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Unlocking Male Youth Soccer Players' Peak Performance Potential: Exploring the Impact of Maturation, Age, and Physical Demands on Neuromuscular Injury Risk and Recovery Following Competitive Matchplay

Imanol Martin-Garetxana [1,2], Francisco Ayala [3], Mark De Ste Croix [4], Jon Larruskain [1], Josean Lekue [1] and Jonathan Hughes [5,*]

[1] Medical Services, Athletic Club, Barrio Garaioltza 147, 48196 Lezama, Bizkaia, Spain; i.martin@athletic-club.eus (I.M.-G.); j.larruskain@athletic-club.eus (J.L.); j.lekue@fundacionathleticclub.eus (J.L.)
[2] Department of Physiology, Faculty of Medicine and Nursing, University of the Basque Country (UPV/EHU), 48013 Bilbao, Bizkaia, Spain
[3] Department of Physical Activity and Sport, Faculty of Sport Sciences, University of Murcia, Campus San Javier, 30720 San Javier, Murcia, Spain; franciscoayalarodriguez@gmail.com
[4] School of Education and Science, University of Gloucestershire, Gloucester GL2 9HW, UK; mdestecroix@glos.ac.uk
[5] Youth Physical Development Centre, Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff CF5 2XJ, UK
* Correspondence: jdhughes@cardiffmet.ac.uk

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Abstract: This study investigated the 7-day recovery period post-soccer matches in elite male academy players. We analyzed changes in physical performance, stretch-shortening cycle capability, landing mechanics, muscle damage, and perceived well-being while also considering the influence of players' maturity status, chronological age, and physical demands on post-match responses. In a prospective, observational, mixed longitudinal study design, twenty-six players (U14 = 14 [age = 13.9 ± 0.2 y, and U16 = 12 [age = 15.1 ± 0.2 y]) undertook testing at baseline (1 h pre-match), immediately post-match (0 h), and 48-, 72-, 96-, and 120 h post-match for measures in creatine kinase (CK), urea (UR), CMJ height, 20 m sprint time, reactive strength index (RSI), leg stiffness (LS), landing mechanics, and perceived well-being. Players were also tested pre [168-h] and post the subsequent match. Results showed significant alterations 0 h post-match in CK (+71.3%), UR (+12.8%), CMJ height (−5.3%), 20 m sprint time (+3.8%), RSI (−9.6%), LS (−11.5%), and perceived well-being (−7.7%), with landing mechanics being unaffected. All parameters returned to baseline at 48 h, except for CK and UR, which remained elevated until 168 h. The players' initial scores influenced how they responded after the match during the week. In conclusion, coaches should focus on post-match strategies to enhance muscle recovery, especially for youth players with a lower training status, given the extended recovery period observed for muscle damage markers.

Keywords: football; fatigue; stretch-shorting cycle; adolescence; and team sports

1. Introduction

Some studies have reported that soccer can induce significant fatigue in young male players, leading to post-match changes in various aspects, such as reduced force production [1], lower performance in countermovement jumps (CMJ) [2–4], slower sprint times [5], and alterations in biochemical markers like creatine kinase (CK) and urea levels [5,6]. Additionally, players may experience a decline in psychometric well-being, including perceived muscle soreness [5]), which can persist for hours or even days. The findings of these studies, while not conclusive, suggest that, within 48 h after a soccer match, changes in neuromuscular capability, physical performance, biochemical levels, and psychometric state may vary. Some measures, such as CK, may show greater impairments compared to others like leg stiffness (LS) [7].

In most major European leagues, a typical competitive season in male academy soccer will run for approximately 8–9 months (August–April) and be divided into 2–3 blocks separated by a 2–4-week break occurring around school holidays. This competitive season is further divided into blocks comprised of 10–15 repeated microcycles lasting a week and structured into 2–4 training sessions during weekdays and a competitive match at weekends. Therefore, in each microcycle, male youth players are afforded a 6–7-day period to recover from the previous match and be ready to re-perform in the subsequent match. However, it is not known if this time between matches is sufficient to allow for full recovery. To our knowledge, only two studies have simultaneously described the acute effects elicited by soccer match-play and the time course of recovery in measures of neuromuscular capability, physical performance, and muscle damage [6,8] in youth players. In particular, de Hoyo et al. [8] observed that decrements in CMJ performance and meaningful increases in muscle damage persisted for 48 h post-match in elite youth male players. Further, Hughes et al. [6] found that both CK and urea levels remained significantly elevated compared to pre-game values for up to seven days following a soccer match in elite youth female players. This would indicate that 7 days between competitive matches is insufficient to allow for a return to physiological readiness to re-perform.

With a high proportion of locomotion activities in soccer requiring fast and forceful stretch-shortening cycle (SSC) actions and, therefore, a high frequency of eccentric muscle actions, this may in part explain the magnitude and time course of post-match responses [4,9]. Recently, in adult soccer players, a meta-analysis demonstrated statistically significant pooled correlations between very high-intensity running (>5.5 m·s^{-1}) and markers of muscle damage 24 h post-competitive match-play [10]. Whether external loads from the physical demands of match-play can measure or be used to predict and monitor youth players' physical responses to a soccer match are unknown as the evidence is scarce. de Hoyo et al. [8] reported male players who covered greater distances across a range of velocities (>14 km·h^{-1} to >21 km·h^{-1}) and performed greater numbers of accelerations (>3 m·s^{-2}) and decelerations (>2 m·s^{-2}) during match-play, demonstrated larger impairments in CMJ performance, and showed increased muscle damage. Further, intrinsic individual factors such as maturity status have also been proposed as a potential predictor of post-match fatigue response in youth players [4–7,9,11]. Few studies have explored interactions between maturity status and post-match fatigue on markers of neuromuscular capability (e.g., LS and reactive strength index [RSI]) and landing mechanics [5,7,9], physical performance (e.g., jump height and sprint time) [5,11], and muscle damage (e.g., CK and urea levels) [5,6].

Players who do not fully recover from soccer match-induced fatigue may find themselves in a vulnerable state, increasing their risk of injury or performing below their best in subsequent training sessions and matches [12]. Understanding the causes and recovery timeline of fatigue in youth players after competitive soccer matches can offer valuable insights in terms of both research and practical interventions. This knowledge has significant implications for enhancing sport performance and preventing injuries. Additionally, it can help determine whether (a) the current 6–7-day gap between consecutive competitions is adequate for preventing players from developing chronic, cumulative fatigue that could hinder their long-term athlete development; (b) coaching staff's typical weekly training load periodization, including one or two initial recovery and light sessions within the first 48–72 h post-match, followed by more intense training sessions later in the week (with a 24–48 h rest period before the next match), is effective.

The primary aim of this study is to document the extent and recovery timeline of various post-soccer match effects over a 7-day period in elite male academy youth soccer players. These effects include changes in physical performance, stretch-shortening cycle capability, landing mechanics, muscle damage, and perceived well-being. A secondary objective is to investigate whether the players' maturity status and chronological age influence their responses to these post-match measures. Additionally, the study seeks to determine whether the physical demands of the match impact the players' fatigue levels over the course of the 7-day period.

2. Materials and Methods

2.1. Sample Size Estimation

A priori statistical power analysis for repeated measures study design was performed based on data from Hughes et al. [6] to calculate the sample size needed to detect meaningful changes. A conservative approach was followed for the sample size estimation so that the lowest effect size reported in Hughes et al.'s study for the different age groups in a pairwise comparison for CK was selected, which was 0.45, considered to be small to moderate using Cohen's [13] criteria. With an alpha = 0.05, power = 0.95, number of groups = 2, and several measurements = 7, the projected sample size needed with this effect size (GPower 3.1) for each group was 12 participants.

2.2. Participants

A total of 72 male youth outfield soccer players from two chronological competition age groups (U14 [n = 34] and U16 [n = 38]) were recruited from a professional soccer club academy. Participants trained four times per week and played one competitive match per week (usually at the weekend) during the season. Exclusion criteria were (a) histories of neuromuscular diseases or serious musculoskeletal injuries specific to the shoulder, hip, knee, or ankle joints at the time of testing; (b) missing one testing, match play, and/or training session during the 7-day data collection phase; and (c) playing less than half of the total minutes of duration of a competitive match at each age group (U14 = 35 min and U16 = 40 min) [5]. Written informed consent was obtained from the players' parents and the children, with additional assent being provided by players. Players completed a health questionnaire before participating in the research. The study was approved by the institution's ethics committee and conformed to the Declaration of Helsinki regarding the use of human subjects. The final sample was 26 male youth soccer players (U14 = 14 [age = 13.9 $\pm$ 0.2 y, stature = 1.63 $\pm$ 0.07 m, body mass = 51 $\pm$ 0.9 kg and maturity offset = -0.5 ± 0.52] and U16 = 12 [age = 15.1 $\pm$ 0.2 y, stature = 1.76 $\pm$ 0.04 m, body mass = 63.7 $\pm$ 3.4 kg and maturity offset = 0.71 $\pm$ 0.33]). The mean match time played was 50.1 $\pm$ 13.7 min (match 1) and 48.6 $\pm$ 15.2 min (match 2) for the U14 and 69.3 $\pm$ 17.3 (match 1) and 61.9 $\pm$ 21.9 min (match 2) for the U16 (Supplementary Figure S1).

2.3. Experimental Design

A prospective, observational, mixed longitudinal (two-group and eight repeated measures) study design was used to address the aims of this study. In particular, all players were tested an hour prior to (baseline) and immediately 0 h (MD), 48 h (MD+2), 72 h (MD-4), 96 h (MD-3) and 120 h (MD-2) post-match-play for muscle damage (CK and UR), jump (CMJ–Abalakov height) and sprint (20 m time) performances, SSC capability (RSI and LS), landing mechanics (frontal plane projection angle [FPPA]), and perceived well-being. Players were also tested before (an hour prior [168 h post-match 1]) and after the following competitive soccer match (post-match 2), which was played 7 days after the initial match. A schematic representation of the experimental design is displayed in Figure 1. Soccer matches were played on outdoor natural grass pitches during the 2016 season (May). The day before both pre-match (1 and 2) testing sessions, the players were not exposed to any high-intensity exercises. Each weekly testing was carried out an hour prior to the start of the training session. The duration of each of the four weekly training sessions carried out by the teams was approximately 75 min. The coaching staff of the teams that participated in this study followed the same weekly training load prioritization scheme. In particular, the first post-match training session (+48 h [MD+2]) was considered, according to the coaches, as a recovery session, including tasks with low physical demands in terms of intensity and volume (e.g., light jogging, stretching, and core training). The successive sessions applied a progressive increase in their physical demands (e.g., different small-side games and plyometric training), with the session that was carried out 120 h post-match 1 (MD-2) being the most physically demanding.

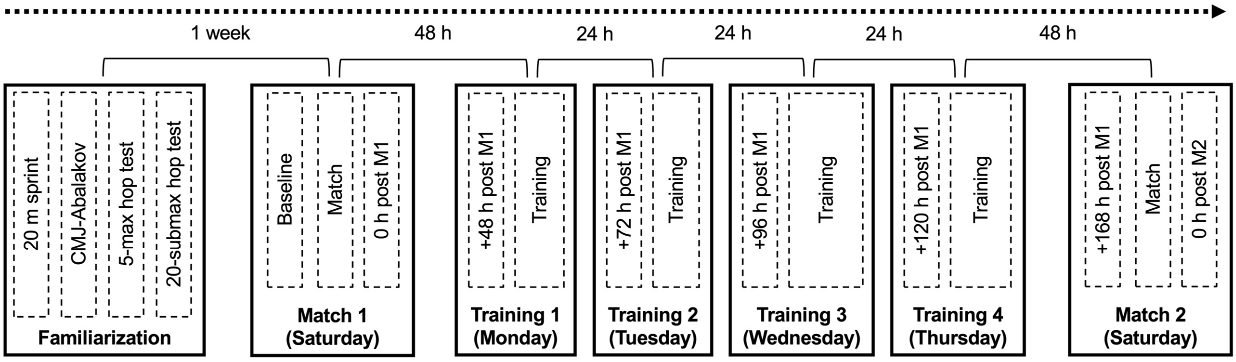

Figure 1. Schematic representation of the study design.

2.4. Testing Procedure

A week before the data collection phase, a 20 min familiarization session was conducted so that players could experience the physical tests (i.e., a 20 m sprint, a CMJ–Abalakov test [jump height and FPPA], 5 maximum hop tests [RSI], 20 sub-maximal bilateral hopping protocols [LS]) several times following a non-structured approach. During each pre- and post-match testing (apart from the 0 h post-match 1 and 2 testing in which no warm-up was performed), participants began by completing their regular warm-up, which lasted for approximately 15 min, consisting of moderate intensity self-selected running and dynamic stretching followed by 6–8 min of soccer-specific intensity activities (e.g., sprinting, jumping and landing, cutting, small-side games). All dependent variables (apart from the well-being questionnaire, which was filled in before the warm-up) were assessed immediately after the warm-up using a randomized "circuit-style" approach. Protocols and reliability for all tests have been described elsewhere [5,14,15].

2.5. Physical Demands

Player physical demand during both matches and the four weekly training sessions were recorded using a GPS unit (STATSports, Viper, Newry, Northern Ireland) integrating a 10 Hz GPS, a 100 Hz gyroscope, a 100 Hz tri-axial accelerometer, and s 100 Hz magnetometer. Thirty minutes before the warm-up, GPS units were switched on and placed outside [16]. Each player used the same pod throughout the experimental period to avoid interunit error. Data recorded by the GPS were downloaded and further analyzed by the STATSport Viper Software (https://pro.statsports.com/feature-focus-viper-readiness-train-app/, accessed on 18 June 2024). For each match and training session, the following time motion variables were recorded: (a) total distance covered, (b) distance covered at four different running speeds (low = <13 km·h^{-1}; moderate = 13 to 16 km·h^{-1}; high = 16 to 19 km·h^{-1} and sprint >19 km·h^{-1}), (c) the number of high-intensity acceleration actions (>2 m·s^{-2}), (d) the number of high-intensity decelerations actions (<−2 m·s^{-2}), and (e) the total match and session durations.

2.6. Statistical Analysis

Statistical analyses were performed using JASP software version 0.13.01 (Amsterdam, The Netherlands), the Statistical Package for Social Sciences (SPSS, v. 25.0 for Mac; SPSS Inc, Chicago, IL, USA), and an online spreadsheet (Hopkins, http://sportsci.org, accessed on 17 June 2023).

An examination of the data in the eight time points indicated that there were very few missing data (92 of 4032 total values were missing [2.3%]), with less than five percent missing for all variables; for many variables (16 out of 21), the proportion of missing data was zero. As there were few missing values (less than five percent for all variables), those values were considered missing at random. Consequently, GPS missing values were interpolated using a multiple imputation method, where a total of 5 imputations were inserted using different predictors, such as age, maturity offset [5,17], body mass index (BMI), and the rest of time motion measures collected from the GPS in the match. Finally, the missing value(s) of each variable was replaced by the data of that imputation, whose mean of the new variable (including the imputed data and those already presented) was closer to the mean of the raw variable (without the imputed values in it) if the predicted values were plausible.

Missing data in outcome variables were not interpolated using a multiple imputation method. Given the longitudinal nature of this study, missing values were replaced (a) by the baseline score (pre-match) only when they belonged to the 0 h post-match testing (intention to treat analysis) or (b) by the average of the participant´s scores obtained in the immediately prior and post-testing sessions.

Descriptive statistics were calculated for each variable separately by age group, including means and standard deviation (±SD).

Variables with only positive values (e.g., 20 m sprint time, CMJ–Abalakov height, LS, UR, and CK) were log-transformed to reduce bias because of the non-uniformity error. Perceived well-being data were analyzed as a percentage of the highest possible score. A separate two-way (time x age group [U14 vs. U16]) Bayesian repeated measures analysis of covariance (RM-ANCOVAs) was conducted to explore both intra and inter-subject differences in the effects elicited by soccer matches on the dependent variables. While time and age group were added as within- and between-subject factors, respectively, in each Bayesian RM-ANCOVA, the maturity offset was considered to be a covariable. Each Bayesian RM-ANCOVA test carried out was adjusted to the dependent variable baseline scores to minimize the regression to the mean phenomenon. In each of the models generated, the quantification of the relative degree of evidence for supporting the null hypothesis (H0 = no effect) or alternative hypothesis (H1 = relevant effect) was performed by means of the Bayesian factor (BF10). The Bayesian factor (BF10) was interpreted using the following previously suggested evidence categories [18]: <1/100 = extreme evidence for H0; from 1/100 to <1/30 = very strong evidence for H0; from 1/30 to <1/10 = strong evidence for H0; from 1/10 to <1/3 = moderate evidence for H0; from 1/3 to <1 anecdotical evidence for H0; from 1 to 3 = anecdotical evidence for H1; from >3 to 10 = moderate evidence for H1; from >10 to 30 = strong evidence for H1; from >30 to 100 = very strong evidence for H1; >100 extreme evidence for H1. Only those models that showed at least strong evidence for supporting H1 (BF10 > 10) with a percentage error < 0.1 were considered robust enough to describe the main effects, and a posterior post hoc analysis was then carried out. In the post hoc analysis, posterior odds were corrected for multiple testing by fixing to 0.5 the prior probability that the null hypothesis holds across all comparisons. For practical reasons, only pairwise differences between 0 h, 48 h, 72 h, 96 h, 120 h, and 168 h (pre-match 2) post-soccer match-play time periods relative to baseline (pre-match-play 1) were further inspected for statistical significance. Paired comparisons between post and pre-match 2 data and between post-match 1 and 2 time points were also carried out. The median and the 95% central CI of the posterior distribution of the standardized effect size (δ;) (i.e., the population version of Cohen d) were also calculated for each of the paired comparisons carried out. Magnitudes of the posterior distribution of the standardized effect size were classified as trivial (<0.2), small (>0.2–0.6), moderate (>0.6–1.2), large (>1.2–2.0), and very large (>2.0–4.0) [19].

For each paired comparison where a statistical significance was observed (BF10 > 10), its potential clinical relevance was explored using a non-clinical magnitude-based decisions (MBD) approach [20,21]. There are currently no cut-off scores in the literature for each dependent variable used in this study from which a change in their initial values might be considered clinically important in terms of sports performance and/or injury risk. Therefore, for each dependent variable, a pairwise difference was considered meaningful or clinically relevant (either positive or negative) when it exceeded the arbitrary value of 1.5 times (80–90% certainty) the magnitude of the standard error of the measurement (SEM) reported in previously published reliability studies [22]. Thus, the following cut-off scores were considered: 20 m sprint time = ±3% [14], CMJ–Abalakov = ±4.5% [23], LS = ±15% [15], and RSI = ±15% [15], and FPPA = ±7° [24]. The following cut-off scores were established for muscle damage and perceived well-being measures: CK = ±6% [6], UR = ±5% [25], and WB = 10% [26]. Probabilities and qualitative inferences of substantial effects were reported using the following standardized thresholds: most unlikely, <0.5%; very unlikely, 0.5–5%; unlikely, 5–25%; possibly, 25–75%; likely, 75–95%; very likely, 95–99.5%; and most likely, >99.5% [20].

A separate 2 (age group) × 6 (two matches and four training sessions) Bayesian analysis of variance was also conducted to explore the differences in physical demands between age groups and matches. All time motion variables were log-transformed to reduce bias due to non-uniformity error. Only those models that showed at least strong evidence for supporting H1 (BF10 > 10) with a percentage error of <0.1 were considered robust enough to describe the main effects, and a posterior post hoc analysis was then carried out.

For each of the paired comparisons in which both statistically significant (BF10 > 10) and clinically relevant differences (i.e., higher than 1.5 times the SEM) were documented, the associations between its pre- vs. post-match changes and all the measures of match and training physical demands taken until that time point, as well as the player´s maturity offset and baseline scores, were explored through Bayesian correlations (Pearson's rho). Magnitudes of correlations were assessed using the following scale of thresholds: <0.3 = negligible, 0.3–0.5 = low, >0.5–07 = moderate, >0.7–0.9 = high and >0.90 = very high [27]. Furthermore, in these paired comparisons, a Bayesian linear regression model was built with those measures that reported significant (BF10 > 10) and at least moderate (Pearson's rho > 0.5) correlation scores with the observed pre-post-match changes (predictors), with the latter being used as the dependent variable.

3. Results

Table 1 displays descriptive (mean and SD) baseline (pre-match 1) and post-match-play data (0 h, 48 h, 72 h, 96 h, 120 h, 168 h, and post-match 2) of muscle damage, sprint and jump performance, SCC capability, landing mechanics, and perceived well-being measures separately by age group.

Table 1. Pre- and post-match-play descriptive statistics (mean ± standard deviation) of the muscle damage, physical performance, SCC capability, landing mechanics, and perceived well-being measures separately by age group.

	Baseline (pre M1)	**0 h Post M1**	**48 h Post M1**	**72 h Post M1**	**96 h Post M1**	**120 h Post M1**	**168 h Post M1**	**Post M2**
Muscle damage								
Creatine kinase ($I \cdot Ul^{-1}$)								
■ U14	241.2 ± 192.4	388.9 ± 343.4	249.9 ± 210.1	350.6 ± 195.9	285 ± 179.7	319.5 ± 157.3	188.9 ± 76.4	336.2 ± 202.3
■ U16	327.3 ± 304.1	580.5 ± 403.5	427.9 ± 480.5	453.3 ± 445.2	464.5 ± 507.1	433.4 ± 278.8	260.2 ± 206.4	548.5 ± 352.8
Urea (mmol/L)								
■ U14	4.92 ± 0.95	5.93 ± 2.21	5.16 ± 1.63	5.57 ± 1.46	6.23 ± 1.95	6.58 ± 1.43	5.25 ± 1.07	6.14 ± 1.37
■ U16	4.95 ± 1.26	5.2 ± 1.7	6.01 ± 1.65	6.23 ± 0.93	6.09 ± 1.19	5.91 ± 1.67	5.27 ± 1.59	5.93 ± 1.44
Physical performance								
CMJ–Abalakov height (cm)								
■ U14	36.9 ± 3.3	35.1 ± 4.8	36.9 ± 3.9	36.4 ± 3.9	36.4 ± 3.4	36.4 ± 3.9	38.3 ± 4	36.3 ± 4.2
■ U16	42.9 ± 3.5	40.6 ± 3.3	41.7 ± 4	41.6 ± 3.6	41.4 ± 3.7	42.7 ± 3.6	43.1 ± 3.7	43 ± 3.6
20 m Sprint time (s)								
■ U14	3.27 ± 0.11	3.38 ± 0.16	3.24 ± 0.09	3.22 ± 0.11	3.19 ± 0.08	3.21 ± 0.08	3.23 ± 0.1	3.3 ± 0.1
■ U16	3.11 ± 0.11	3.21 ± 0.18	3.09 ± 0.12	3.12 ± 0.09	3.06 ± 0.09	3.04 ± 0.09	3.13 ± 0.1	3.14 ± 0.08
SCC capability								
Leg stiffness ($kN \cdot m^{-1}$)								
■ U14	29.6 ± 3.3	27.2 ± 2.7	27.9 ± 3.8	27.4 ± 3.8	26.2 ± 1.9	26.2 ± 3.1	26.4 ± 2.7	26.7 ± 4.7
■ U16	28.8 ± 4.5	24.7 ± 4.8	29.5 ± 8.4	26 ± 3.9	26.7 ± 3.6	27.2 ± 5.8	26.3 ± 4.7	26.7 ± 3.9
Reactive strength index								
■ U14	1.07 ± 0.26	0.96 ± 0.28	1.06 ± 0.29	1.04 ± 0.26	0.99 ± 0.32	1.01 ± 0.32	1.05 ± 0.31	0.92 ± 0.29
■ U16	0.95 ± 0.22	0.89 ± 0.26	1.05 ± 0.23	1.01 ± 0.31	1.08 ± 0.27	1.11 ± 0.37	1.15 ± 0.31	1.05 ± 0.27
Landing mechanics								
FPPA (right) (°)								
■ U14	22.7 ± 16.6	28.8 ± 25.5	18.3 ± 12.7	10.6 ± 13.4	9.9 ± 15.9	16.3 ± 12.1	12.9 ± 15.9	20.9 ± 15.7
■ U16	11.6 ± 10.4	17.2 ± 7.6	17.6 ± 12.1	15.3 ± 12.3	13.2 ± 16.9	14.1 ± 16.9	11.7 ± 12.9	15.5 ± 16.8
FPPA (left) (°)								
■ U14	12.9 ± 11.4	18.6 ± 15.8	14.1 ± 12.2	14.7 ± 12.8	12.9 ± 14.9	10.2 ± 10.6	17.1 ± 13.2	17.7 ± 14.6
■ U16	12.9 ± 10	11.9 ± 12	11.4 ± 12.8	7.9 ± 11.2	13.9 ± 8.2	10 ± 12.7	12.7 ± 9.7	13.8 ± 12.7
Perceived well-being								
■ U14	78 ± 6.2	74.6 ± 6.6	78.9 ± 6.7	79.4 ± 10.6	76 ± 8.1	78.3 ± 8.8	80 ± 6.5	70.3 ± 8.5
■ U16	77.1 ± 6.9	68.7 ± 5.6	78.5 ± 4.8	78.5 ± 7.2	74.9 ± 5.1	75.6 ± 6	74.2 ± 5.8	71.3 ± 6.1

FPPA: frontal plane projection angle.

3.1. Physical Performance

For 20 m sprint time, a significant main effect for time was observed (BF10 > 100), with the average time spent covering 20 m being longer at 0 h and shorter at 96 and 120 h post-match play 1 in comparison to pre-match 1 (baseline). However, only pre vs. 0 h post-match 1 differences could be defined as clinically relevant (possibly likely) (Figure 2a). Post-match play 2 sprint time scores were also significantly longer (from a statistically not clinically relevant perspective) than pre-match play 2. On the contrary, for this variable, there were neither significant interaction effects for time x age group (BF10 = 0.43) nor main effects for age (BF10 = 0.89).

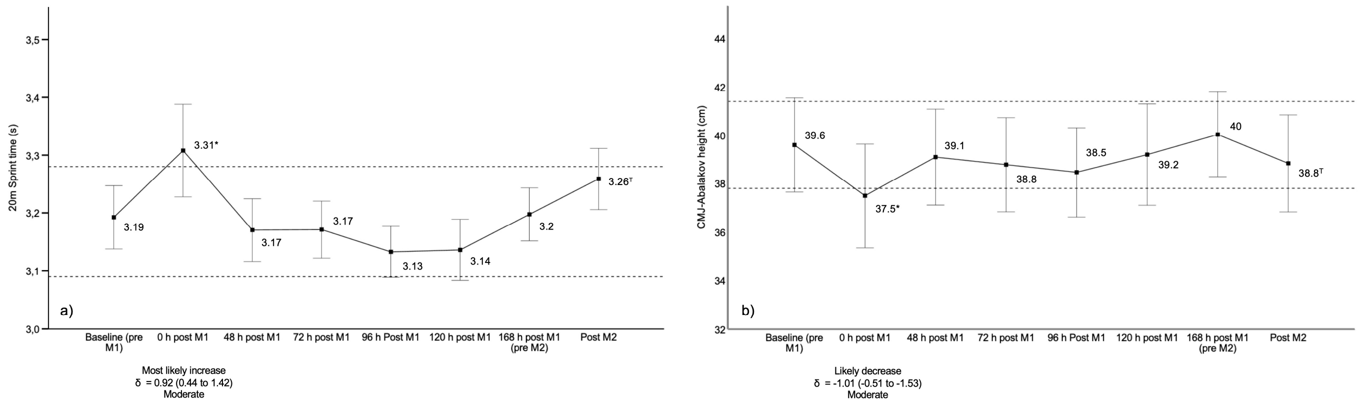

Figure 2. (**a**,**b**) Time course of performances in sprint and jump parameters. Data are mean ± SD, with * denoting significantly different. Dotted lines delimit an area where post-soccer match changes at each time point relative to baseline are considered trivial or not clinically relevant, as they do not exceed 1.5 times the magnitude of the standard error of measurement reported in previously published reliability studies (see Section 2). The effect size for each statistically significant paired comparison was also provided, including its qualitative interpretation.

For jump height, no statistically significant interactions for time x age (BF10 = 0.83) or main effects of age were observed; however, the main effects for time (BF10 > 100) were found (BF10 = 0.53), as was the covariable maturity offset (BF10 = 0.11). Subsequent post hoc analysis revealed statistically significant 0 h post-match 1 and 2 decreases in CMJ–Abalakov scores compared to the baseline and pre-match 2 values, respectively. Only pre (baseline) versus 0 h post-match 1 differences were clinically relevant (likely decrease) (Figure 2b).

3.1.1. SSC Capability

For LS and RSI, no statistically significant interactions for time × age (BF10 = 0.29: BF10 = 7.9) were found. Likewise, no main effects were observed for age (BF10 = 0.29: BF10 = 2.83). However, for LS there were main effects for time (BF10 > 100) whereby measurements taken at 0 h, 72 h, 96 h, 120 h, and 168 h post-match-play were significantly lower than pre-match-play 1 (Figure 3a). In contrast, post-match 2 scores were neither higher nor lower than pre-game 2 values. Only the paired comparison conducted between the baseline and 0 h post-match 1 scores reported a possible clinical relevance. For RSI, there were also main effects for time (BF10 = 21.7) and the covariable RSI baseline (BF10 = 36.7). Post hoc paired comparisons between the RSI baseline scores and the values obtained in the six successive time point testing sessions were non-significant (BF10 < 10) (Figure 3b). On the contrary, statistically significant differences between pre- vs. post-match 2 comparison were observed (BF10 > 100) but were not clinically relevant.

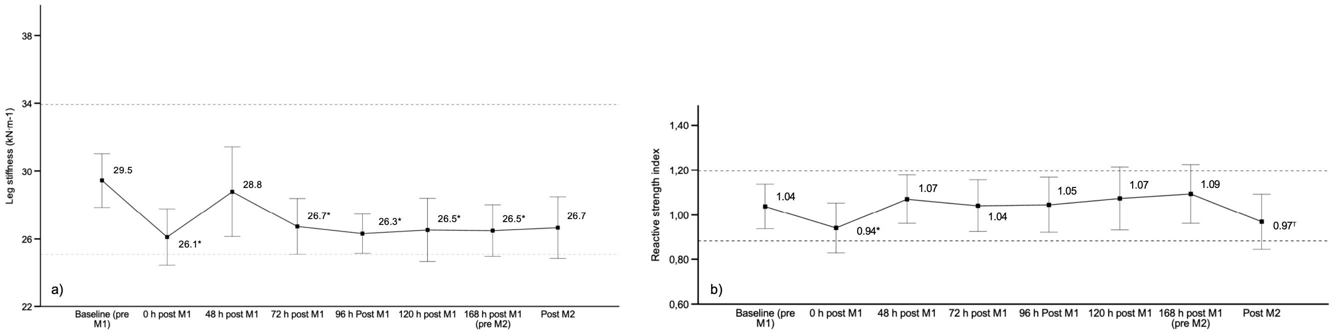

Figure 3. (**a**,**b**) Time course of neuromuscular responses. Data are mean ± SD, with * denoting significantly different. Dotted lines delimit an area where post-soccer match changes at each time point relative to baseline are considered trivial or not clinically relevant, as they do not exceed 1.5 times the magnitude of the standard error of measurement reported in previously published reliability studies (see Section 2). The effect size for each statistically significant paired comparison was also provided, including its qualitative interpretation.

3.1.2. Landing Mechanics

For FPPA (right), no statistically significant interactions for time × age (BF10 = 1.7) were found. Likewise, no main effects were observed for factor age (BF10 = 0.8) nor the covariable maturity offset (BF10 = 0.3). However, there were main effects for the covariable RSI baseline (BF10 > 100) and the factor time (BF10 = 26.2), and none of the paired comparisons conducted in the post hoc analysis were statistically significant (BF10 < 10) (Figure 3b). For FPPA (left), no statistically significant interactions for time × age (BF10 = 0.01), main effects for the factors age (BF10 = 0.3) and time (BF10 = 0.1) (Figure 4b) nor for the covariable maturity offset (BF10 = 0.6) were observed.

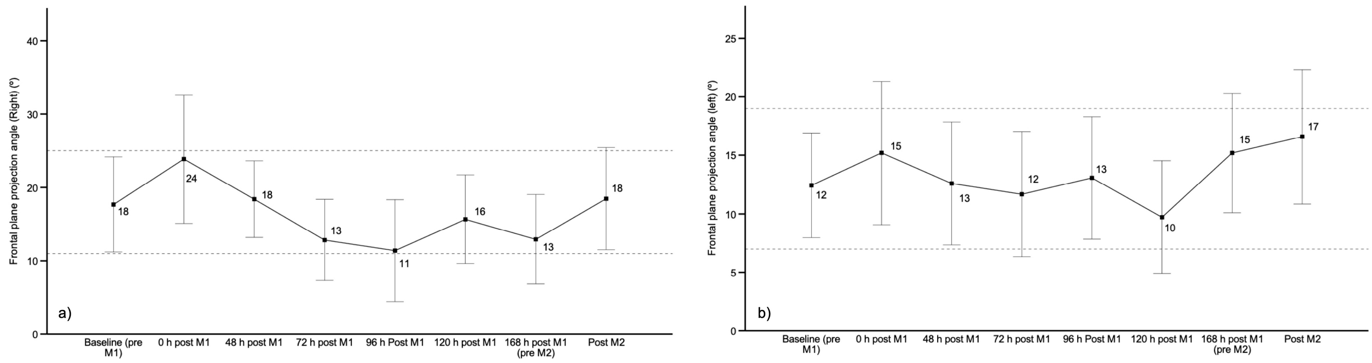

Figure 4. (**a**,**b**) Time course of Frontal Knee Projection Angle. Data are mean ± SD. Dotted lines delimit an area where post-soccer match changes at each time point relative to baseline are considered trivial or not clinically relevant, as they do not exceed 1.5 times the magnitude of the standard error of measurement reported in previously published reliability studies (see Section 2). The effect size for each statistically significant paired comparison was also provided, including its qualitative interpretation.

3.1.3. Muscle Damage

The CK and UR showed no statistically significant interactions for time × age (BF10 = 0.34 [CK] and 0.09 [UR]), main effects for age (BF10 = 0.56 [CK] and 0.95 [UR]), or for the covariate of maturity offset (BF10 = 0.73 [CK] and 0.19 [UR]). However, significant main effects were found for the covariable baseline scores in both muscle damage markers (BF10 = 356 [CK] and 62.5 [UR]), but time effects were only significant for the CK model. Post hoc analysis comparing baseline (pre-match 1) CK values with the following time points 0 h, 72 h, 96 h, and 120 h post-match 1 showed significant (BF10 > 100) and clinically relevant differences (most likely increases). Likewise, both significant (BF10 > 100) and clinically relevant (most likely) increases in CK were observed from pre- to post-match 2 (Figure 5a).

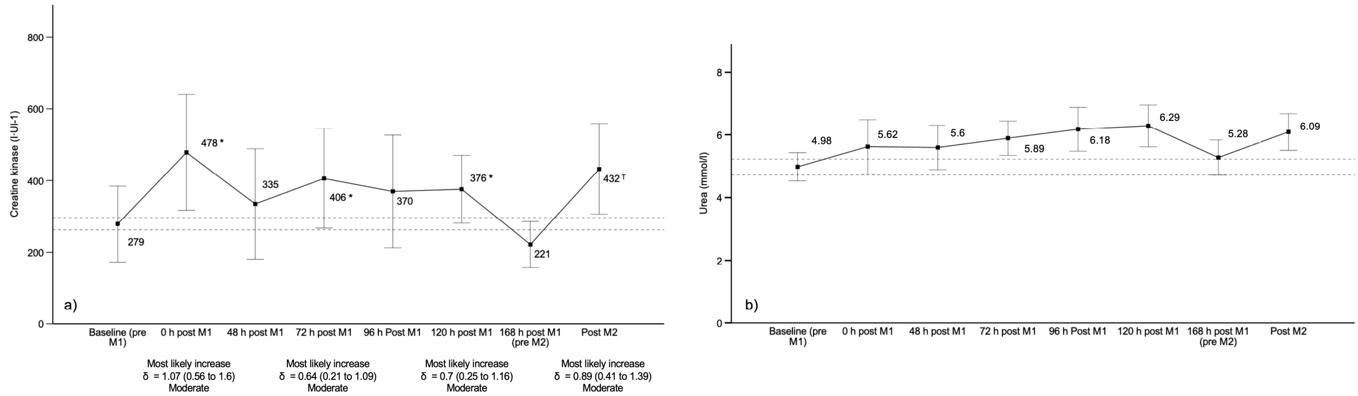

Figure 5. (**a**,**b**) Biochemical alterations following match play and training. Data are mean ± SD, with * denoting significantly different. Dotted lines delimit an area where post-soccer match changes at each time point relative to baseline are considered trivial or not clinically relevant, as they do not exceed 1.5 times the magnitude of the standard error of measurement reported in previously published reliability studies (see Section 2). The effect size for each statistically significant paired comparison was also provided, including its qualitative interpretation.

3.1.4. Perceived Well-Being

For well-being, no statistically significant interactions for time x age (BF10 = 1.2) were found. Likewise, no main effects were observed for age (BF10 = 1) nor for the covariable maturity offset (BF10 = 0.8). However, there were main effects for the covariable well-being baseline (BF10 > 100) and for the fixed factor time (BF10 > 100), whereby measurements taken at 0 h and 168 h post-match 1 were significantly lower (from a statistical but not clinical standpoint) than pre-match-play 1 and post-match 2, respectively (Figure 6).

3.1.5. Physical Demands

Players' match and training physical demands are also presented separately by age group in Table 2. The results of the Bayesian ANOVA conducted with each measure of physical demand showed no significant differences between either match. However, significant differences were obtained between the physical demands collected by the GPS devices in the matches and the training sessions. Likewise, only between-age-group differences were found for distance covered sprinting (BF10 = 61.9), whereby the U16 players covered a higher distance through the week than the U14 players.

Table 2. Match and training physical demands separately by age group.

	Match 1	48 h Post-Match 1	72 h Post-Match 1	96 h Post-Match 1	120 h Post-Match 1	Match 2
			Total distance covered (m) *†‡			
■ U14	$5913.3 \pm 1653.8^{\text{48H,72H,96H}}$	$4523.5 \pm 569.2^{\text{M1,72H,M2}}$	$3217.3 \pm 473.9^{\text{M1,48H,96H,120H,M2}}$	$4590 \pm 447.2^{\text{M1,72H,M2}}$	$4859.9 \pm 646.2^{\text{72H}}$	$6355.5 \pm 2256.4^{\text{48H,72H,96H}}$
■ U16	$8558.1 \pm 1369.2^{\text{48H,72H,96H,120H}}$	$4517.8 \pm 473.7^{\text{M1,72H,M2}}$	$3476.5 \pm 258.3^{\text{M1,48H,96H,M2}}$	$4256.8 \pm 495.8^{\text{M1,72H,M2}}$	$3629.6 \pm 849.6^{\text{M1,M2}}$	$6738.3 \pm 1932.3^{\text{48H,72H,96H,120H}}$
			Distance covered at low-speed running (<13 km/h) (m) *†			
■ U14	$4606.6 \pm 1357.7^{\text{72H}}$	$3691.9 \pm 407.6^{\text{72H}}$	$2852.9 \pm 331.9^{\text{M1,48H,96H,120H,M2}}$	$3925.6 \pm 351.1^{\text{72H}}$	$3825.5 \pm 451.4^{\text{72H}}$	$5053.5 \pm 1815.1^{\text{72H}}$
■ U16	$6237.8 \pm 2091^{\text{48H,72H,96H,120H}}$	$3648.5 \pm 320.1^{\text{M1,72H,M2}}$	$3120.0 \pm 213.4^{\text{M1,48H,96H,M2}}$	$3592.5 \pm 380.4^{\text{M1,72H,M2}}$	$2977.5 \pm 734.7^{\text{M1,M2}}$	$5535.2 \pm 1603.5^{\text{48H,72H,96H,M2}}$
			Distance covered at moderate-speed running (13–16 km/h) (m) *†‡			
■ U14	$706.3 \pm 199^{\text{72H,96H}}$	$508.5 \pm 186.3^{\text{72H}}$	$244.2 \pm 120.4^{\text{M1,48H,96H,120H,M2}}$	$390.6 \pm 96.0^{\text{M1,72H,120H,M2}}$	$548.6 \pm 156.3^{\text{72H,96H}}$	$741.5 \pm 265.1^{\text{72H,96H}}$
■ U16	$939.5 \pm 259.9^{\text{M1,48H,72H,96H,120H,M2}}$	$481.9 \pm 115.7^{\text{M1,72H}}$	$201.6 \pm 62.5^{\text{M1,48H,96H,120H,M2}}$	$355.2 \pm 86.5^{\text{M1,72H,M2}}$	$347.5 \pm 111^{\text{M1,72H,M2}}$	$609.9 \pm 179.8^{\text{M1,72H,96H,120H}}$
			Distance covered at high-speed running (16–19 km/h) (m) *†			
■ U14	$368.5 \pm 106.3^{\text{72H,96H}}$	$248.6 \pm 119.9^{\text{72H}}$	$98.1 \pm 47.1^{\text{M1,48H,96H,120H,M2}}$	$199.6 \pm 49.6^{\text{M1,72H,120H,M2}}$	$335.0 \pm 105.1^{\text{72H,96H}}$	$354.1 \pm 162.6^{\text{72H,96H}}$
■ U16	$488.6 \pm 149.8^{\text{48H,72H,96H,120H}}$	$274.3 \pm 76.2^{\text{M1,72H}}$	$109.9 \pm 46.5^{\text{M1,48H,96H,120H,M2}}$	$206.8 \pm 58.6^{\text{M1,72H}}$	$193.7 \pm 55.3^{\text{M1,72H}}$	$320.3 \pm 125.9^{\text{M1,72H}}$
			Distance covered sprinting (>19 km/h) (m) *†‡			
■ U14	$232.0 \pm 76.4^{\text{48H,72H,96H,120H}}$	$91.6 \pm 57.8^{\text{M1,72H,M2}}$	$22.1 \pm 24.9^{\text{M1,48H,96H,120H,M2}}$	$74.5 \pm 26.3^{\text{M1,72H,120H,M2}}$	$150.9 \pm 70.8^{\text{M1,72H,96H,M2}}$	$263.7 \pm 116.4^{\text{48H,72H,96H,120H}}$
■ U16	$439.3 \pm 132.5^{\text{48H,72H,96H,120H}}$	$113 \pm 45.4^{\text{M1,72H,M2}}$	$44.9 \pm 28.6^{\text{M1,48H,96H,120H,M2}}$	$102.2 \pm 41.5^{\text{M1,72H,M2}}$	$110.7 \pm 57.7^{\text{M1,72H,M2}}$	$273 \pm 134^{\text{48H,72H,96H,120H}}$
			Accelerations (number) †			
■ U14	32.3 ± 13	35.3 ± 10.6	32.1 ± 10.8	34.5 ± 8.7	33.4 ± 8	31.7 ± 15.5
■ U16	$49 \pm 10.5^{\text{120H}}$	38.8 ± 12	39.9 ± 15.2	42.8 ± 12.8	$27.8 \pm 13.1^{\text{M1}}$	46.3 ± 16.2
			Decelerations (number)			
■ U14	43.3 ± 12.6	39.1 ± 11.3	35.6 ± 15.1	46.6 ± 14.9	51.3 ± 15.5	50.5 ± 21.6
■ U16	56 ± 22.2	38.3 ± 11.4	38.1 ± 11.7	46 ± 18.1	37.2 ± 11	53.6 ± 14.7
			Sprints (number) *†‡			
■ U14	$20.2 \pm 6.8^{\text{48H,72H,96H}}$	$9.6 \pm 5.1^{\text{M1,72H,120H,M2}}$	$2.2 \pm 2.3^{\text{M1,48H,96H,120H,M2}}$	$8.2 \pm 3^{\text{M1,72H,120H,M2}}$	$16.9 \pm 7.2^{\text{48H,72H,96H}}$	$20.7 \pm 7.8^{\text{48H,72H,96H}}$
■ U16	$35.6 \pm 11.9^{\text{48H,72H,96H,120H}}$	$14.3 \pm 6^{\text{M1,72H}}$	$6.1 \pm 2.9^{\text{M1,48H,96H,M2}}$	$12.5 \pm 4.5^{\text{M1,72H}}$	$11.1 \pm 4.7^{\text{M1,M2}}$	$22.8 \pm 10.3^{\text{72H,120H}}$

*: significant two-way interactions for time × age group; †: significant main effects for the factor time ‡: significant inter-age group differences; M1: statistically significant differences with respect to post match 1; 48H: statistically significant differences with respect to 48H post-match 1; 72H: statistically significant differences with respect to 72H post-match 1; 96H: statistically significant differences with respect to 96H post-match 1; 120H: statistically significant differences with respect to 120H post-match 1; M2: statistically significant differences with respect to post match 2.

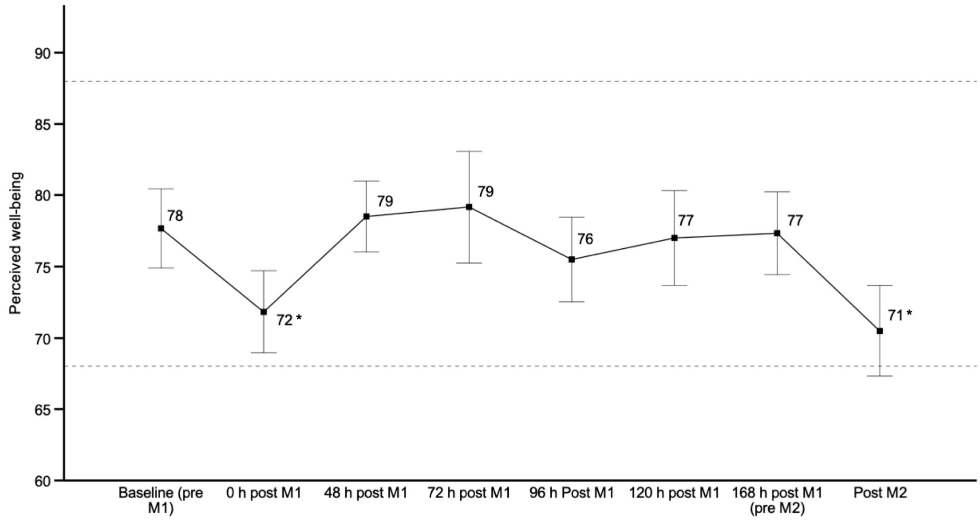

Figure 6. Perceptions of well-being across the study period. Data are mean ± SD, with * denoting significantly different. Dotted lines delimit an area where post-soccer match changes at each time point relative to baseline are considered trivial or not clinically relevant, as they do not exceed 1.5 times the magnitude of the standard error of measurement reported in previously published reliability studies (see Section 2). The effect size for each statistically significant paired comparison was also provided, including its qualitative interpretation.

3.1.6. Correlation and Regression Analyses

For each dependent variable, significant changes in baseline scores (pre-match 1 and 2) reported at any time point post-match 1 and 2 were not associated (BF10 < 10) with any measure of match and training physical demand. Consequently, no regression model was built with pre- and post-match changes in any dependent variable at any time point.

4. Discussion

The main purpose of this study was first to describe the magnitude of change across several measures, including markers of muscle damage, physical performance, stretch-shortening cycle capability, landing mechanics, and perceptions of well-being following competitive soccer match-play; the secondly purpose was to track the time course of recovery across a 7-day training week in elite male academy youth soccer players. A further purpose was to explore whether the players' maturity status, chronological age, and pre-match state influenced the post-match responses of outcome measures. Finally, this study sought to determine whether players' physical demands during a match modulated their fatigue responses across a training week.

4.1. Physical Performance

Like adult soccer players [28], our cohort of youth male soccer players showed significant impairments in sprint time (+4%) and jump height (−5%) after competitive matches regardless of their age group. However, unlike in adults, the impairments in this study did not consistently surpass the clinically relevant threshold established in previous reliability studies (>3% for 20 m sprint time and >4.5% for CMJ–Abalakov height) [14,23]. This was evidenced by the pre- and post-match 2 differences in both physical performance measures, where the differences were 2% and 3% for sprinting and jumping, respectively.

Analyzing the recovery time course for physical performance measures in each age group, it appears that 48 h may suffice for players to fully recover from soccer match-induced impairments. The CMJ performance recovery profile in young soccer players differed from that observed in adults [28], as adults required 72 h to return to their pre-match values. It is plausible that the higher number of explosive movements with a significant proportion of eccentric muscle actions performed by adult players during matches [29,30] could lead to more muscle damage and greater compromise of their jump performance compared to adolescents. This may necessitate a longer recovery time.

4.2. SSC Capability

The study found statistically significant but not clinically relevant decreases in LS (−11.5% [post-match 1]) and RSI (−9.6% [post-match 1] and −11% [post-match 2]) immediately after soccer match-play. Although these post-match-play reductions in LS and RSI did not exceed the thresholds to be considered clinically relevant (15%), they were close to them. Furthermore, the acute post-soccer match play responses of LS and RSI in the present study were comparable to those observed in previous youth studies [3,4] for both measures (RSI [Δ ranged from −6.4 to −13%] and LS [Δ ranged from −4 to −10%]). Since both LS and RSI measures represent SSC capability, soccer match-induced fatigue may affect the muscle-tendon unit's ability to stabilize the knee joint and efficiently handle the high tensile forces from repeated explosive movements executed by players. Both LS and RSI are two of the strongest predictors of sprint time and jump height in youth athletes [31]. Consequently, acute post-competitive soccer match-play inhibition of the SSC function can partly explain the responses to sprint and CMJ observed in both age groups.

The temporary decreases in LS and RSI following soccer matches in both age groups resolved within 48 h (Figure 3). Additionally, the training sessions during the microcycle had minimal impact on these two measures of SSC capability, as their responses remained relatively consistent from 48 h to 168 h post-soccer match-play. Chronic accumulated fatigue did not negatively affect LS or RSI during a standard mixed-content microcycle in this group of male youth soccer players. To the best of our knowledge, our study is the first to explore these post-soccer competition response patterns of LS and RSI over a 7-day mixed-content microcycle, making comparisons with other studies unavailable.

4.3. Landing Mechanics

This study's findings indicate that competitive soccer match-play does not significantly affect the landing mechanics of adolescent male players regardless of their chronological age and maturity status. Similar results were reported by Smeets et al. [32] and Wright et al. [33], who did not find significant alterations in landing kinematics (hip, knee, and ankle angles) after having completed simulated soccer match-play protocols in adult soccer players. Therefore, it may be suggested that soccer-induced fatigue is not large enough to alter youth players' movement patterns and motor control strategies in the frontal plane during the execution of a single-leg landing task. It should be pointed out that during the six months preceding the data collection phase of the current study, the recruited players had performed a substantial number of exercises in their training sessions aimed at improving their movement competence, including jumping and landing mechanics. These exercises were part of their periodized annual training plan, as indicated by anecdotal information provided by the coaches during informal meetings. This circumstance was clearly observed in the fact that most players exhibited good landing mechanics during pre-match testing (see Table 2 and Figure 4). It is plausible to think that, among the adaptations resulting from the movement competence training to which the participants were subjected, there could have been not only an improvement in landing mechanics but also a greater resistance to fatigue-related impairments. This could partly explain the results obtained in this study for this variable. However, future studies are necessary to support (or refute) this hypothesis.

4.4. Markers of Muscle Damage

As has been found in previous youth soccer studies [5–7,34], our results showed that moderate to large post-soccer match-play increases in CK activity in both age groups, although these were more prominent in the older players (U14 = 61.3% and U16 = 82.3%). Therefore, this supports recent findings demonstrating that children and adolescents may be considered CK responders and that both the lack of skeletal maturation [35] and the lower proportion of type II fibers [36,37] of younger players may partially explain the lower susceptibility they present to accumulate muscle damage following high-intensity exercise.

Interestingly, both the acute CK activity post-soccer match-play and its time course of recovery throughout the training week were similar in both age groups. Figure 3a shows that this marker of muscle damage peaked immediately post-competition and then decreased, demonstrating significantly lower values after 48 h. This decrease in CK activity also coincided with the players' reduced exposure to soccer, with no scheduled training sessions occurring. However, the magnitude of the decreases observed in players' CK activity was not large enough for them to return their pre-match 1 values (pre-match vs. 48 h post-match average difference = 73.6 I·Ul-1 [95%IC = −38.5 to 185.8]) despite the statistical analysis demonstrating non-significant differences between the two testing sessions. However, over the subsequent 3 days, the CK stabilized, though it remained higher than the pre-match values. Within this timeframe, the players were scheduled to train, and, following a 48 h rest period, the players underwent another testing session, which was carried out immediately before the second match, which was 168 h post-soccer match play 1. During this testing session, the CK values showed a significant decrease compared to the scores obtained in the testing sessions conducted 48-, 72-, and 120 h post-match-play. These values were like the pre-match 1 values, indicating that some recovery from muscle damage had occurred. Therefore, as evidenced in adult soccer [38,39], it may be suggested that more than 48 h (and likely less than 96 h) of non-exposure to soccer (or any high-intensity activity) is required for full CK recovery in youth players post-match.

It appears that the time course of CK recovery observed in the current study for adolescent male soccer players differs from the findings reported by Hughes et al. [6] for female youth players. Hughes et al. [6] demonstrated a sustained elevation in CK that also showed a delayed recovery to baseline. There may be several reasons for this, including differences in physical fitness levels and training status between the two groups. Specifically, the higher baseline CK values and the lower post-match-play percentage decreases in CK observed in adolescent male soccer players may be due to their higher levels of exposure to soccer-related exercise over the years and greater muscle mass compared to their female counterparts [40]. These factors may have contributed to the sex-related differences in the CK time course of recovery observed in the two studies.

Post-match UR values were higher than those obtained pre-match and greater in the U14 group, but, despite not being statistically significant, there was moderate evidence for H1 in all age groups for an increase. These post-match increases in UR values were similar in magnitude (~13%) to those observed by Martin-Garetxana et al. [5] also in youth soccer players, suggesting strenuous efforts during match-play. Slight increases in this maker of muscle damage values were also observed whenever the players were exposed to training with no more than 24 h of rest between sessions. Despite urea not being a direct marker of muscle damage, it is useful as an indicator of muscle breakdown and protein metabolism [41]. During intense exercise or muscle damage, muscle proteins are broken down, and the amino acids released from these proteins are used to produce energy or to build new proteins. This breakdown of proteins results in an increase in urea production and can lead to an increase in blood urea nitrogen (BUN) levels.

We found that UR values steadily increased in the first 120 h after a competitive match-play and that a 48 h rest period before the next match was not sufficient for the UR values to return to pre-match levels. This would suggest that accumulated fatigue may impair the players' ability to perform. Additionally, the study suggests that the load distribution of the microcycle applied by the teams' staff may have contributed to a chronic increase in UR values throughout the subsequent week until a prolonged rest period was applied. However, caution is advised, as only one microcycle was analyzed, and this study is the first to examine the response dynamics of UR values throughout a typical training week in adolescent populations.

4.5. Perceived Well-Being

Players' well-being was impaired (from a Bayesian statistic standpoint) immediately after the soccer competitions, recovering their pre-game values within the following 48 h. These acute post-soccer match-play perturbations in players´ well-being were comparable to those documented in previous studies for intermittent team-sport youth athletes [42]. Players' well-being corroborates the peak magnitude of muscle damage and neuromuscular measures immediately post-match play. However, players´ well-being (subjective) recovery dynamics seem not to mirror muscle damage (objective) responses even though both have been considered markers of the stress imposed by training and competition [43]. These findings are not in line with the results reported by Silva et al. [28] on adult soccer players, in which substantial elevations in perceptual fatigue-related markers were still observed at 48 and 72 h post-soccer match play. Therefore, it could be suggested that perceived well-being as a marker to monitor fatigue-related responses in youth soccer players should be used cautiously.

4.6. Moderating Factors to Post-Soccer Match-Play Response Dynamics

The baseline scores of muscle damage, physical performance, SSC capability, landing mechanics, and perceived well-being showed significant interactions with post-match response dynamics throughout the microcycle. Specifically, visual inspection (see Supplementary Table S2) of each player's post-soccer match-play response dynamics, especially within the first 48 h post-competition, suggests that players with higher pre-match muscle damage values, poorer physical performance, and SSC capability are more susceptible to negative fatigue-related effects. These effects are evident in measures such as CK levels, 20 m sprint time, CMJ–Abalakov height, LS, and RSI, which were significantly impaired after the matches, either statistically or clinically. These findings suggest that youth players with a higher training status and experience in repeated high-intensity actions (e.g., sprinting, sudden accelerations, decelerations, explosive changes in direction) may be more adapted to the "repeated bout effect" [44,45], which has positive effects on the biochemical milieu and neuromuscular system. The baseline scores of each dependent variable, particularly muscle damage measures (CK and UR), showed no statistical association with physical demand, including playing time. This suggests that players with potentially sub-optimal muscle integrity did not engage in fewer or less intense locomotive actions during soccer matches compared to those with normal CK and UR values. This underscores the importance of keeping muscle damage within normal physiological ranges before soccer matches. Doing so can minimize fatigue-related effects on biological systems, improve recovery dynamics, and lower the risk of injury.

Finally, the study found that maturation status, chronological age, and physical demands are not strong predictors of post-soccer match-play responses in youth players regarding measures of muscle damage, physical performance, SSC capability, landing mechanics, and perceived well-being. These results may not necessarily mean that these measures should be disregarded by coaches and physical trainers when monitoring the effects of soccer competition on the different biological systems. These findings support the theory of complex systems, viewing athletes as intricate entities where various factors can interact nonlinearly in response to events like soccer match-play. Instead of isolated components with significant modulating effects, it suggests that multiple components interact collectively to strongly influence different biological systems' responses to sports events. Future research should employ contemporary statistical techniques like Bayesian networks to identify relationships between measures reflecting the state of various biological systems, physical demands, and player characteristics. This analysis can estimate their influence on response patterns (acute effects and recovery dynamics) after soccer competitions.

5. Conclusions

Competitive soccer match-play causes considerable fatigue in youth players characterized by significant post-match-play neuromuscular alterations (SSC capability), physical performance impairments (CMJ–Abalakov height and 20 m sprint time), perturbations in the biochemical milieu (CK and UR), and worsening in the psychometric state (e.g., perceived well-being). On the contrary, landing mechanics remained unaffected after competitive soccer match-play. A period of 48 h of non-exposure to soccer (or any high-intensity activity) seems to be sufficient for the measuring of SCC capability, physical performance, and psychometric state to return to pre-match levels in this population cohort; however, for the markers of muscle damage (CK and UR), longer resting periods (>72 h) may be needed for a full recovery. The results of this study also highlight that, unlike maturation status, chronological age, and physical demands, the baseline scores of the measures analyzed moderate to some extent post-match response dynamics throughout the microcycle, specifically within the first 48 h post-competition. Players with higher pre-match muscle damage values, poorer physical performance, and SSC capability are more susceptible to negative fatigue-related effects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/youth4030081/s1. Figure S1 : Decision making tree of inclusion and exclusion criteria of players; Table S1: Bayesian correlations between pre-match 1 scores of the dependent variables and players' physical demands in match 1; Table S2 : Bayesian correlations between pre-match 2 scores of the dependent variables and players' physical demands in match 2.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data supporting this study's findings are available from Francisco Ayala upon reasonable request.

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