighted before [5].

With regard to the first point, Staunton et al. [6] calculated the workload and the ACWR based on time (exercise duration), intensity (e.g., accelerations, ACC (external), RPE (internal)), and volume (e.g., high-speed running distance, HSRD) metrics related to the amount of physical stress during exercise [6]. It is well known that an imbalance between acute and chronic workload is largely associated with a higher incidence of injury and peak performance [7–10].

Most ACWR calculations use the sRPE [11], which concurrently combines both the subjective (physiological stress tolerated) and objective (session time) components and is easy to adopt. From a mechanical point of view, external load metrics such as total distance and HSRD or ACC may better quantify or represent the sustained demands. Another useful approach to monitor intensity in professional soccer is the metabolic power concept [12]. The high metabolic load distance (HMLD) corresponds to the distance covered at a speed of >5.5 m/s (>25.5 W/kg) with a change in velocity at $\geq$2 m/s$^{-2}$ [13,14]. Although the metabolic power concept does not fully capture the internal load and only broadly represents the external load [15], the ratio of its acute and chronic results may be useful in identifying players at risk of non-contact injuries. In this context and in view of the weaknesses mentioned above, it is essential and a further development of the approaches described (sRPE, $ACWR_{HMLD}$) to relate the physical load (ACWR, acute or chronic part) with the individual EP ($ACWR_{HMLD}$/EP) measured by several lactate thresholds (v2, v4, $v_{LT}$) or $VO_{2max}$.

Therefore, the main aim of this analysis was to evaluate the relationship between $ACWR_{HMLD}$/EP (including acute and chronic components) and non-contact injuries. According to several studies [8,16], we hypothesized that a high level of EP would allow higher loads to be tolerated, thereby favoring a reduction in the risk of injury.

## 2. Materials and Methods

### *2.1. Subjects*

Twenty-three male German first league soccer players (Table 1) were studied over the course of an entire season.

**Table 1.** Age and anthropometric characteristics of players depending on position. Values are given as mean ± standard deviation (SD). Maxima marked in bold.

| | Playing Positions | | | | Total (n = 23) |
|---|---|---|---|---|---|
| | GK (n = 3) | DF (n = 7) | MF (n = 8) | FW (n = 5) | |
| **Age** [years] | **28.7 ± 6.1** | 23.7 ± 2.8 | 24.3 ± 3.0 | 23.4 ± 1.9 | 24.5 ± 3.5 |
| **Height** [m] | **1.93 ± 0.03** | 1.86 ± 0.07 | 1.79 ± 0.03 | 1.83 ± 0.10 | 1.84 ± 0.08 |
| **Mass** [kg] | **89.1 ± 11.1** | 86.4 ± 7.6 | 74.9 ± 6.1 | 80.1 ± 10.1 | 81.4 ± 9.4 |
| **BMI** [kg/m$^2$] | 23.9 ± 2.4 | **25.0 ± 0.7** | 23.4 ± 1.5 | 23.9 ± 1.2 | 24.1 ± 1.5 |
| **Body fat** [%] | **12.2 ± 1.5** | 11.5 ± 3.1 | 12.0 ± 2.6 | 9.3 ± 1.8 | 11.3 ± 2.6 |

GK, goalkeepers; DF, defenders; MF, midfielders; FW, forwards.

The data collection was approved by the Ethics Committee of the Martin Luther University of Halle-Wittenberg (reference number: 2013-13), conformed to the Declaration of Helsinki [17], and met the ethical standards in the Sport and Exercise Science Research [18].

### *2.2. Injury Occurrence*

Only five players had no injuries (contact and non-contact) during the season. Eighteen injured players were divided as follows: n = 7 (contact + non-contact); n = 6 (contact only); n = 5 (non-contact only). Injuries in team sports can occur with or without the influence of another person. They are therefore classified as contact or non-contact injuries. However, the exact definition of non-contact injuries is controversial [19,20]. Following Walden et al. [21], we defined a non-contact injury as one that occurred without physical contact with another player. Contact injuries can be caused by contact with another person, a high-energy fall, or another form of collision. Non-contact injuries are usually considered preventable because they are usually associated with overstressed structures. Fourteen contact injuries occurred during the season. The 18 non-contact injuries were distributed among 11 players (defenders: n = 5; midfielders: n = 3; strikers: n = 3). Only the first non-contact injury of all 11 players was used for the statistical analysis. At the same time, these players were matched with 11 players (same position) without injuries during the same time period (4 weeks) before the injury.

Most of the non-contact injuries occurred in April (4), October (3), and November (3). Considering only the first incidence, these 11 injuries resulted in a total of 260 days of absence from team training or competition. Each of these 11 injuries occurred during a match. Of these 11 non-contact injuries, eight were muscle injuries (71% (5/7) between the 20th and 70th minute of the match; range: 18–88 minutes of match). A brief description of all 11 non-contact injuries is given below:

- Overloading of the tendon insertion (atraumatic, chronic),
- Overloading of the back (vertebral stress reaction; atraumatic, chronic),
- Muscle fiber tear of the quadriceps (traumatic),
- Neurogenic hypertension hamstrings (atraumatic, chronic),
- Muscle fiber tear of the thigh (traumatic),
- Hypertonus hip flexors/adductors (atraumatic, chronic),
- Muscle fiber tear of the hamstrings (traumatic),
- Muscle fiber tear of the hamstrings (traumatic),
- Low back pain (atraumatic, chronic),
- Myofascial strain of the quadriceps (traumatic),
- Adductor myofascial strain (traumatic).

### *2.3. Experimental Design and Injury Documentation*

At the beginning of the season, all players of the team were assessed for their endurance performance by means of lactate diagnostics and spiroergometry to determine the individual lactate thresholds and $VO_{2max}$. In addition, anthropometric and BIA examinations (parameters: height, mass, BMI, body fat) were performed. Load data were collected throughout the entire season (training and matches) using a GPS-based tracking system.

Musculoskeletal injuries and injury mechanisms were recorded consecutively by the medical staff [22]. In order to consider only serious non-contact injuries, non-contact injuries with at least 5 days of team-training absence from team training were included. To avoid correlated observations (in case of occurred re-injuries), the first injury was considered for the statistical analysis.

The following inclusion and exclusion criteria were used:

Inclusion criteria

- All players of the team registered for the 2020/2021 season.
- All players who have attended all training (or rehab) sessions of the men's team as an official team member.

Exclusion criteria

- Any player who has not been in the team for the whole season or who has left the team during the winter break (due to transfer or loan).

## 2.4. Measurement Systems

### 2.4.1. Bioelectrical Impedance Analysis (BIA)

A BIA system (InBody770, InBody USA, Cerritos, CA, USA) was used for body composition analyses. This is a hand-to-foot BIA that uses alternating currents that pass segmentally (extremities and trunk) or through the whole body [23].

### 2.4.2. Endurance Performance Diagnostics

Pre-season endurance tests were performed on a treadmill (quasar, h/p/cosmos, Traunstein, Germany). All players first completed a submaximal test protocol (8 km/h + 1.5 km/h; 3 min; 0° incline) with lactate measurement (Biosen C-Line, EKF Diagnostic, Barleben, Germany) until a lactate increase of 1.5 mmol/L per step was reached. The lactate threshold (LT) was then determined by interpolation [24,25].

Therefore, at first, the best fitting lactate-velocity regression function (f = La(v) (where La(v) is the value of La at a given running velocity v) and based on the function La(v)) was first determined. LT was defined as the velocity v at which the delta value of lactate (v + 1.5) and La(v) reached 1 mmol/L lactate for the first time (e.g., $La(v + 1.5) - La(v) = 1$).

After a short recovery period of 8 min (4 min walking, 4 min passive), a ramp test (start: $v_{LT}$; + 1 km/h per min; 0° incline) with respiratory gas evaluation (Metalyzer 3B, Cortex Medical, Leipzig, Germany) was performed until physical exhaustion.

### 2.4.3. Tracking

Seasonal external load data from team training were collected by using the Apex Pro system (sampling rates: GPS: 18 Hz, GNSS: 10 Hz, triaxial accelerometer: 952 Hz, gyroscope: 952 Hz, magnetometer: 10 Hz; STATSports Group Limited (Newry, North Ireland)). Team's home match data was optically analyzed by the Chiron Hego system (Chiron Hego, Cologne, Germany). Data from additional national-team camps and matches were provided by the respective national teams.

As defined in previous research [13], ACWR, originally developed as a training load metric, was calculated as the ratio of the mean high metabolic load distance (HMLD) of the last seven days to the mean HMLD of the last 28 days ($ACWR_{HMLD}$). $Acute_{HMLD}$ (average of the last 7 days) and $chronic_{HMLD}$ (average of the last 28 days) are therefore included in this parameter. Only the coupled ACWR was calculated, as the coupled and uncoupled ACWR calculations showed an almost perfect relationship [26].

The documented non-contact injuries were used to evaluate the predictive ability of $ACWR_{HMLD}$, AW, and CW. In a second step, the same calculation was performed for the EP-related parameters ($ACWR_{HMLD}$/EP, $AW_{HMLD}$/EP, $CW_{HMLD}$/EP). Weekly $ACWR_{HMLD}$ was used to compare and analyze seasonal changes in the training load of the athletes. Due to the significantly higher AUC values and for content reasons (dependency between load and EP), only the results of the second calculation are presented.

### *2.5. Statistics*

Data collection and analysis were performed using SPSS version 28.0 for Windows (IBM, Armonk, NY, USA). Descriptive statistics (mean, standard deviation, 95% confidence interval) were reported for selected parameters to describe the sample studied. Weekly $ACWR_{HMLD}$ over the last four weeks prior non-contact injury was calculated.

In an area under the curve analysis (AUC), the coordinates of the receiver operating characteristic (ROC) curves were used to determine appropriate assessment cut-off values. The cut-off values were determined by accumulating sensitivity and specificity (boundary condition: sensitivity > specificity) from the ROC curves. Based on the load-stress concept and the need to generate appropriate cut-off values, aerobic capacity had to be considered (v2, v4, $v_{LT}$, $VO_{2max}$ relative).

According to a sample size calculation, a review of the corresponding scientific literature showed that no other comparable study had performed a power analysis in order to estimate a suitable sample size. The only study to address this issue was Nobari et al. [27], who also conducted a literature search. They concluded that their sample size of n = 21 was sufficient to avoid a type II error. Overall, the sample sizes of the above studies ranged from 10 [28] to 37 [16].

## 3. Results

### *3.1. Endurance Performance (EP)*

Due to the markedly low number of load days provided by the GPS system for goalkeepers (87 ± 18) and their unique activity profile, particularly in terms of running demands, these players were excluded from further analyses. Figure 1a,b shows the results of an initial treadmill EP diagnostic using heart rate, lactate measurements, and spirometry stratified by playing position.

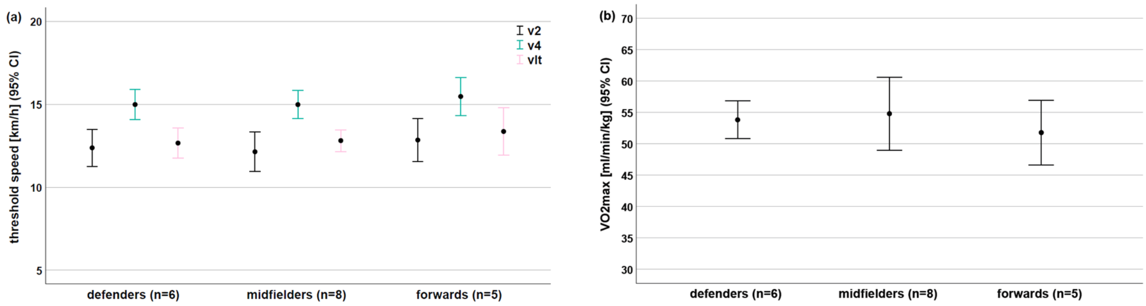


**Figure 1.** (**a**,**b**). Endurance performance characteristics of players depending on playing positions. Presented are different lactate threshold speeds (**a**) and the relative maximum oxygen uptake (**b**).

The entire team displayed an aerobic capacity measured using different lactate thresholds of 12.4 ± 1.33 km/h (Figure 1a, v2), 15.1 ± 1.04 km/h (Figure 1a, v4), and 12.8 ± 0.93 km/h (Figure 1a, $v_{lt}$). Regarding the relative maximum oxygen uptake (Figure 1b), all players ranged from 47 to 62 mL/min/kg (53.9 ± 4.64 mL/min/kg).

Table 2 summarizes the absolute and normalized HMLD results with the injury data and the averaged load days (training days + match days) of the field players by playing position.

**Table 2.** HMLD with seasonal injury and load data of players depending on position. Values are given as mean ± standard deviation with minimum and maximum. Maxima marked in bold.

| | Playing Positions | | | Total (n = 18) |
|---|---|---|---|---|
| | **DF (n = 7)** | **MF (n = 6)** | **FW (n = 5)** | |
| **Total HMLD per load day** [m] | 639 ± 84 (494–771) | 681 ± 147 (474–867) | **683 ± 77** (595–777) | 667 ± 109 (121–846) |
| **Total HMLD** [m/min] | 11.8 ± 1.2 (9.6–13.1) | 13.0 ± 2.1 (9.9–15.9) | **13.4 ± 1.0** (12.4–15.0) | 11.3 ± 3.9 (1.7–15.9) |
| **Match HMLD** [m] | 1.383 ± 253 (1.015–1.794) | **1.561 ± 303** (1.032–1.861) | 1.245 ± 335 (876–1.682) | 1.404 ± 304 (876–1.861) |
| **Match HMLD** [m/min] | 19.5 ± 1.9 (17.5–22.4) | 23.1 ± 3.2 (19.7–28.4) | **25.5 ± 1.8** (23.7–28.0) | 22.3 ± 3.4 (17.5–28.4) |
| **Injuries** [n]/**Injured players** [n] | 7/5 | 6/3 | 5/3 | 18/11 |
| **Injury days** | 36 ± 19 (10–62) | **66 ± 25** (46–94) | 32 ± 12 (19–43) | 43 ± 23 (10–94) |
| **Load days** | 164 ± 8 (152–176) | 152 ± 31 (77–174) | **165 ± 4** (160–170) | 160 ± 21 (77–176) |

HMLD, high metabolic load distance; DF, defenders; MF, midfielders; FW, forwards.

### *3.2. Load Related to Selected Endurance Parameters*

Depending on the week and the different EP parameters used, the chronic component of the ACWR showed the highest number (6/7, 86%) of significant AUC values (Table 3) within the first two weeks before the injury. The cut-off values, including sensitivity and specificity, are shown in Table 3.

**Table 3.** Cut-off values, sensitivity (%) and specificity (%) based on the receiver operating characteristic curves and calculated by adding sensitivity and specificity (boundary condition: sensitivity > specificity) reported for different endurance performance parameters. AUC with $p < 0.05$ marked in bold. Sens = sensitivity [%]; Spec = specificity [%].

| | Week before Injury | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | | | | **2** | | | | **3** | | | | **4** | | | |
| | **AUC** | ***p*** | **Cut-Off** | **Sens/Spec** | **AUC** | ***p*** | **Cut-Off** | **Sens/Spec** | **AUC** | ***p*** | **Cut-off** | **Sens/Spec** | **AUC** | ***p*** | **Cut-Off** | **Sens/Spec** |
| | **chronic** | | | | | | | | | | | | | | | |
| **v2** | **0.76** | **0.041** | 42.8 | **70/91** | **0.76** | **0.041** | 40.0 | 80/73 | 0.73 | 0.078 | 37.6 | 70/64 | 0.71 | 0.105 | 40.4 | 70/82 |
| **v4** | **0.76** | **0.041** | 34.5 | 70/82 | **0.78** | **0.029** | 31.8 | 80/73 | 0.74 | 0.067 | 30.7 | 70/64 | 0.69 | 0.139 | 33.3 | 70/73 |
| **$VO_{2max}$** | 0.77 | 0.050 | 9.70 | 78/70 | 0.76 | 0.055 | 9.4 | 67/70 | 0.71 | 0.131 | 8.5 | 78/60 | 0.66 | 0.236 | 8.5 | 67/50 |
| **$v_{LT}$** | **0.81** | **0.022** | **40.7** | **78/80** | **0.78** | **0.041** | 38.6 | **78/80** | 0.72 | 0.102 | 34.9 | 78/60 | 0.68 | 0.191 | 38.3 | 67/70 |
| | **acute** | | | | | | | | | | | | | | | |
| **v2** | 0.56 | 0.673 | 47.4 | 40/73 | 0.54 | 0.778 | 49.1 | 50/82 | 0.73 | 0.078 | 28.8 | **90/64** | 0.73 | 0.078 | 43.6 | 60/91 |
| **v4** | 0.57 | 0.573 | 33.7 | 60/54 | 0.53 | 0.833 | 33.7 | 50/54 | 0.73 | 0.078 | 23.5 | **90/64** | **0.76** | **0.049** | 36.1 | 60/91 |
| **$VO_{2max}$** | 0.63 | 0.348 | 10.0 | 67/70 | 0.58 | 0.540 | 9.80 | 67/70 | 0.70 | 0.142 | 6.50 | 89/60 | 0.73 | 0.86 | 10.2 | **67/90** |
| **$v_{LT}$** | 0.62 | 0.369 | 42.2 | 56/70 | 0.58 | 0.568 | 44.3 | 56/70 | 0.70 | 0.142 | 27.6 | 90/60 | 0.78 | 0.041 | 42.5 | **67/90** |
| | **ACWR** | | | | | | | | | | | | | | | |
| **v2** | 0.71 | 0.105 | 0.9 | 80/64 | 0.71 | 0.105 | 0.9 | 80/64 | 0.71 | 0.105 | 0.9 | 80/64 | 0.71 | 0.105 | 0.9 | 80/64 |
| **v4** | 0.46 | 0.751 | 0.08 | 50/64 | 0.38 | 0.360 | 0.07 | 50/45 | 0.71 | 0.113 | 0.06 | 70/73 | 0.73 | 0.078 | 0.07 | 80/64 |
| **$VO_{2max}$** | 0.48 | 0.903 | 0.02 | 56/40 | 0.41 | 0.488 | 0.02 | 67/30 | 0.71 | 0.131 | 0.02 | 78/60 | 0.68 | 0.178 | 0.02 | 67/60 |
| **$v_{LT}$** | 0.49 | 0.967 | 0.09 | 56/70 | 0.39 | 0.438 | 0.08 | 56/40 | 0.76 | 0.060 | 0.07 | **78/80** | 0.67 | 0.206 | 0.08 | 67/60 |

The most appropriate parameter "chronic related to $v_{LT}$—second HMLD week before injury" ranged between a minimum and maximum value of 21.2 m/min (sensitivity: 100%, specificity: 0%) and 55.9 m/min (sensitivity: 0%, specificity: 100%), respectively. A sensitivity of 100% was detected for 22.8 m/min (specificity: 10%). Conversely, a specificity of 100% was obtained for 44.4 m/min (sensitivity: 44%).

Separately (weeks before the injury, parameters: acute, chronic, ACWR) AUC analysis revealed marked differences between weeks and parameters (Figure 2a–d). The largest predictive ability was calculated for the relationship between the chronic component of the ACWR and the $v_{LT}$ in the first week before the injury (AUC = 0.81, $p = 0.022$; Figure 2d). All of the other AUCs did not exceed an amount of 0.80.

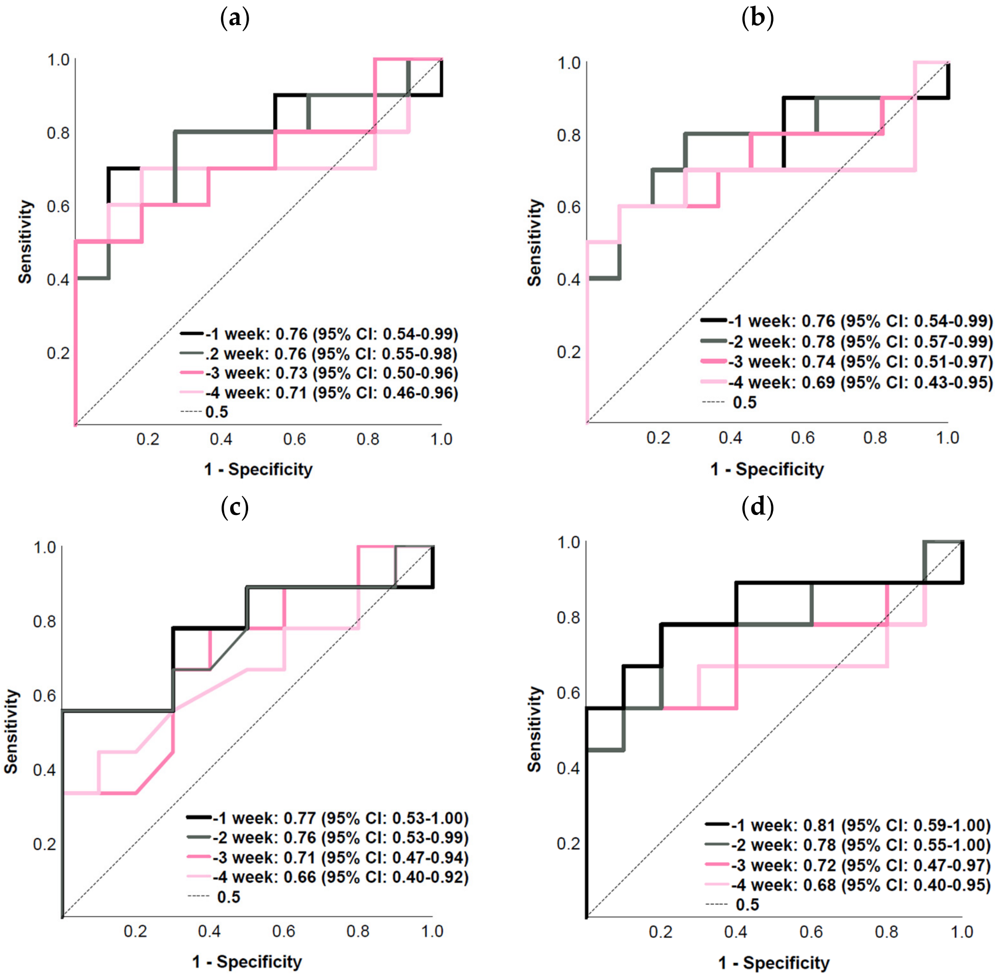


**Figure 2.** (**a**–**d**). Receiver operating characteristic curve (ROC) depending on week before the injury and different EP parameters related to the chronic component of ACWR. AUC values and 95% CI are reported. (**a**) chronic related to v2. (**b**) chronic related to v4. (**c**) chronic related to $VO_{2max.}$ (**d**) chronic related to $v_{LT}$.

## 4. Discussion

In this study, training and match load parameters were recorded (including HMLD) in first division soccer players over one season. By including velocity and acceleration to estimate workload and calculate ACWR, we compared players who sustained a non-contact injury with uninjured players. In addition, the workload parameters were related to the pre-season EP in order to interrelate workload (HMLD) and resilience as measured by EP (v2, v4, $v_{LT}$, $VO_{2max}$).

Based on the four weeks before the non-contact injuries, a sensitivity of 78% and a specificity of 80% were calculated for the relationship between the chronic component (CW) of ACWR in the first week before the injury and the $v_{LT}$. The observed accuracy for the v2 (CW, first week before the injury) was slightly (3%) higher (sensitivity: 70%, specificity: 91%). Apparently, only the CW of the ACWR is related to the occurrence of non-contact injuries.

It is important for soccer coaching, especially for the athletic coaches, to understand that the load must be assessed in relation to the EP level of the players, particularly the aerobic capacity. These findings are in line with several investigations [3,8,16], who stated that relatively higher body strength (lower limbs) and a high level of aerobic capacity are important factors for injury prevention. At the same time, these findings are in significant contrast to the widely used approach of calculating ACWR by training duration and the sRPE as an indicator for the internal training loads [3,6]. This is the first published suggestion based solely on objective load and stress data that takes into account individual aerobic capacity.

The aerobic capacity calculated by $VO_{2max}$ during EP diagnostics was lower in our cohort (53.7 ± 4.9 mL/min/kg) compared to other studies [29–31]. However, in agreement with previous studies, the injured players had a significantly lower $VO_{2max}$ than the matched uninjured players (53.2 ± 4.0 vs. 56.3 ± 6.5 mL/min/kg; d = 0.6). Various studies have reported and recommended $VO_{2max}$ values from 62 to 64 mL/min/kg to fulfill the aerobic capacity requirements for male professional soccer players [29,30]. It should be noted, however, that the endurance diagnostics in this study took place at the beginning of the pre-season. In line with this, Vasileios et al. [31] measured $VO_{2max}$ before and after two months of soccer training and reported values of 53.6 ± 7.7 mL/min/kg (before) and 64.4 ± 5.7 mL/min/kg (after) from soccer players of the first Greek division. The endurance performance data of the studied players were similar to those of German second and third division players, independent from playing position [32,33]. The importance of aerobic capacity for soccer performance has been widely documented. Moreover, Reinhardt et al. [34] showed that the threshold performance at v4 was highly correlated (r = 0.91) with the ability to recover. Therefore, the authors recommended 15.0 km/h (4.2 m/s) at the 4 mmol/L lactate threshold as a minimum endurance performance level [33] to cope with the demands of a competitive soccer season.

Compared to the match HMLD, the absolute and relative total HMLD recorded during the training sessions was significantly lower. This is due to the lower HMLD completed during the training sessions. However, the different relative HMLD magnitudes between the playing positions indicate that the training intensities adequately met the position-specific match demands. In a study of 18,131 individual match observations over two full competitive seasons, Spanish first and second division professional soccer players showed no absolute differences in HMLD between competitive levels [35]. On average, the first division players covered a HMLD of 2350 m per match, with the central midfielders covering the highest relative HMLD (29.3 m/min). The absolute match HMLD of our sample was significantly lower than that of the Spanish first division players, probably due to shorter playing times. In contrast, the highest relative match HMLD values were found for forwards (28.5 m/min).

In contrast to our approach, a study published by Gabbett [3] used the sRPE as an indicator of internal training loads. Although sRPE has been shown to be a valid and reproducible tool for assessing the internal load of moderate and hard training [36,37], there are also limitations to this parameter. It has been shown to change with time after exercise [38,39] and has difficulty in correctly assessing regenerative or low-intensity training [40]. Therefore, we decided to rely on an objective marker such as ACWR using HMLD in relation to EP.

From a coach's point of view, it is particularly interesting to analyze the pre-injury $ACWR_{HMLD}$ in order to anticipate injuries and reduce athletic absence from training. Only three injured players did not show an $ACWR_{HMLD}$ outside the range of Gabbett [3] more than 4 weeks before the injury. In particular, the two weeks prior to injury appear to be predictive of subsequent injury. Bowen et al. [9] also reported that changes in acute and chronic workload were associated with an increase in injury risk. They observed that the risk of injury in Premier League soccer players was associated with low chronic workloads (accelerations, decelerations, total distances) and that the non-contact injury risk was five to seven times higher when the ACWR values were increased (2.14–2.32) in the aforementioned variables.

## 5. Limitations

The first and main limitation of our study was the high number of missing data points during the data collection period. This was due to several external factors beyond our control (e.g., player transfers). As a result, the load days analyzed only reflect team training days with the GPS tracking system and not strength or individual training sessions. This type of data, however, is unlikely to have a significant impact on the overall HMLD distance. Nevertheless, the data presented most likely underestimated the actual training load of the players. It is also important to note that the distance and speed data collected throughout the whole season were based on different measurement systems. However, this was unavoidable in order to ensure that the data collected was as complete as possible. Furthermore, the number of events is fortunately (content consideration) very small (n = 11), which is a disadvantage for the statistical analysis. For these reasons, an external validation seems very reasonable to verify the reported results. Finally, this work only includes men, which is why the inclusion of female soccer players should also be considered in the future.

## 6. Conclusions

The main findings and practical applications of this work are:

- Do not use the sRPE as a subjective indicator of internal load. A more sufficient option is the HMLD as an objective indicator of internal load!
- It is extremely necessary to standardize the ACWR using the aerobic capacity. The isolated use of load parameters is insufficient.
- Based on these results, we recommend the $v_{LT}$ as a sufficient indicator for the aerobic capacity.
- The chronic component (CW) of the ACWR, especially in the last week before the injury, is more appropriate than the ACWR or the acute component (AW) of the ACWR.
- From a practical point of view, weekly analyses of the training load seem to be more appropriate than the usual 4-week period.

In summary, this work provides evidence for the need to further develop the metabolic load concept into a metabolic load resilience concept.

**Author Contributions:** Conceptualization, E.K., R.P.M., S.S. and R.S.; methodology, S.S., E.K., R.S. and J.-N.D.; formal analysis, K.-S.D., R.S. and H.R.; investigation, R.P.M. and R.S.; resources, R.P.M., H.R.; data curation, R.P.M., E.K.; writing—original draft preparation, E.K., S.S., R.S., J.-N.D. and K.-S.D.; writing—review and editing, S.S., R.S., R.P.M., H.R. and K.-S.D.; visualization, S.S.; supervision, S.S., R.P.M. and R.S.; project administration, R.P.M., K.-S.D. and H.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** The data collection was approved by the Ethics Committee of the Martin Luther University of Halle-Wittenberg (reference number: 2013-13), conformed to the Declaration of Helsinki and met the ethical standards in the Sport and Exercise Science Research.

**Informed Consent Statement:** Informed consent was obtained from all individual participants included in the study.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author. Data were obtained from [R.P.M.] and are available via [R.P.M.] with the permission of [RasenBallsport Leipzig GmbH].

**Acknowledgments:** The authors would like to thank the soccer players, as well as their coaches for their cooperation and outstanding efforts. We acknowledge the financial support of the Open Access Publication Fund of the Martin Luther University Halle-Wittenberg.

**Conflicts of Interest:** Authors Robert Percy Marshall, Jan-Niklas Droste and Helge Riepenhof were employed by the company RasenBallsport Leipzig GmbH. The remaining authors declare that the re-search was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References

1. Foster, C. Monitoring training in athletes with reference to overtraining syndrome. *Med. Sci. Sports Exerc.* **1998**, *30*, 1164–1168. [CrossRef] [PubMed]
2. Hulin, B.T.; Gabbett, T.J.; Caputi, P.; Lawson, D.W.; Sampson, J.A. Low chronic workload and the acute: Chronic workload ratio are more predictive of injury than between-match recovery time: A two-season prospective cohort study in elite rugby league players. *Br. J. Sports Med.* **2016**, *50*, 1008–1012. [CrossRef] [PubMed]
3. Gabbett, T.J. The training-injury prevention paradox: Should athletes be training smarter and harder? *Br. J. Sports Med.* **2016**, *50*, 273–280. [CrossRef] [PubMed]
4. Impellizzeri, F.M.; McCall, A.; Ward, P.; Bornn, L.; Coutts, A.J. Training Load and Its Role in Injury Prevention, Part 2: Conceptual and Methodologic Pitfalls. *J. Athl. Train.* **2020**, *55*, 893–901. [CrossRef]
5. Impellizzeri, F.M.; Menaspà, P.; Coutts, A.J.; Kalkhoven, J.; Menaspà, M.J. Training Load and Its Role in Injury Prevention, Part I: Back to the Future. *J. Athl. Train.* **2020**, *55*, 885–892. [CrossRef]
6. Staunton, C.A.; Abt, G.; Weaving, D.; Wundersitz, D.W.T. Misuse of the term 'load' in sport and exercise science. *J. Sci. Med. Sport* **2022**, *25*, 439–444. [CrossRef]
7. Gabbett, T.J.; Domrow, N. Relationships between training load, injury, and fitness in sub-elite collision sport athletes. *J. Sports Sci.* **2007**, *25*, 1507–1519. [CrossRef]
8. Gabbett, T.J.; Ullah, S. Relationship between running loads and soft-tissue injury in elite team sport athletes. *J. Strength Cond. Res.* **2012**, *26*, 953–960. [CrossRef]
9. Bowen, L.; Gross, A.S.; Gimpel, M.; Bruce-Low, S.; Li, F.X. Spikes in acute:chronic workload ratio (ACWR) associated with a 5-7 times greater injury rate in English Premier League football players: A comprehensive 3-year study. *Br. J. Sports Med.* **2020**, *54*, 731–738. [CrossRef]
10. Gabbett, T.J. Debunking the myths about training load, injury and performance: Empirical evidence, hot topics and recommendations for practitioners. *Br. J. Sports Med.* **2020**, *54*, 58–66. [CrossRef]
11. Andrade, R.; Wik, E.H.; Rebelo-Marques, A.; Blanch, P.; Whiteley, R.; Espregueira-Mendes, J.; Gabbett, T.J. Is the acute: Chronic workload ratio (ACWR) associated with risk of time-loss injury in professional team sports? A systematic review of methodology, variables and injury risk in practical situations. *Sports Med.* **2020**, *50*, 1613–1635. [CrossRef] [PubMed]
12. Osgnach, C.; Poser, S.; Bernardini, R.; Rinaldo, R.; di Prampero, P.E. Energy cost and metabolic power in elite soccer: A new match analysis approach. *Med. Sci. Sports Exerc.* **2010**, *42*, 170–178. [CrossRef] [PubMed]
13. Clemente, F.M.; Silva, R.; Chen, Y.S.; Aquino, R.; Moreira Praca, G.; Castellano, J.; Nobari, H.; Mendes, B.; Rosemann, T.; Knechtle, B. Accelerometry-workload indices concerning different levels of participation during congested fixture periods in professional soccer: A pilot study conducted over a full season. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1137. [CrossRef] [PubMed]
14. Guitart, M.; Casals, M.; Casamichana, D.; Cortes, J.; Valle, F.X.; Mc Call, A.; Cos, F.; Rodas, G. Use of GPS to measure external load and estimate the incidence of muscle injuries in men's football: A novel descriptive study. *PLoS ONE* **2022**, *17*, e0263494. [CrossRef]
15. Buchheit, M.; Simpson, B.M. Player-tracking technology: Half-full or half-empty glass? *Int. J. Sports Physiol. Perform.* **2017**, *12*, 235–241. [CrossRef]
16. Malone, S.; Owen, A.; Mendes, B.; Hughes, B.; Collins, K.; Gabbett, T.J. High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? *J. Sci. Med. Sport* **2018**, *21*, 257–262. [CrossRef]
17. Millum, J.; Wendler, D.; Emanuel, E.J. The 50th anniversary of the Declaration of Helsinki: Progress but many remaining challenges. *JAMA* **2013**, *310*, 2143–2144. [CrossRef]
18. Harriss, D.J.; Macsween, A.; Atkinson, G. Standards for ethics in sport and exercise science research: 2018 update. *Int. J. Sports Med.* **2017**, *38*, 1126–1131. [CrossRef]
19. Krosshaug, T.; Andersen, T.E.; Olsen, O.E.; Myklebust, G.; Bahr, R. Research approaches to describe the mechanisms of injuries in sport: Limitations and possibilities. *Br. J. Sports Med.* **2005**, *39*, 330–339. [CrossRef]
20. Marshall, S.W. Recommendations for defining and classifying anterior cruciate ligament injuries in epidemiologic studies. *J. Athl. Train.* **2010**, *45*, 516–518. [CrossRef]
21. Waldén, M.; Krosshaug, T.; Bjørneboe, J.; Andersen, T.E.; Faul, O.; Hägglund, M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *Br. J. Sports Med.* **2015**, *49*, 1452–1460. [CrossRef] [PubMed]
22. Fuller, C.W.; Ekstrand, J.; Junge, A.; Andersen, T.E.; Bahr, R.; Dvorak, J.; Hägglund, M.; McCrory, P.; Meeuwisse, W.H. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br. J. Sports Med.* **2006**, *40*, 193–201. [CrossRef] [PubMed]
23. Moon, J.R. Body composition in athletes and sports nutrition: An examination of the bioimpedance analysis technique. *Eur. J. Clin. Nutr.* **2013**, *67* (Suppl. S1), 54–59. [CrossRef] [PubMed]
24. Thoden, J.S.; Wilson, B.A.; MacDougall, J.D. Testing aerobic power. In *Physiological Testing of the Elite Athlete*; MacDougall, J.D., Wenger, H.A., Green, H.J., Eds.; Human Kinetics: Champaign, IL, USA, 1991; pp. 107–173.

25. Stöggl, T.L.; Blumkaitis, J.C.; Strepp, T.; Sareban, M.; Simon, P.; Neuberger, E.W.I.; Finkenzeller, T.; Nunes, N.; Aglas, L.; Haller, N. The Salzburg 10/7 HIIT shock cycle study: The effects of a 7-day high-intensity interval training shock microcycle with or without additional low-intensity training on endurance performance, well-being, stress and recovery in endurance trained athletes—Study protocol of a randomized controlled trial. *BMC Sports Sci. Med. Rehabil.* **2022**, *14*, 84. [CrossRef]
26. Gabbett, T.J.; Hulin, B.; Blanch, P.; Chapman, P.; Bailey, D. To couple or not to couple? For acute: Chronic workload ratios and injury risk, Does it really matter? *Int. J. Sports Med.* **2019**, *40*, 597–600. [CrossRef]
27. Nobari, H.; Mainer-Pardos, E.; Zamorano, A.D.; Bowman, T.G.; Clemente, F.M.; Perez-Gomez, J. Sprint variables are associated with the odds ratios of non-contact injuries in professional soccer players. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10417. [CrossRef]
28. Nathan, A.L.; Simpkin, A.J.; Moseley, S.; Turner, G.; Homer, M.; Redgrave, A.; Pedlar, C.R.; Burden, R. Increased oxidative stress in injured and Ill elite international olympic rowers. *Int. J. Sports Physiol. Perform.* **2020**, *15*, 625–631. [CrossRef]
29. Helgerud, J.; Rodas, G.; Kemi, O.J.; Hoff, J. Strength and endurance in elite football players. *Int. J. Sports Med.* **2011**, *32*, 677–682. [CrossRef]
30. Tonnessen, E.; Hem, E.; Leirstein, S.; Haugen, T.; Seiler, S. Maximal aerobic power characteristics of male professional soccer players, 1989–2012. *Int. J. Sports Physiol. Perform.* **2013**, *8*, 323–329. [CrossRef]
31. Vasileios, A.; Athanasios, S.; Antonios, S.; Nikos, G.; Giorgos, P. The increase of VO2max variation and the specific biochemical parameters in soccer players after a pre-season training program. *J. Phys. Educ. Sport.* **2018**, *18*, 686–694. [CrossRef]
32. Altmann, S.; Kuberczyk, M.; Ringhof, S.; Neumann, R.; Woll, A. Relationships between performance test and match-related physical performance parameters—A study in professional soccer players across three seasons. *Ger. J. Exerc. Sport Res.* **2018**, *48*, 218–227. [CrossRef]
33. Schwesig, R.; Schulze, S.; Reinhardt, L.; Laudner, K.G.; Delank, K.S.; Hermassi, S. Differences in player position running velocity at lactate thresholds among male professional german soccer players. *Front. Physiol.* **2019**, *10*, 886. [CrossRef] [PubMed]
34. Reinhardt, L.; Schulze, S.; Schwesig, R.; Kurz, E. Physical match performance in sub-elite soccer players—Introduction of a new index. *Int. J. Sports Med.* **2020**, *41*, 858–866. [CrossRef] [PubMed]
35. Garcia-Calvo, T.; Ponce-Bordon, J.C.; Pons, E.; Lopez Del Campo, R.; Resta, R.; Raya-Gonzalez, J. High metabolic load distance in professional soccer according to competitive level and playing positions. *PeerJ* **2022**, *10*, e13318. [CrossRef] [PubMed]
36. Ciolac, E.; Mantuani, S.; Neiva, C.; Veradi, C.; Pêssoa-Filho, D.; Pimenta, L. Rating of perceived exertion as a tool for prescribing and self regulating interval training: A pilot study. *Biol. Sport* **2015**, *32*, 103–138. [CrossRef]
37. Haddad, M.; Stylianides, G.; Djaoui, L.; Dellal, A.; Chamari, K. Session-RPE Method for Training Load Monitoring: Validity, Ecological Usefulness, and Influencing Factors. *Front. Neurosci.* **2017**, *11*, 612. [CrossRef]
38. Tibana, R.A.; de Sousa, N.M.F.; Cunha, G.V.; Prestes, J.; Fett, C.; Gabbett, T.J.; Voltarelli, F.A. Validity of Session Rating Perceived Exertion Method for Quantifying Internal Training Load during High-Intensity Functional Training. *Sports* **2018**, *6*, 68. [CrossRef]
39. Mann, R.H.; Williams, C.A.; Clift, B.C.; Barker, A.R. The Validation of Session Rating of Perceived Exertion for Quantifying Internal Training Load in Adolescent Distance Runners. *Int. J. Sports Physiol. Perform.* **2019**, *14*, 354–359. [CrossRef]
40. Inoue, A.; Dos Santos Bunn, P.; do Carmo, E.C.; Lattari, E.; da Silva, E.B. Internal Training Load Perceived by Athletes and Planned by Coaches: A Systematic Review and Meta-Analysis. *Sports Med. Open.* **2022**, *8*, 35. [CrossRef]