INFLUENCE OF THE NUMBER OF TRIALS AND THE EXERCISE TO REST RATIO IN REPEATED SPRINT ABILITY, WITH CHANGES OF DIRECTION AND ORIENTATION

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ABSTRACT

Ruscello, B, Tozzo, N, Briotti, G, Padua, E, Ponzetti, F, and D'Ottavio, S. Influence of the number of trials and the exercise to rest ratio in repeated sprint ability, with changes of direction and orientation. *J Strength Cond Res* 27(7): 1904–1919, 2013—The purpose of this investigation was to determine if there were different trends in physical fatigue observed in 3 different sets, of 7 trials each, in repeated sprint training, performed in 3 different modes: straight sprinting over 30 m, shuttle sprinting over 15 + 15 m, and sprinting over 30 m with changes of direction. Recovery time among trials in the sets was administered according to the 1:5 exercise to rest ratio. The sets were performed on 3 different days, with at least 48 hours between each set. The study involved 17 trained male soccer players (height, 177.33 ± 6.21 cm; body mass, 71.63 ± 9.58 kg; body mass index, 23 ± 2.39 $\text{kg}\cdot\text{m}^{-2}$; age, 21.94 ± 3.58 years). To compare the different values of the time recorded, an index of fatigue was used. Significant differences among trials within each set (repeated measures analysis of variance; $p < 0.05$) and between the sets (factorial analysis of variance; $p < 0.001$) were found. Significant correlations between each test and countermovement jump and stiffness values recorded pre exercise were found ($p < 0.05$). Significant differences between countermovement jump and stiffness values recorded pre and post exercise were also found ($p < 0.05$). This study suggests that training sessions aimed at increasing the capacity of repeated sprint ability in nonlinear and multidirectional sprints (shuttle and change of direction), which might imply a different number of trials within the set or different exercise to rest ratios from the ones usually adopted for straight sprinting, to induce similar trends of fatigue. As practical applications, the estimated numbers of necessary trials in the different sets and the possible exercise to rest ratios, resulting from mathematical modeling, are provided for each investigated sprinting mode.

KEY WORDS agility, soccer, training, mathematical modeling

INTRODUCTION

The umbrella term *agility* summarizes a broader construct that has been the subject of many studies over the last years (3,5,26–28) investigating the relationship between this psychomotor construct and team sports. These studies highlighted the complex nature of the motor tasks required in players, characterized by the ability of performing fast movements in different directions, anticipating or reacting to the ongoing situations, to solve specific competitive problems. The term agility seems to encompass this complex nature: Players have to sprint during a game many times and not in a straight line only! Indeed, the quality of the physical performance in team sports seems to rely on this ability the most.

In this regard, a component perceived as very important is the "explosiveness" with which these motor behaviors have to be performed (as a neuromuscular component of the agility), witnessed by the high gradient of force applied in very short times, to produce significant acceleration rates (both positive and negative), aimed at a sudden change of direction (COD) or orientation or verse (shuttle running), both in a 2-dimensional space (monoplanar CODs) and in a 3-dimensional one (CODs and altitude).

In recent years, the studies on repeated sprint ability (RSA) in team sports (i.e., the ability to repeat and sustain significant acceleration, lasting for a few seconds each time (≈1–10 seconds) but taking place many times during a match, with intermittent recovery periods, dictated by the technical and tactical contingency of the game), have highlighted the key role played by this ability, considered among insiders and practitioners as

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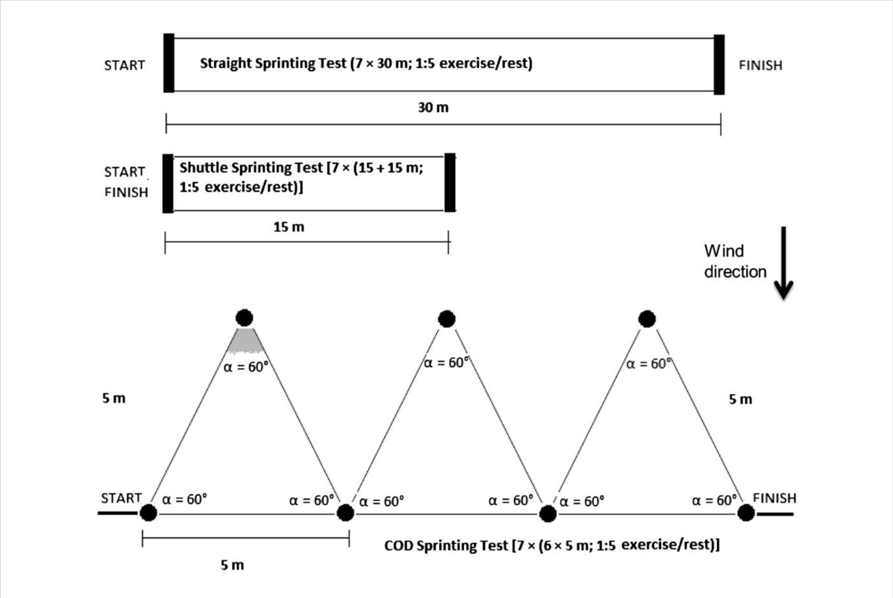
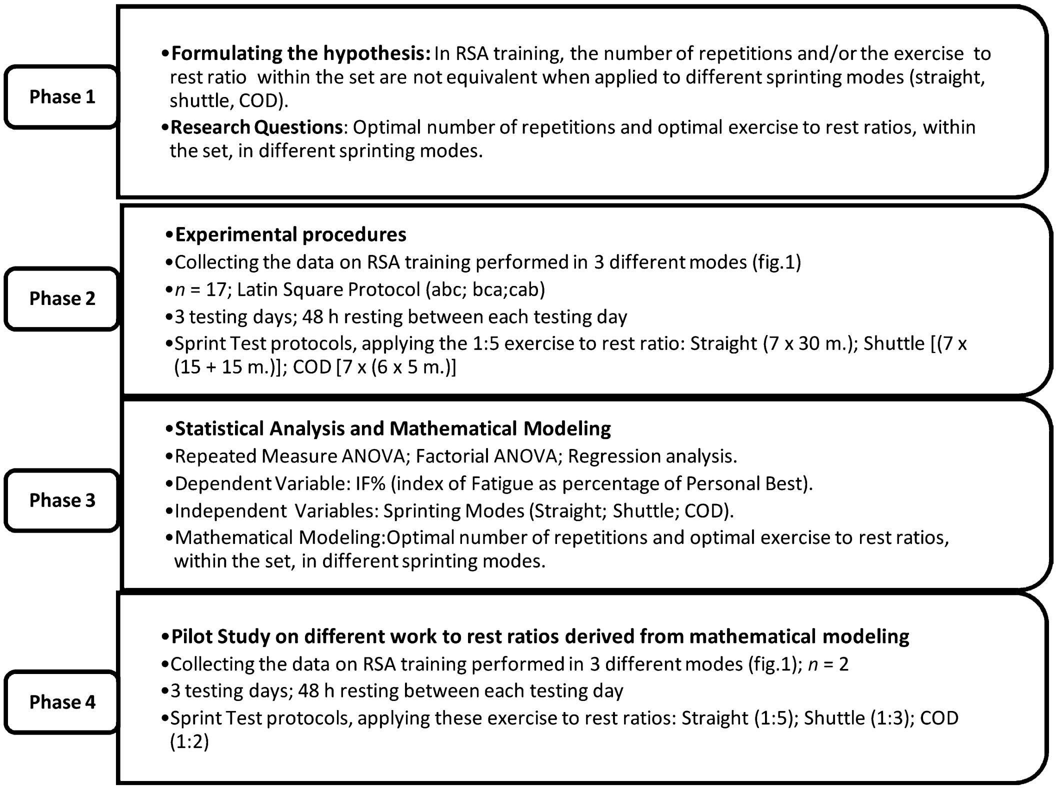


Figure 1. Sprinting modes adopted in this study: straight, shuttle, and COD sprinting. COD = change of direction.

one of the most important indicators in discriminating elite players from subelite players (1,4,7,12,13,17,21–23).

Performance analysis in football, hockey, and rugby (11,13–15,18,24), especially with the advent of global positioning system technology applied to sport, highlighted the "fatigue" phenomena progressively affecting the performance of players during the game.

Training sessions aimed at improving the RSA are usually designed as repetitions and sets of sprints, with a recovery time according to a 1:5 exercise to rest ratio, i.e., for each working second, 5 seconds of passive rest should be observed (1,8–10,19). The purpose of these methods is to stress the capacity of the alactacid anaerobic



- **Formulating the hypothesis:** In RSA training, the number of repetitions and/or the exercise to rest ratio within the set are not equivalent when applied to different sprinting modes (straight, shuttle, COD).
- **Research Questions**: Optimal number of repetitions and optimal exercise to rest ratios, within the set, in different sprinting modes.

- **Experimental procedures**
- Collecting the data on RSA training performed in 3 different modes (fig.1)
- *n* = 17; Latin Square Protocol (abc; bca;cab)
- 3 testing days; 48 h resting between each testing day
- Sprint Test protocols, applying the 1:5 exercise to rest ratio: Straight (7 x 30 m.); Shuttle [(7 x (15 + 15 m.)]; COD [7 x (6 x 5 m.)]

- **Statistical Analysis and Mathematical Modeling**
- Repeated Measure ANOVA; Factorial ANOVA; Regression analysis.
- Dependent Variable: IF% (index of Fatigue as percentage of Personal Best).
- Independent Variables: Sprinting Modes (Straight; Shuttle; COD).
- Mathematical Modeling:Optimal number of repetitions and optimal exercise to rest ratios, within the set, in different sprinting modes.

- **Pilot Study on different work to rest ratios derived from mathematical modeling**
- Collecting the data on RSA training performed in 3 different modes (fig.1); *n* = 2
- 3 testing days; 48 h resting between each testing day
- Sprint Test protocols, applying these exercise to rest ratios: Straight (1:5); Shuttle (1:3); COD (1:2)

Figure 2. The phases of this study.

Table 1. Testing protocols.*

Test	No. of repetitions in the set	Exercise to rest ratio	Type of recovery
Straight sprinting 7 × (30 m)	7	1:5	Passive
Shuttle sprinting 7 × (15 + 15 m)	7	1:5	Passive
COD sprinting: 7 × (6 × 5 m)	7	1:5	Passive

*COD = change of direction.

Table 2. Testing sequence: Latin square protocol.*

Test	Day 1	Day 2	Day 3
Straight sprinting 7 × (30 m)	Group A	Group B	Group C
Shuttle sprinting 7 × (15 + 15 m)	Group B	Group C	Group A
COD sprinting: 7 × (6 × 5 m)	Group C	Group A	Group B

*COD = change of direction.

system, primarily through the progressive fatigue induced by the repeated trials; nevertheless, the aim of this method (6) is also to keep the level of performance within a certain degree of decay (7–10%, according to different authors), i.e., the ability to sustain that kind of physical effort still definable as belonging to the domain of speed (or agility). Practitioners use the number of repetitions, the number of sets, and the exercise to rest ratio within the trials and within the sets, to modulate the training load according to the goal set. The level of decay of performance could be measured as the ratio between the best personal performance on a single trial and the actual time, recorded during each trial of the set. This level of decay might be also assumed, according to Fitzsimmons (9) as percent index of fatigue (IF%).

The study we presented originates from the application of a common training protocol of RSA, based on 7 repetitions of 30 m each with an exercise to rest ratio of 1:5, performed in 3 different sprinting modes: straight, shuttle, and slalom with CODs (Figure 1).

Several times we have noted that applying the exercise to rest ratio 1:5 to nonstraight sprinting aimed at improving a specific RSA (shuttle sprinting, slalom, or COD sprinting),s and different responses in the performance of the players involved were observed, having the feeling that the rest period adopted according to the 1:5 ratio would be probably inadequate to reach the desired training effects.

Thus, we hypothesized that in RSA training, the number of repetitions and the exercise to rest ratio within the sets is not equivalent when applied to different sprinting modalities. The main research questions we asked ourselves were as follows:

- What might be the best exercise to rest ratio when training RSA in nonstraight sprinting, such as shuttle sprinting or sprinting with COD?
- What might be the optimal number of trials in the sets of repetitions, when training this “nonlinear” RSA?
- Might it be possible to derive specific information about the level of fatigue induced by the different sprinting modes, through a noninvasive tool such as the flight time recorded in jump test, performed just before and after the training?
- Therefore, the main aims of this study were to answer these questions, through an experimental approach and by the means of mathematical modeling. Before performing the experimental procedures, face validity was established using expert judgment procedures.

METHODS

Experimental Approach to the Problem

This study was completed in 4 phases (Figure 2). To answer the research questions and to verify the hypothesis, we made (Figure 2: phase 1), we investigated how the IF% (set as dependent variable) was influenced by the exercise to rest ratio 1:5, in 3 different sprinting modes (set as independent variables). To do that, we normalized all the chronometrical measures, taken during testing, as percentages of the personal

Table 3. ICC for each test.*

Test	ICC (single measure)	CI (95%)	p
Straight sprinting 7 × (30 m)	0.753	0.583–0.894	<0.001
Shuttle sprinting 7 × (15 + 15 m)	0.885	0.780–0.957	<0.001
COD sprinting: 7 × (6 × 5 m)	0.885	0.784–0.954	<0.001

*ICC = intraclass correlation coefficient; CI = confidence interval; COD = change of direction.

Table 4. Straight sprinting (30 m): recorded time in seconds.*

					CI for the mean (95%)	
	n	Mean	*SD*	*SE*	Lower limit	Upper limit
Trial 1	17	4.34	0.21	0.05	4.23	4.44
Trial 2	17	4.43	0.20	0.05	4.33	4.53
Trial 3	17	4.49	0.26	0.06	4.36	4.62
Trial 4	17	4.55	0.27	0.07	4.41	4.68
Trial 5	17	4.59	0.25	0.06	4.46	4.72
Trial 6	14	4.60	0.25	0.07	4.45	4.74
Trial 7	14	4.74	0.36	0.10	4.53	4.95
Total	113	4.53	0.28	0.03	4.47	4.58

*CI = confidence interval.

Table 5. Normative data reported as percentile range (seconds).

	5	10	25	50	75	90
Trial 1	4.04	4.07	4.16	4.27	4.40	4.56
Trial 2	4.09	4.11	4.28	4.41	4.49	4.68
Trial 3	4.21	4.22	4.28	4.39	4.56	4.87
Trial 4	4.29	4.30	4.35	4.44	4.61	4.85
Trial 5	4.29	4.32	4.36	4.54	4.75	5.01
Trial 6	4.32	4.37	4.43	4.51	4.71	5.11
Trial 7	4.36	4.43	4.55	4.63	4.75	5.52

bests (PBs), performed within each different sprinting mode and assumed as IF%.

Thus, our experimental approach (phase 2) was as follows:

- Identifying the “pattern of fatigue” in straight sprinting, induced through a standard protocol of RSA training, with a 1:5 exercise to rest ratio, among the trials (7 ×30 m), to be used as reference for successive comparisons.

Table 6. Pattern of fatigue in straight sprinting.*†

	IF%
Trial 1	0.28
Trial 2	2.30
Trial 3	3.61
Trial 4	4.88
Trial 5	5.71
Trial 6	5.91
Trial 7	8.69

*IF% = percent index of fatigue.
†Values are expressed as percentage of PB (IF%).

Table 7. Shuttle sprinting (30 m: 15 + 15 m): recorded time in seconds.*

					CI for the mean (95%)	
	n	Mean	*SD*	*SE*	Lower limit	Upper limit
Trial 1	17	5.75	0.22	0.05	5.64	5.86
Trial 2	17	5.78	0.36	0.09	5.60	5.96
Trial 3	17	5.79	0.39	0.10	5.59	5.99
Trial 4	17	5.85	0.39	0.09	5.65	6.05
Trial 5	17	5.95	0.39	0.09	5.75	6.15
Trial 6	14	6.10	0.26	0.07	5.95	6.25
Trial 7	13	6.14	0.25	0.07	5.99	6.29
Total	112	5.89	0.35	0.03	5.83	5.96

*CI = confidence interval.

Table 8. Normative data reported as percentile range (seconds).

	5	10	25	50	75	90
Trial 1	5.40	5.45	5.59	5.77	5.93	6.05
Trial 2	5.54	5.57	5.63	5.81	5.99	6.04
Trial 3	5.43	5.44	5.70	5.83	5.94	6.25
Trial 4	5.44	5.55	5.75	5.90	5.99	6.35
Trial 5	5.47	5.60	5.83	6.06	6.14	6.37
Trial 6	5.65	5.71	5.92	6.07	6.22	6.45
Trial 7	5.79	5.80	5.99	6.10	6.37	6.54

Table 9. Pattern of fatigue in shuttle sprinting.*†

	IF%
Trial 1	1.18
Trial 2	1.70
Trial 3	1.87
Trial 4	2.87
Trial 5	4.50
Trial 6	6.85
Trial 7	7.46

*IF% = percent index of fatigue.
†Values are expressed as percentage of PB (IF%).

Table 10. COD sprinting (30 m: 6 × 5 m): recorded time in seconds.*

	n	Mean	*SD*	*SE*	CI for the mean (95%) Lower limit	CI for the mean (95%) Upper limit
Trial 1	17	8.37	0.39	0.09	8.17	8.57
Trial 2	17	8.40	0.39	0.10	8.20	8.60
Trial 3	17	8.40	0.43	0.11	8.18	8.63
Trial 4	17	8.43	0.40	0.10	8.23	8.63
Trial 5	17	8.51	0.42	0.10	8.30	8.72
Trial 6	14	8.72	0.37	0.10	8.51	8.93
Trial 7	14	8.79	0.34	0.09	8.60	8.99
Total	113	8.51	0.41	0.04	8.43	8.58

*COD = change of direction; CI = confidence interval.

- Identifying the patterns of fatigue induced in the other 2 different sprinting modes (shuttle and COD sprinting), performed on the same distance (30 m) and with the same exercise to rest ratio (1:5), adopted in straight sprinting.
- Verifying by the means of vertical jumping tests whether differences occur among the estimate heights recorded before and after each test (within) and between tests.
- Analyzing the different patterns of fatigue (phase 3) to (a) determine the possible cutoff in the different sets (i.e., checking when the decays of the chronometric performances become significant in the different sets) and (b) verify the existence of significant differences between these patterns of fatigue, confirming the different physical loads induced, using these testing protocols.
- Designing, by the means of statistical-mathematical analysis, the optimal number of repetitions and the appropriate exercise to rest ratios within the trials, for shuttle and COD sprinting sets, able to induce the same pattern of fatigue found in straight sprinting set.
- Verifying experimentally, through a pilot study (phase 4) in a small sample, the infield response of the hypotheses we made by the means of mathematical modeling.

Subjects

Seventeen trained male soccer players ($n = 17$; height, 177.3 ± 6.2 cm; body mass, 71.6 ± 9.6 kg; body mass index, 23 ± 2.4 $kg \cdot m^{-2}$; age, 21.9 ± 3.6 years) volunteered to participate in the study. The players had at least 3 years (range 3–7 years) of experience at this competitive level (i.e., *Italian Lega Pro*) and performed at least 4 training sessions a week for the development of specific fitness.

Agility has been always part of their usual training, especially in competitive season, which is the period investigated in this article (March).

Written informed consent was obtained from all the participants after familiarization and explanation of the benefit and risks involved in the procedures of this study. All participants were informed that they were free to withdraw from the study at any time without penalty. The Institutional Research Board (the Ethical Committee of the School of Sports and Exercise Science, University of Rome "Tor Vergata," Faculty of Medicine and Surgery) approved our research protocol and provided clearance for the procedures before the commencement of this study. All procedures were carried out in accordance with the Declaration of Helsinki of the World Medical Association as regards the conduct of clinical research. Before undergoing test procedures, all participants were required to provide a certificate of medical fitness, which would exclude pathologies that contraindicated high-intensity physical activities.

All players were tested in the same week of March 2011, for 3 days. To avoid undue stress on the players in the days preceding the testing, training loads were intentionally reduced and familiarization sessions were also considered. The players were advised to maintain a regular diet during the day before testing (i.e., 60, 25, and 15% of carbohydrates, fat, and protein, respectively) and to refrain from smoking

Table 11. Normative data reported as percentile range (seconds).

	5	10	25	50	75	90
Trial 1	7.65	7.81	8.13	8.40	8.72	8.95
Trial 2	7.85	7.89	8.15	8.37	8.86	9.00
Trial 3	7.77	7.88	8.10	8.39	8.84	9.15
Trial 4	7.72	7.90	8.20	8.54	8.80	9.04
Trial 5	8.16	8.16	8.25	8.51	8.97	9.20
Trial 6	8.22	8.28	8.41	8.66	9.14	9.27
Trial 7	8.29	8.33	8.52	8.74	9.08	9.28

Table 12. Pattern of fatigue in shuttle sprinting.*†

	IF%
Trial 1	1.03
Trial 2	1.38
Trial 3	1.38
Trial 4	1.73
Trial 5	2.66
Trial 6	5.00
Trial 7	5.76

*IF% = percent index of fatigue.
†Values are expressed as percentage of PB (IF%).

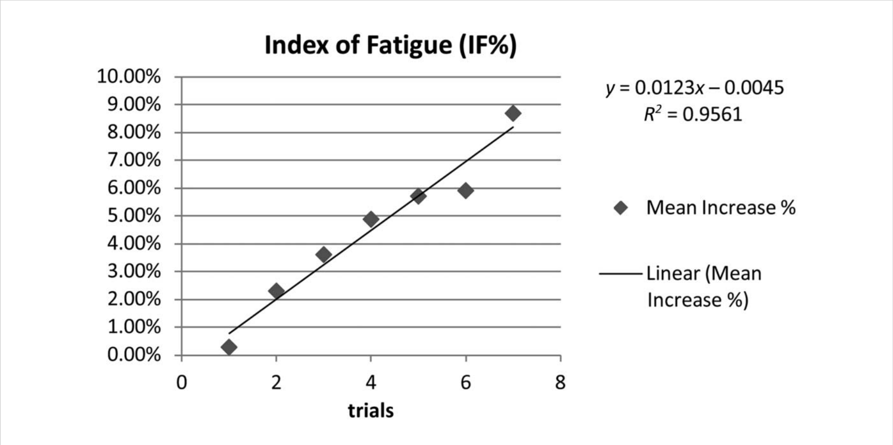


Figure 3. Straight sprinting (6 × 30 m): percent index of fatigue (IF%) computed as the ratio of the time recorded in each trial (actual value [AV]) and the personal best (PB).

and caffeinated drinks during the 2 hours preceding testing. To avoid hypohydration, players were allowed to drink fluids according to their personal needs.

Procedures

The tests were performed in March 2011, on 3 separate days, at the same hours of the day (i.e., 2–4 PM) in a sport center in Rome, on a synthetic surface soccer pitch, approved for national level competitions. The average weather conditions during the 3 days were fine, with an average temperature and wind speed, respectively, of 14° and 1.9 $m \cdot s^{-1}$ on day 1, 16° and 2.0 $m \cdot s^{-1}$ on day 2, and 17° and 1.9 $m \cdot s^{-1}$ on day 3. To limit the influence of the wind, we oriented the direction of sprinting at right angles, in relation to the wind direction.

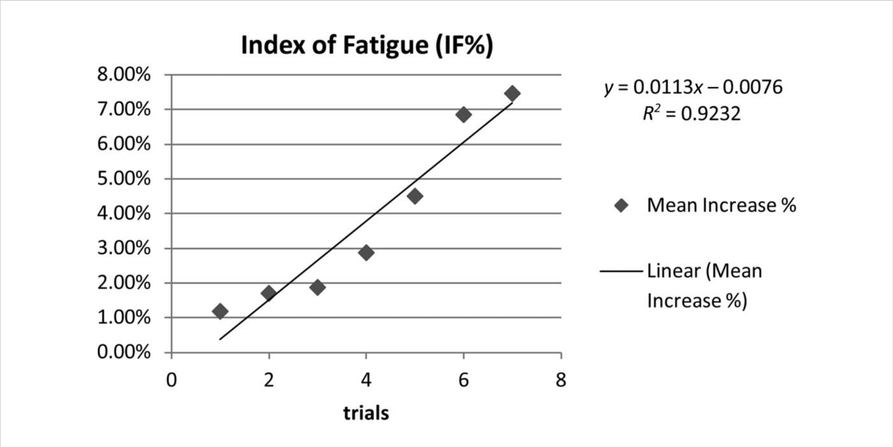


Figure 4. Shuttle sprinting (7 × [15 + 15 m]): percent index of fatigue (IF%) computed as the ratio of the time recorded in each trial (actual value [AV]) and the personal best (PB).

The tests were performed at the end of a standard warm-up consisting each time of 15 minutes of slow jogging, followed by static stretching (5 minutes) and agility and sprint practice (10 minutes).

The test performance was assumed as total time and assessed using a telemetric photocell system (Polifemo Kit Racetime2; Microgate, Bolzano, Italy). To avoid undue switch-on of the timing system, players had to position the front foot immediately before a line set 0.3 m from the photocell beam. The photocell beam was positioned at 1 m height and 2 m apart. All the players performed the tests with a self-administered start, and maximum performance was induced through strong verbal encouragements by the same test administrator during all the test durations.

Flight time and the estimate of the heights in the countermovement jump test (16) and in the stiffness test (2) were measured using an electronic device ("FreePower Jump"; Sensorize, Rome, Italy) (20).

Participants performed the testing described in Table 1: Among each different test, there was a recovery period of at least 48 hours.

To control the variables that suffer influences from repeated tests on different days, we designed a Latin square protocol, in which the group ($n = 17$) was randomly split into 3 subgroups (a, $n = 6$; b, $n = 6$; c, $n = 5$), working differently each testing day (Table 2). The groups performed different tests according to this sequence: At the end of the testing period, all the 17 participants ($n = 17$) performed all the 3 tests.

Before each test, participants were asked to provide the maximal performance on a single trial (PB). In some cases, PBs recorded in the single trial were worse (higher) than those recorded during the test (usually in the first trial or the second one); in these cases, the best results recorded in the sets were considered as

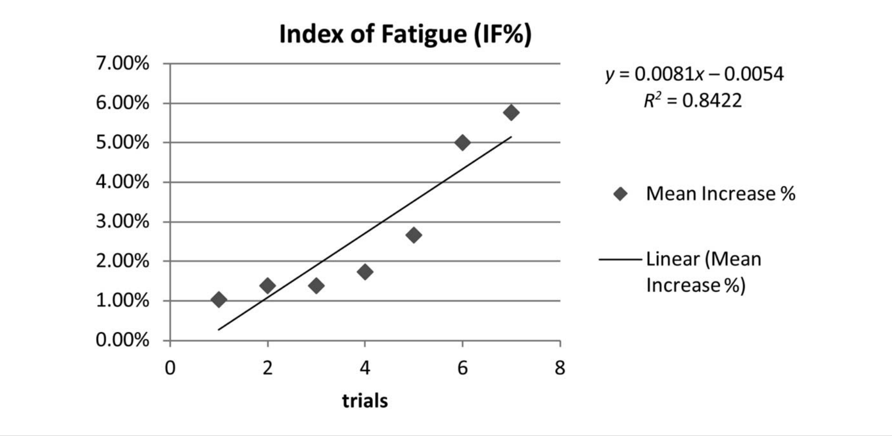


Figure 5. Change of direction sprinting (7 × [6 × 5 m]): percent index of fatigue (IF%) computed as the ratio of the time recorded in each trial (actual value [AV]) and the personal best (PB).

the best personal time (PB) and then used as the dividend for the estimation of (IF%), according to Equation 1.

$$\mathrm{IF\%} = \left(1 - [\text{personal best}]/[\text{trial}]\right) \times 100. \qquad (1)$$

Countermovement jump (CMJ) and stiffness values, recorded before and after each test, were also collected.

Statistical Analyses

Data are presented as mean ± *SD* and 95% confidence intervals (95% CIs). The assumption of normality was assessed using the Shapiro-Wilk's test. Parametric and nonparametric statistics were used when appropriate. Normative data were reported as percentile range. To normalize all the values recorded in different tests, a ratio between personal best and actual value (PB:AV) for each trial was assumed as an IF%.

The intraclass correlation coefficients for single measure are provided as indices of relative reliability of the tests.

To identify significant points of fatigue (cutoff), analysis of variance for repeated measures was performed, for each test. Data were analyzed as absolute values of time (seconds) recorded in each test and as percentage (IF%) of PB. After performing the Mauchly's test of sphericity, the Greenhouse-Geisser's ε was used when appropriate.

To test the main effect and the interactions between factors (type of test and amount of resting time as independent variables and the IF% as a dependent variable), a factor analysis of variance was performed.

Effect size (ES) in analysis of variance (ANOVA) was computed as ω^2, to assess meaningfulness of differences, with $\omega^2 < 0.01$, $0.01 < \omega^2 < 0.06$, $0.06 < \omega^2 < 0.14$, and $\omega^2 > 0.14$, as trivial, small, moderate, and large ES, respectively.

Pearson's product moment of correlations among the different physical tests was also performed (among the various sprint tests and running and jumping tests, performed before and after each sprint test). The corresponding p values are provided for each analysis. The value of statistical significance was accepted with $p \leq 0.05$. SPSS 15.0 for Windows was used to analyze and process the collected data.

RESULTS

As a measure of the relative reliability of measurements obtained during testing, the intraclass correlation coefficient was computed (Table 3).

TABLE 13. Correlations among different sprinting tests: time recorded (seconds).*

	Straight (30 m)	Shuttle (15 + 15 m)	COD (6 × 5 m)
Straight (30 m)	$r = 1$ $n = 113$	$r = 0.219$† $p = 0.020$ $n = 112$	$r = 0.346$‡ $p = 0.000$ $n = 113$
Shuttle (15 + 15 m)	$r = 0.219$† $p = 0.020$ $n = 112$	$r = 1$ $n = 112$	$r = 0.632$‡ $p = 0.000$ $n = 112$
COD (6 × 5 m)	$r = 0.346$‡ $p = 0.000$ $n = 113$	$r = 0.632$‡ $p = 0.000$ $n = 112$	$r = 1$ $n = 113$

*COD = change of direction.
†$p < 0.05$.
‡$p < 0.01$.

Test 1: Linear Sprint (30 m)

The descriptive statistics (mean ± *SD*, 95% CI) of the time recorded during the 7 repetitions are provided (Table 4). The values, normative data recorded and sorted into percentiles (50–90), are reported (Table 5).

The ratios PB:AV (IF%), showing the increase of the time recorded along the set, in relation to PB, and assumed as an IF%, are reported (Table 6 and Figure 3). During testing, 3 participants withdrew at sixth

Table 14. Correlations among different sprinting tests.*

	IF%: straight	IF%: shuttle	IF%: COD
IF%: straight	$r = 1$ $n = 113$	$r = 0.461$† $p = 0.000$ $n = 112$	$r = 0.559$† $p = 0.000$ $n = 113$
IF%: shuttle	$r = 0.461$† $p = 0.000$ $n = 112$	$r = 1$ $n = 112$	$r = 0.386$† $p = 0.000$ $n = 112$
IF%: COD	$r = 0.559$† $p = 0.000$ $n = 13$	$r = 0.386$† $p = 0.000$ $n = 112$	$r = 1$ $n = 113$

*IF% = percent indices of fatigue; COD = change of direction.
†$p < 0.01$.

and seventh trials ($n = 17$ [trials 1–5]; $n = 14$, trials 6 and 7).

We found a clear increase in the absolute value of time recorded during the test, as evidence of fatigue induced by the test type, with a final increase (trials 1–7) of 8.44%.

This increase is statistically significant (repeated measures ANOVA: $F_{2.07,26.90} = 22.062$, $p < 0.001$; ES as $\omega^2 = 0.26$; power 1.000, $\alpha = 0.05$, with adjustment Greenhouse-Geisser's ε).

Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed statistically significant differences between the values, starting from the second trial ($p = 0.017$).

The dependent variable IF%, according to the Equation 1, was then considered. A marked increase in this percentage, confirming the fatigue induced with this test, with a difference of 8.42% between the first and seventh trial, was noted.

This difference is statistically significant (repeated measures ANOVA: $F_{2.52,30.24} = 25.258$, $p < 0.001$; ES = as $\omega^2 = 0.53$; power 1.000, $\alpha = 0.05$, with adjustment Greenhouse-Geisser's ε). Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed statistically significant differences among the IF% values, starting already in the second trial ($p = 0.014$).

Test 2: Shuttle Sprint (30 m: 15 + 15 m)

The descriptive statistics (mean ± *SD*, 95% CI) of the time recorded during the 7 repetitions are provided (Table 7). The values, recorded and sorted into percentiles (50–90), are reported (Table 8). The ratios PB:AV (IF%), showing the increase of the time recorded along the set, in relation to PB, and assumed as an IF%, are reported in Table 9 and Figure 4. During testing, 3 participants withdrew at the sixth trial and 4 at the seventh trial ($n = 17$, trials 1–5; $n = 14$, trial 6; and $n = 13$, trial 7).

We found a clear increase in the absolute value of the time recorded during the test, as evidence of fatigue induced by the test type, with a final increase (1–7 trials) of 6.74%.

This increase is statistically significant (repeated measures ANOVA: $F_{2.83,26.90} = 45.470$, $p < 0.001$; ES = as $\omega^2 = 0.27$; power 1.000; $\alpha = 0.05$, with adjustment Greenhouse-Geisser's ε).

Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed statistically significant differences between the values starting from the fourth trial ($p = 0.007$).

The variable (IF%), according to Equation 1, was then considered. A marked increase in this percentage, confirming the fatigue induced with this test, with a difference of 6.28% between first and seventh trials, was noted.

Table 15. Mean values of all the performances in the tests (seconds), the estimated and actual recovery periods (seconds), and the %GIF.*

	Straight	Shuttle	COD
Mean performance times	4.53	5.89	8.50
Mean estimated recovery period (ratio 1:5)	22.63	29.47	42.53
Actual recovery period taken (ratio 1:5)	22.00	30.00	42.00
GIF%	4.76	3.45	2.48

*GIF% = percent general indices of fatigue; COD = change of direction.

Table 16. Patterns of fatigue (IF%) within and between sets.*

	Straight	Shuttle	COD
Trial 1	0.28	1.18	1.03
Trial 2	2.30	1.70	1.38
Trial 3	3.61	1.87	1.38
Trial 4	4.88	2.87	1.73
Trial 5	5.71	4.50	2.66
Trial 6	5.91	6.85	5.00
Trial 7	8.69	7.46	5.76
Mean	4.48	3.78	2.71
SD	0.03	0.03	0.02

*IF% = percent index of fatigue; COD = change of direction.

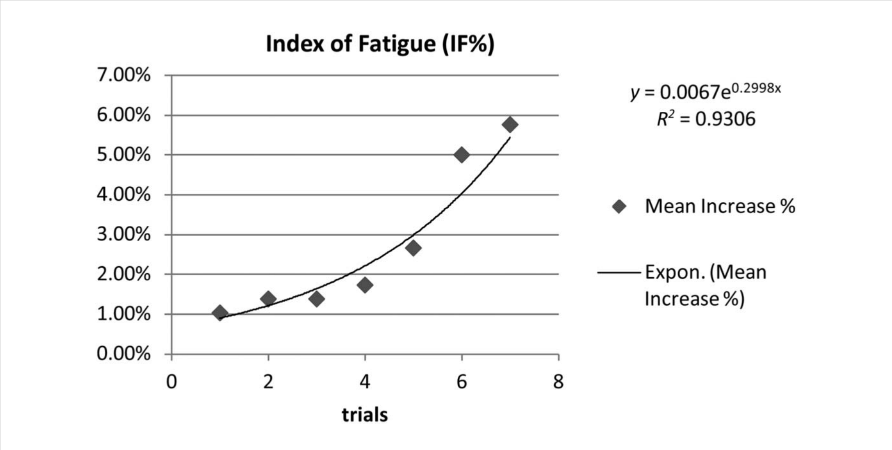


Figure 6. Change of direction sprinting (7 × [6 × 5 m]): percent index of fatigue (IF%) computed as the ratio of the time recorded in each trial (actual value [AV]) and the personal best (PB). An exponential trend line is provided. Consider the R^2 value.

This difference is statistically significant (repeated measures ANOVA: $F_{3.02,36.23} = 46.520$, $p < 0.001$; ES = as $\omega^2 = 0.754$; power 1.000; $\alpha = 0.05$, with adjustment Greenhouse-Geisser's ε). Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed statistically significant differences among the IF% values, starting from the fourth trial ($p = 0.004$).

Test 3: Change of Direction (30 m: 6 × 5 m)

The descriptive statistics (mean ± *SD*, 95% CI) of the time recorded during 7 repetitions are provided in Table 10. The values, recorded and sorted into percentiles (50–90), are reported in Table 11. The PB:AV ratios (IF%), showing the increase of the time recorded along the set, in relation to PB, and assumed as an IF%, are reported in Table 12 and Figure 5. During testing, 3 participants withdrew at the sixth trial and 4 at the seventh trial ($n = 17$, trials 1–5; $n = 14$, trial 6; and $n = 13$, trial 7).

We found an increase in the absolute value of the time recorded during the test, as evidence of fatigue induced by the test type, with a final increase (1–7 trials) of 4.78%.

This increase is statistically significant (repeated measures ANOVA: $F_{2.97,38.58} = 17.849$, $p < 0.001$; ES = as $\omega^2 = 0.12$; power 1.000; $\alpha = 0.05$, with adjustment Greenhouse-Geisser's ε).

Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed statistically significant differences between the values starting from the fifth trial ($p = 0.023$).

The variable (IF%), according to Equation 1, was then considered. A significant increase in this percentage, confirming the fatigue induced with this test, with a difference of 4.73% between the first and seventh trials, was noted (Figure 4).

This difference is statistically significant (repeated measures ANOVA $F_{3.05,39.65} = 17.856$, $p < 0.001$; ES = as $\omega^2 = 0.45$; power 1.000; $\alpha = 0.05$, with adjustment Greenhouse-Geisser's ε). Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed statistically significant differences among the IF% values, starting from the fifth trial ($p = 0.02$).

To better fit the data into a trend line of the scatter plot, an exponential one is also considered. The resulting R^2 value (0.930) with $p < 0.01$ are provided in Figure 6.

Average velocity and acceleration rates in straight, shuttle, and COD sprinting were 6.62 $\text{m}\cdot\text{s}^{-1}$ and 1.46 $\text{m}\cdot\text{s}^{-2}$, 5.09 $\text{m}\cdot\text{s}^{-1}$ and 0.86 $\text{m}\cdot\text{s}^{-2}$, and 3.53 $\text{m}\cdot\text{s}^{-1}$ and 0.41 $\text{m}\cdot\text{s}^{-2}$, respectively.

Correlations

Tables show the values of correlation (Pearson's *r*) among the observed time in absolute values (Table 13) and among the IF% (Table 14) observed in the trials carried out in 3 different tests.

Table 17. Cutoff points observed in the different tests, referring to the IF%.*†

Test	Cutoff (no. of repetitions per set)	*p*
Straight sprinting	2/7	0.014
Shuttle sprinting	4/7	0.004
COD sprinting	5/7	0.020

*IF% = percent index of fatigue; COD = change of direction.

†Post hoc repeated measures ANOVA with Bonferroni's correction.

Table 18. CMJ tests pre and post all sprinting tests (centimeters).*

	n	Mean	*SD*	Minimum	Maximum
CMJ pre test	51	46.84	4.37	36.30	53.00
CMJ post test	51	43.27	4.91	30.70	48.60

*CMJ = countermovement jump.

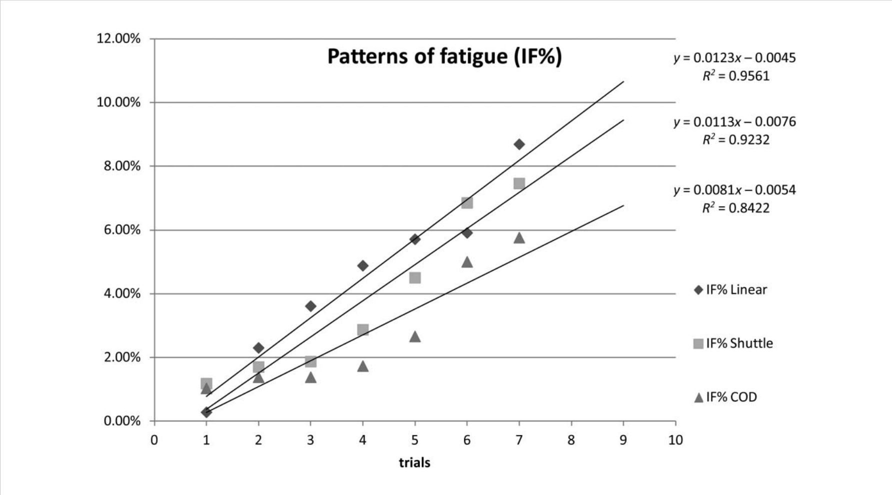


Figure 7. Lines of best fit, equation, and R^2, in 3 different tests. Note the possible estimated values in trials 8 and 9, according to those lines.

Differences in Percent Indices of Fatigue Observed Among the Sprinting Tests

To calculate an average general index of fatigue from the data found in the 3 tests, we used the formula proposed by Fitzsimmoms (Equation 2), which takes into account the ideal total time (ITT) estimated as the product of the total number of repetitions (Nr) by the PB recorded, according to Equation 3, and the real total time (RTT) calculated as the sum of the times (tt) actually recorded in the trials of each test (Equation 4):

$$\mathrm{GIF} = \left(\frac{\mathrm{RTT}}{\mathrm{ITT}}\times 100\right) - 100 \tag{2}$$

$$\mathrm{ITT} = \mathrm{Nr}\times\mathrm{PB} \tag{3}$$

$$\mathrm{RTT} = \Sigma\mathrm{tt}. \tag{4}$$

Table 15 shows the mean values of all the performances (seconds) recorded for each tests, the estimated recovery period (seconds) according to the ratio 1:5, the actual recovery time taken (seconds), and the IF%, calculated according to the Fitzsimmons' formula, reported above (Equation 2).

Table 16 and Figure 7 show the different patterns of fatigue within trials (IF%), between sets. To analyze the differences observed among the IF% (dependent variable) among the different types of tests (independent variables) and the recovery modes, we performed a factorial ANOVA 3 × 7. A statistically significant difference among the tests

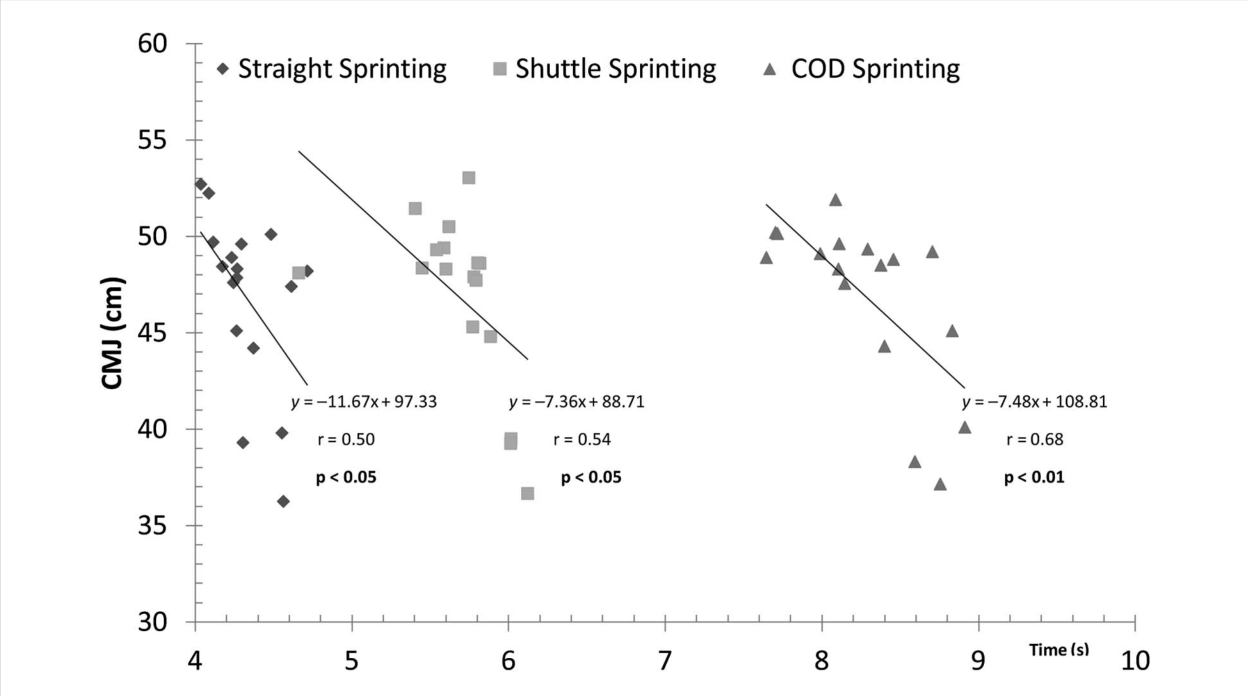


Figure 8. Correlation between the different types of sprinting tests and the countermovement jump (CMJ) test.

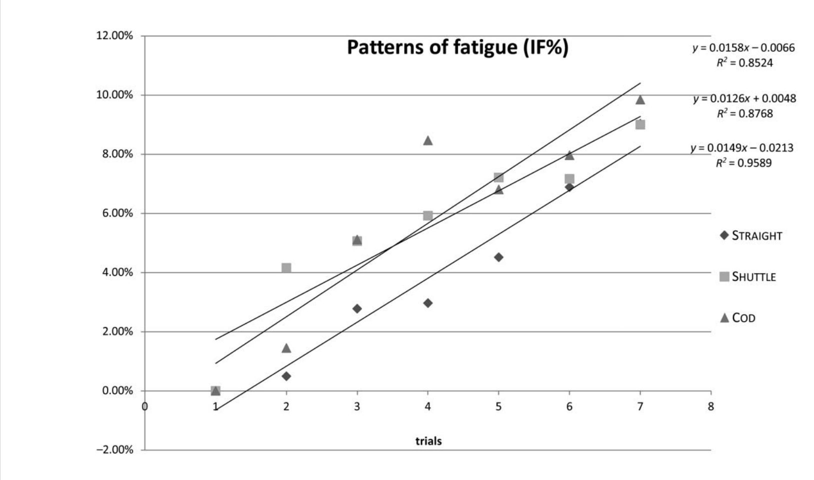


Figure 9. Trends of the percent index of fatigue (IF%) observed using the different exercise to rest ratios proposed by the authors (pilot study; *n* = 2).

was found (factorial ANOVA: $F_{3.05,115.65} = 79.615$, $p < 0.001$; ES = as $\omega^2 = 0.54$; power 1.000, $\alpha = 0.05$, with Greenhouse-Geisser's ε adjustment), confirming the different level of fatigue induced by the different types of test.

Subsequent post hoc tests, performed with Bonferroni's correction of significance level, showed significant differences between the values of IF%, observed in test 1 (linear: 30 m) compared with the other 2 tests (test 2, shuttle, $p = 0.022$ and test 3, COD, $p < 0.001$).

We also observed a statistically significant interaction between the IF% recorded during the tests and the recovery ($F_{6.09,115.65} = 3.414$, $p = 0.004$; ES = partial $\eta^2 = 0.152$; power 0.935 with $\alpha = 0.05$).

Table 19. CMJ test before and after the straight sprinting test (centimeters).*

	n	Mean	*SD*	Minimum	Maximum
CMJ pre test	17	46.81	4.54	36.30	52.70
CMJ post test	17	43.29	4.95	32.60	48.60

*CMJ = countermovement jump.

Table 22. Wilcoxon's nonparametric ANOVA.*

	Z	*p*
CMJ: straight sprint	−3.622	<0.001
CMJ: shuttle sprint	−3.622	<0.001
CMJ: COD sprint	−3.627	<0.001

*ANOVA = analysis of variance; CMJ = countermovement jump; COD = change of direction.

Table 20. CMJ test before and after the shuttle sprinting test (centimeters).*

	n	Mean	*SD*	Minimum	Maximum
CMJ pre test	17	46.87	4.47	36.70	53.00
CMJ post test	17	43.00	5.07	30.70	48.30

*CMJ = countermovement jump.

Cutoff points within each test were computed by the means of repeated measures ANOVA, finding in each test the turning point (Table 17) in which the difference among trials became significant ($p < 0.05$).

The different IF% trends, assumed as patterns of fatigue and observed during the 3 tests, are reported (Figure 7). To estimate the possible behavior of IF% in 2 possible

Table 21. CMJ test before and after the COD sprinting test (centimeters).*

	n	Mean	*SD*	Minimum	Maximum
CMJ pre test	17	46.85	4.37	37.20	51.90
CMJ post test	17	43.54	4.99	32.20	47.90

*CMJ = countermovement jump; COD = change of direction.

Table 23. Stiffness tests pre and post sprinting tests (centimeters).

	n	Mean	*SD*	Minimum	Maximum
Stiffness pre test	51	37.66	4.73	24.50	46.00
Stiffness post test	51	34.71	4.09	23.60	44.10

TABLE 24. Stiffness test before and after the 30 m straight sprinting test (centimeters).

	n	Mean	*SD*	Minimum	Maximum
Stiffness pre test	17	37.71	4.65	28.90	44.90
Stiffness post test	17	34.60	4.14	27.30	44.10

TABLE 25. Stiffness test before and after the 30 m shuttle sprinting test (centimeters).

	n	Mean	*SD*	Minimum	Maximum
Stiffness pre test	17	37.16	4.74	24.50	42.80
Stiffness post test	17	34.16	3.89	23.60	38.70

subsequent trials, beyond the 7 actually performed, we considered the linear trend lines of best fit.

The 3 lines of best fit have the following equations, values of R^2 and standard error of prediction (25): IF% 30 m linear ($y = 0.0123x - 0.0045$) − ($R^2 = 0.9561$) − (standard error of prediction ± 0.63); IF% 30 m shuttle ($y = 0.0118x - 0.0076$) − ($R^2 = 0.9232$) − (standard error of prediction ± 0.77); IF% 30 m COD ($y = 0.0081x - 0.0054$) − ($R^2 = 0.8422$) − (standard error of prediction ± 0.83); IF% 30 m COD (log transformation) ($y = 0.1302x - 0.1762$) − ($R^2 = 0.9296$) − (standard error of prediction ± 0.84).

TABLE 26. Stiffness test before and after the COD sprinting test (centimeters).*

	n	Mean	*SD*	Minimum	Maximum
Stiffness pre test	17	38.11	5.04	28.90	46.00
Stiffness post test	17	35.39	4.39	27.30	43.10

*COD = change of direction.

TABLE 27. Wilcoxon's nonparametric ANOVA: stiffness test before and after the same test.*

	Z	*p*
Stiffness: straight sprint	−3.481	<0.001
Stiffness: shuttle sprint	−3.622	<0.001
Stiffness: COD	−3.623	<0.001

*ANOVA = analysis of variance; COD = change of direction.

Countermovement Jump Tests Pre and Post Test

Evaluation tests of lower limb explosive power (CMJ), before (pre) and after (post) the 3 different types of sprinting tests, were performed (Table 18: descriptive statistics of all jumps performed pre and post tests).

There were no significant differences (Kruskal-Wallis) in CMJs performed before ($\chi^2 = 0.192$, $df = 2$, $p = 0.908$) and after each test ($\chi^2 = 0.868$, $df = 2$, $p = 0.648$) between the 3 different tests. Differences found in CMJs performed before and after each single test are presented in Tables 19–21

TABLE 28. Estimates of the possible increase of IF% in further trials, beyond the actual seventh trial (8–10).*†

	Trial 8: estimated IF% ± standard error of prediction	Trial 9: estimated IF% ± standard error of prediction	Trial 10: estimated IF% ± standard error of prediction
Test 30 m straight ($y = 0.0123x - 0.0045$)	≈9.5 ± 0.6	≈10.7 ± 0.6	≈12 ± 0.6
Test 30 m shuttle ($y = 0.0118x - 0.0076$)	≈8.5 ± 0.7	≈9.8 ± 0.7	≈11 ± 0.7
Test 30 m COD ($y = 0.0081x - 0.0054$)	≈6% ± 0.8	≈6.7 ± 0.8	≈7.5 ± 0.8
Test 30 m COD ($y = 0.1302x - 0.1762$)†	≈7 ± 0.8	≈9 ± 0.8	≈13 ± 0.8

*IF% = percent index of fatigue; COD = change of direction.
†With log transformation of *y*.

TABLE 29. Estimate of the exercise to rest ratios in different motor tasks and the optimal recovery time between trials.*

	IF%	MTP (s)	MRT (s)	IIR	OTR (s)
Straight test (7 × 30, ratio 1:5)	4.48	4.53	22	0.204	≈22 (1:5)
Shuttle test (7 × 30, ratio 1:5)	3.78	5.90	29	0.130	≈14 (≈ 1:2.5)
COD test (7 × 30, ratio 1:5)	2.71	8.50	41	0.066	≈10 (≈1:1)

*IF% = percent index of fatigue; MTP = mean time of performance; MRT = mean recovery time; IIR = index of influence of recovery; OTR = optimal time of recovery and exercise to rest ratio; COD = change of direction.

TABLE 30. Estimate of the optimal time of recovery and exercise to rest ratio with a correction factor (OTR corrected).*

Time ratio in different tests	Correction factor	OTR corrected (seconds ± standard error of prediction and ratio)
$\frac{t(30\ m\ straight)}{t(30\ m\ shuttle)}$	0.232	≈18 ± 2 (≈1:3), in shuttle training
$\frac{t(30\ m\ straight)}{t(30\ m\ COD)}$	0.467	≈12 ± 2 (≈1:2), in COD training

*OTR = optimal time of recovery; COD = change of direction.

(descriptive statistics) and Table 22 (nonparametric ANOVA).

Highly significant differences ($p < 0.001$) between the jumps performed before and after each test were observed (Table 22), as evidence of fatigue affecting the participants in the study in a similar way.

Stiffness

Evaluation tests of stiffness of the lower limbs before (pre) and after (post) the 3 different types of sprinting tests were performed (Table 23: descriptive statistics).

No significant differences (Kruskal-Wallis) among the tests were found in stiffness tests performed before ($\chi^2 = 0.492$, $df = 2$, $p = 0.782$) and after each test ($\chi^2 = 0.762$, $df = 2$, $p = 0.683$).

Differences found in stiffness tests performed before and after each single test are presented in Tables 24–26 (descriptive statistics) and Table 27 (nonparametric ANOVA).

Highly significant differences ($p < 0.001$) between the stiffness tests performed before and after each test were observed (Table 27), as evidence of fatigue affecting the participants in the study in a similar way, thus confirming the observation made about CMJ tests.

Pilot Study

To analyze the differences observed among the IF% (dependent variable) among the different types of test (independent variables) with the exercise to rest ratios obtained through mathematical modeling, we carried out a pilot study with the same procedures described in Table 1 and Figure 2, phase 4 (Figure 9). A factorial ANOVA 3 × 7 showed no significant differences among these sets of different motor tasks ($F_{2,18} = 0.674$; $p = 0.522$). Correlations between straight and shuttle ($r = 0.879$, $r^2 = 0.760$; $p = 0.009$), straight and COD ($r = 0.872$, $r^2 = 0.772$; $p = 0.010$) and shuttle and COD ($r = 0.912$, $r^2 = 0.831$; $p = 0.004$) were highly significant. The standard errors of prediction found were, respectively, 0.73, 1.51, and 1.66%.

DISCUSSION

This is the first study to examine the different behavior of the process of fatigue in RSA training, when applying a standard protocol based on 7 repetitions with a 1:5 exercise to rest ratio, in different sprinting modes. To do that, the measurements of the flight time in vertical jump tests (CMJ, stiffness test) before and immediately after the end of each set were taken. The chronometric measurements, taken during testing, were also collected (Tables 4, 7, and 10), analyzed, and then processed to derive the specific patterns of fatigue and to hypothesize the optimal number of repetitions within the set and the best exercise to rest ratios, when shuttle and COD sprint training are performed. The results of this study showed that the patterns of fatigue over time within the different sets, induced by the 3 different sprinting modes, are not the same (Tables 6, 9, 12, and 16) keeping fixed the training protocol parameters (number of repetitions and the 1:5 exercise to rest ratio). Significant differences were found (factorial ANOVA 3 × 7; $p < 0.05$), between the different sprinting sets as indication of different patterns of fatigue, when each score was analyzed as percentage of the PB recorded in each test (IF%). As expected, we found significant differences within each jump test too, performed before and at the very end of each set ($p < 0.001$), as clear evidences of the neuromuscular fatigue induced by each different sprinting effort, but no differences between sets were found ($p > 0.05$), thus not allowing us to use these results as valid and reliable indicators of the different patterns of fatigue induced, as the chronometric results do. Indeed, the analysis of the chronometric results, normalized as percentage of the PBs recorded in each test (IF%), showed a greater sensitivity in discriminating the different patterns of fatigue found for each investigated sprinting mode.

The exercise to rest ratio 1:5 within trials is commonly used in RSA training, over straight sprinting, and it has proved to be effective to induce a significant exertion (derived from the percentage of decay over the repeated trials), while allowing the player the ability to keep exercising within the speed domain (Bishop et al. (1) and Girard et al. (13)). The average percentage of decline between the first and last trials is reported to be about 9%, and the trend over time of this decline, expressed as IF%, tends to follow a curve, fairly well described by a straight line in straight sprinting ($r^2 = 0.96$ in this study). When analyzing the patterns of fatigue in shuttle and slalom sprinting (COD), we found different patterns, as probable indicators of lower levels of fatigue induced by the different sprinting modes. This is probably because of several causes, among which we consider fundamental:

- A too long recovery time that is obtained from applying the 1:5 exercise to ratio to the shuttle or COD sprinting (13).
- The different muscle effort required to perform these specific motor tasks, in which the *construct* of agility might play an important role (1,3,26–28).

We also sought to determine if there were significant differences and associations between the sprint tests and the lower limb explosive power, measured through the CMJ and the stiffness tests, performed before and after each sprint test.

Figure 8 reports that the sprint tests performed have statistically significant correlations ($p < 0.05$) with the values of explosive power measured before each test (CMJ: straight sprinting $r = 0.50$, $p < 0.05$; CMJ: shuttle sprinting $r = 0.54$, $p < 0.05$; CMJ-COD sprinting $r = 0.68$, $p < 0.01$), suggesting that the ability of accelerating needed to meet the performance requirements of these types of tests is very likely linked to the physiological capacity of explosive muscle power, measured through the CMJ test. Significant differences ($p < 0.001$) were found between the results measured pre and post test, in the same test (Tables 18–21), underlining the fatigue phenomena induced by the trials performed in the sets. However, the small differences found between the measures obtained in the different sprint tests, before and after the sets, are not significant ($p = 0.868$ for differences in pretests, $p = 0.648$ for differences in posttests). Therefore, the values recorded during the CMJ testing seem not appropriate indicators of the different indices of fatigue found and probably induced by the different types of motor task performed and the exercise to rest ratio used. A similar behavior was observed with respect to the stiffness values measured before and after each sprint test (Tables 22–27).

Significant correlations were found in different types of test (Tables 13 and 14). These correlations are particularly significant: e.g., between the 30 m straight sprinting test and the 30 m COD sprinting test ($r = 0.346$, $n = 113$, $p < 0.001$) and between the 30 m shuttle sprinting test and the 30 m COD sprinting test ($r = 0.632$, $n = 113$, $p < 0.001$). Although different abilities and neuromuscular skills are involved to meet the different requirements in these different motor tasks, nevertheless, the relevance of the general ability to accelerate (positive and negative acceleration) is clear.

In this study, we analyzed the patterns of time recorded in the tests, both as absolute (the actual time needed to sprint for 30 m in different modalities) and relative values (as the percentage of the increased time of performance in the trials compared with PB), and assumed as an IF%. The purpose was to identify, within the sets, possible cutoffs (turning points) able to indicate at which level the symptoms of fatigue became statistically significant as indicators of the progressive performance decay (Tables 16 and 17 and Figure 7). These cutoff points, significant from a statistical point of view ($p < 0.05$), suggest different dynamics of fatigue in relation to the different tests and recovery time, determined by the 1:5 exercise to rest ratio. It is clear that the 30 m straight sprinting test induced an increase of the time of performance at the earliest repetition in the set and gradually led to an IF% that settled around 9% in the last trial of the set (average 4.48% in the set, Table 16). Differences are observed in the other 2 tests, with particular reference to the 30 m COD sprinting test, where the different motor tasks (shuttle sprinting or continuous COD) induced a significantly longer exercising time on the same distance (30 m), with average speeds (and mean acceleration rates) significantly lower than those recorded in the straight sprinting test but with a rest time within trials of an almost double dimension in the COD test than that of the straight one (according to the 1:5 exercise to rest ratio, Table 29).

The differences found in the indices of fatigue (straight vs. shuttle, $p = 0.022$; straight vs. COD, $p < 0.001$) are emphasized by the different cutoffs observed, respectively, at the second, fourth, and fifth trials in the different tests (Tables 16 and 17).

The interaction between the types of test and the recovery time was found to be significant in the factorial ANOVA performed ($p = 0.004$), allowing us to suggest that, in addition to the intrinsic structure of the tests organized for 30 m, but with different modes of execution, an important role in the variance of the observed patterns might be played by the recovery time, administered by the 1:5 ratio.

The present work suggests that training sessions aimed at increasing the capacity of RSA in nonlinear and multidirectional sprints (shuttle and COD sprinting) might imply exercise to rest ratios different from the one adopted in straight and unidirectional sprinting task, very likely because of the lower average speeds and in consideration of the different modulations of acceleration that these motor tasks involve. Increasing the number of repetitions in the set might also be assumed as an efficient alternative to induce an adequate level of fatigue.

The study of the considered variables has allowed the construction of a mathematical regression model that could offer the opportunity to estimate the optimal number of repetitions within the sets, in nonlinear and multidirectional repeated sprint training (Figure 7), keeping the 1:5 exercise to rest ratio.

We can note that by making an estimate within 3 trials beyond the actual seventh trial performed (trials simulated 8–10), the possible level of IF% leads to the situation reported in Table 28.

Obviously, the authors stress the mere indicative value of this extrapolation, which starts from an oversimplification of the biological phenomenon fatigue, reduced to a non–real linearity, purely for study purposes.

However, through the analysis of the possible increases of IF %, beyond the seventh trial (Table 28) and considering the actual IF% as indicator of the effects of fatigue observed in players engaged in training sessions aimed at improving the RSA through different motor tasks, we can suggest that training sessions based on shuttle and particularly COD sprinting, with the 1:5 exercise to rest ratio or designing sets with 6–7 repetitions, cannot raise effectively the levels of fatigue, recognized as the training target to reach (approximately 9% in the last trial, and about 5% as the average increase on all trials, Table 15, percent general index of fatigue , according to Fitzsimmons (9)).

In particular, the motor tasks involving sprinting with CODs seem to be unable to stimulate at their best the energy systems involved (in particular the capacity of the anaerobic alactacid system) if the number of repetitions in the set and the exercise to rest ratio are the same used for straight sprinting training (Table 15). We can observe (Table 28) that in a hypothetical 10th trial in the COD test, assuming linearity, one would expect a still high potential level of performance (IF% at about 7.5), probably not specifically aimed at increasing a specific RSA.

Again through a mathematical model, the authors have tried to isolate the influence of the recovery on the observed performances, to provide an exercise to rest ratio able to induce the level of fatigue observed in the 30 m straight test, according to the protocol presented in Table 1.

To estimate the influence of the recovery time on the IF% recorded in the different tests, we related the IF% found in the 30 m straight test, with the mean recovery time and the mean time of performance collected in all the trials for each test, thus obtaining an index of influence of the recovery on the overall performance.

Through proportionality, the hypothetical optimal time of recovery is then estimated in order to be proposed in the various sprinting tasks (Table 29) to induce a level of fatigue similar to that observed in straight trials.

The authors also considered the possibility of a correction factor on the estimate of the optimal time of recovery for nonlinear and multidirectional sprint activities.

This factor takes into account the mean time of performance of the 2 different tests (shuttle and COD) and their ratio with the 30 m linear test, taken as an absolute reference (Table 30).

The exercise to rest ratios proposed by the authors and derived from the mathematical models presented in this study (straight ≈ 1:5, 22 seconds; shuttle ≈ 1:3, 18 seconds; COD ≈ 1:2, 12 seconds) were already experimentally applied in a pilot study, with a small sample ($n = 2$), using the same protocol as in the main study, and adopting the lower limits of the estimated rest time, proposed in Table 30. They proved to be able to induce similar trends in fatigue in a training protocol based on sets of 7 repetitions each, over 30 m, in the 3 different sprinting tasks investigated (Figure 9).

This study has some limitations that should be highlighted to manage properly the conclusions we reached and the practical implications we are proposing; of course, they both call for future investigations. This refers in particular to the following:

- The size of the sample ($n = 17$, main research; $n = 2$, pilot study) and the possible generalization of the results (external validity).
- The mathematical models adopted to provide possible predictors about the optimal number of repetitions in the sets and the optimal exercise to rest ratios; these inferences are made by the authors with a full awareness of the likelihood limit present in a simple mathematical model in comparison with reality, especially while attempting to represent complex biological phenomena, such as fatigue, in high coordinative motor tasks.

PRACTICAL APPLICATIONS

The number of high-intensity repeated sprint bouts performed during a soccer match is a major factor that discriminates international competition from national and domestic level competition (12). Match analysis procedures have confirmed that straight sprinting may not be considered the unique mode of traveling on the pitch during the matches, whereas an important role of the performance is played by the ability of the players to accelerate while changing direction and orientation (3,27). The need of effective training methods specifically aimed at improving these RSAs is widely recognized among practitioners (1,3,10,13). Crucial components of these methods are the number of repetitions within the set, the exercise to rest ratio within each repetition, and the number of sets and the exercise to rest ratio within each set (1,9,13). In the present study, we focused on the optimal number of repetitions and the exercise to rest ratio within each trials, when different modalities of sprinting, such as shuttle or COD, are performed. The data presented are limited by subject number and do not provide any information about the possible physiological variations. Nevertheless, the current report provides insight into the fatigue phenomena investigated by the mean of the time of performance and the mathematical modeling. Some useful practical applications may derive from this study. We are referring to the possibility of designing specific and effective RSA training sessions, aimed at improving the repeated COD or shuttle sprint abilities. These practical applications may be considered as guidelines for choosing the optimal number of repetitions and the opportune exercise to rest ratios within trials, when training the repeated shuttle or COD sprint ability:

- Adopting the 1:5 exercise to rest ratio, the fatigue phenomena observed through the repeated trials in different tests suggest the existence of different dynamics of fatigue depending on the type of sprinting patterns required. In the light of this, the estimated number of required repetitions, to obtain an opportune level of fatigue, is clearly a function of the ratio adopted (Table 28). In particular, we emphasize that training sessions aimed at improving the repeated sprint ability with COD, keeping a 1:5 ratio, might allow an amount of exercise in the sets up to 10–12 repetitions, thus greater than the usual amount adopted in this kind of training (6–8 repetitions).
- If a different approach is needed (e.g., in tapering period) and a sensible reduction in exercising volume is opportune, we suggest a different exercise to rest ratio for shuttle sprinting ($\approx 1{:}3$) and COD sprinting ($\approx 1{:}2$) training, to reach a level of fatigue similar to that obtained in straight sprinting training, within 6–7 repetitions per set.

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