Strength and Endurance in Elite Football Players

Article *in* International Journal of Sports Medicine · May 2011

DOI: 10.1055/s-0031-1275742 · Source: PubMed

Strength and Endurance in Elite Football Players

Authors J. Helgerud[1,2,3], G. Rodas[4], O. J. Kemi[5], J. Hoff[1,6]

Affiliations Affiliation addresses are listed at the end of the article

Key words
- 1RM
- sprint performance
- counter movement jump
- VO_{2max}
- running economy
- Champions League

Abstract

We aimed to improve the physical capacity of a top-level elite football team during its pre-season by implementing a maximal strength and high-intensity endurance training program. 21 first league elite football players (20–31 yrs, height 171–194 cm, mass 58.8–88.1 kg) having recently participated in the UEFA Champions' League, took part in the study. Aerobic interval-training at 90–95% of maximal heart rate and half-squats strength training with maximum loads in 4 repetitions × 4 sets were performed concurrently twice a week for 8 weeks. The players were not familiar with maximal strength training as part of their regular program. Maximal oxygen uptake (VO_{2max}) increased 8.6% (1.7–16.6) ($p<0.001$), from 60.5 (51.7–67.1) to 65.7 (58.0–74.5) $mL \cdot kg^{-1} \cdot min^{-1}$ whereas half-squat one repetition maximum increased 51.7% (13.3–135.3) ($p<0.001$), from 116 (85–150) to 176 (160–210) kg. The 10-m sprint time also improved by 0.06 s (0.02–0.16) ($p<0.001$); while counter movement jump improved 3.0 cm (0.1–6.2) ($p<0.001$), following the training program. The concurrent strength and endurance training program together with regular football training resulted in considerable improvement of the players' physical capacity and so may be successfully introduced to elite football players.

Introduction

Strength and endurance are important co-determinants of football performance, as they are key features of physical capacity and main regulators of important football-specific tasks [21]. Maximal strength is associated with power production, as reflected by the relationship between one repetition maximum (1RM) in half-squat and acceleration, movement velocity and jumping [22, 32, 36]. On average, short sprints occur every 90 s during a football match. Sprints last 2–4 s [4, 28], start with a sudden change in running direction and/or from a running start accentuating the accelerative component even more [35], and are almost always shorter than 30 m, with half of them being shorter than 10 m [34]. It should though be noted that the players' position influences the extent of sprinting with forwards sprinting most frequently [30, 35]; however, sprinting constitutes only 1–6% of the total distance covered during a match or 0.5–3% of the effective play time [1, 4, 28]. Nonetheless, such strength- and power-demanding activities often comprise the decisive parts of a football match. In addition, the high-intensity bouts are performed above the lactate threshold (LT), and depend thus on anaerobic energy sources [16].

Maximal strength training has also shown to improve running economy in distance runners and in non-elite football players [23, 33]. Hoff and Helgerud [23] reported significant improvements in running economy (RE) of 4.7% among football players after a maximal strength training intervention that improved their half-squat 1RM by 33%. No changes were observed in body weight or maximal oxygen uptake (VO_{2max}).

It is the player's aerobic capacity that aids recovery in between the exhaustive power-demanding sprints and the high-intensity bouts. Moreover, aerobic capacity and its key factor VO_{2max} are crucial in top-level football to fuel the extensive running and movement required during a match [21], during which a player covers 8–12 km at an average intensity of 80–90% of maximal heart rate (f_{cmax}), or close to LT [16]. Increasing VO_{2max} increases the distance covered during a match and has also been linked to a corresponding 25% increase in ball involvements and 100% increase in number of sprints performed [16].

accepted after revision
March 18, 2011

Bibliography
DOI http://dx.doi.org/10.1055/s-0031-1275742
Published online: 2011
Int J Sports Med

ISSN 0172-4622

Correspondence
Prof. Jan Helgerud, PhD
Norwegian University of Science and Technology
Department of Circulation and Medical Imaging
N-7489 Trondheim
Trondheim
Norway
Tel.: +47/91/821 892
Fax: +47/72/828 372
Jan.Helgerud@ntnu.no

As elite football seasons are getting longer and pre-seasons correspondingly shorter, training programs need focus on strength and endurance training concurrently, together with technical and tactical exercises. However, previous studies have shown that concurrent strength and endurance training will result in a reduced capacity to develop strength, but will not affect the magnitude of increase in VO_{2max} [11,19,27]. Others have shown that both strength and endurance capabilities can be attenuated [7,18]. The reduced physiological adaptations typical of single-mode training are also shown on the hormonal, muscular and molecular level [8,24]. Few data are available regarding the effect of simultaneous strength and endurance training that have investigated fit individuals who are able to tolerate much higher intensity exercise training programs [18,24].
It has now become apparent that strength and endurance training requires maximal efforts and high intensity to yield best effects [17,21]. However, previous interventions have, without exception, never had access to top international-level football teams. Coaches at this level are often afraid of negative side effects from intensive training periods, such as injuries as well as fatigue and loss of trainability. This study using elite footballers is necessary as coaches are not willing to transfer the results from trials using lower level teams.
The main aim of the study was to implement a 2-month concurrent maximal strength training and high aerobic intensity interval endurance training during the pre-season period to study if elite footballers achieved similar beneficial adaptations as previously only reported in groups at a lower performance level. An improvement in VO_{2max} and maximal strength of similar magnitude as that attained by Helgerud et al. [16] for youth players and by Hoff and Helgerud [23] for adult players were hypothesised. Secondary aims of this study were to report any negative side effects from intensive training periods and present normative physiological data on professional elite football players.

Materials and Methods

Subjects

21 male elite football players from their premier league took part in the study. They had successfully competed in the UEFA Champions' League tournament in the preceding year. A non-controlled study was conducted introducing strength and endurance training intervention twice weekly over an 8-week period. The players were full-time professional football players and trained on a daily basis. Intervening in a team at this level presented a constitutional problem, because the team management did not permit randomisation. Also, a control group outside the football team was neither feasible nor appropriate, as such a group would not be comparable to the professional players and nor would they receive the same attention from the team management during the intervention period, as the team proceeded with its regular seasonal training program with the addition of this intervention. Thus a one-group pretest – posttest design was used. The players' physical characteristics are presented in ▶ **Table 1**. Each subject reviewed and signed consent forms approved by the Human Research Review Committee prior to entering the study. The study has also been performed in accordance with the ethical standards of the International Journal of Sports Medicine [13].

Table 1 Physical characteristics, maximal oxygen uptake and running economy of the players, pre- and post-testing.

Subject	Age (yrs)	Height (cm)	Mass (kg)		VO_{2max}						CR 11 km·h^{-1} (mL·kg$^{-0.75}$·m^{-1})		f_{cmax} (beats·min^{-1})		RER	
					L·min^{-1}		mL·kg^{-1}·min^{-1}		mL·kg$^{-0.75}$·min^{-1}							
			Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
1	26	189	87.6	87.0	5.60	6.48	63.9	74.5	196	228	0.91	0.84	190	188	1.12	1.14
2	24	182	77.4	77.5	4.69	5.10	60.6	65.8	180	195	0.85	0.78	200	197	1.08	1.10
3	25	184	77.6	78.1	4.47	4.64	57.6	59.4	171	177	0.89	0.85	200	198	1.15	1.13
4	26	190	88.0	88.1	5.69	6.06	64.7	68.8	198	211	0.85	0.80	190	192	1.17	1.19
5	26	173	58.8	60.1	3.92	4.26	66.7	70.9	185	197	0.80	0.77	210	208	1.12	1.10
6	20	171	68.0	70.1	4.52	5.07	66.5	72.3	191	209	0.79	0.78	206	202	1.07	1.10
7	24	187	78.7	82.0	4.26	4.85	54.1	59.1	161	178	0.84	0.78	210	206	1.09	1.13
8	23	183	72.6	74.9	4.47	4.88	61.6	65.2	157	154	0.86	0.84	197	200	1.15	1.13
9	26	185	80.9	81.8	5.43	5.65	67.1	69.1	201	208	0.88	0.83	178	176	1.18	1.19
10	24	188	77.2	78.2	4.17	4.88	54.0	62.4	160	186	0.85	0.80	210	208	1.06	1.08
11	23	183	80.8	83.5	5.17	5.63	64.0	67.4	192	204	0.86	0.82	200	202	1.11	1.14
12	23	194	70.0	71.8	4.14	4.78	59.1	66.6	171	194	0.86	0.82	204	200	1.17	1.15
13	24	187	83.7	82.5	4.65	4.97	55.6	60.2	168	182	0.86	0.85	185	187	1.09	1.14
14	26	188	87.3	88.8	4.75	5.41	54.4	60.9	166	187	0.83	0.82	198	195	1.20	1.17
15	31	183	86.0	84.7	4.45	4.91	51.7	58.0	149	151	0.81	0.82	182	180	1.10	1.13
16	23	181	79.1	81.1	4.62	4.82	58.4	59.4	174	178	0.87	0.84	195	197	1.15	1.17
17	20	185	75.7	77.5	4.60	4.96	60.8	64.0	179	190	0.83	0.81	206	204	1.13	1.10
18	27	176	71.0	71.2	4.66	5.15	65.6	72.3	191	210	0.84	0.80	200	202	1.11	1.15
19	23	183	76.5	78.5	5.05	5.80	65.8	73.9	195	220	0.91	0.88	197	193	1.07	1.12
20	31	186	86.1	84.4	5.24	5.68	60.9	67.3	185	204	0.86	0.82	206	203	1.12	1.11
21	29	184	82.8	85.7	4.83	5.37	58.3	62.7	176	191	0.86	0.83	196	197	1.14	1.18
average	25	184	78.4	79.4*	4.73	5.21*	60.5	65.7*	178	193*	0.85	0.82*	198	197	1.12	1.14
min	20	171	58.8	60.1	3.92	4.21	51.7	58.0	149	151	0.79	0.77	178	176	1.06	1.08
max	31	194	88.0	88.8	5.69	6.48	67.1	74.5	201	228	0.91	0.88	210	208	1.20	1.19

VO_{2max}: maximal oxygen uptake; CR: running economy; f_{cmax} : maximal heart rate; RER: respiratory exchange ratio at VO_{2max}
Differences between pre- and post-tests: * , $p < 0.001$

Testing

After a 20 min thorough warm-up at approximately 50–60% of VO_{2max}, a 20-m sprint test was performed on an indoor parquet-covered sports field, with photocells (Brower Timing Systems, Draper, UT, USA) 1 m above the ground that recorded the time taken. Each subject ran 2 sprint trials, separated by 5 min of rest, with the best result used in the analysis. The players self-started from a static position with one foot on the starting line, and with the time being recorded from when the photocell beam was intercepted by the trunk. The magnitude of test-retest error for 10 m sprinting has been reported as 0.02 s or <1% [12].

Counter movement jump (CMJ) was measured 5 min later on a force platform (Kistler, Winterthur, Switzerland) using Bioware software, and was determined as the centre of mass displacement calculated from body mass-corrected force development. The best jump from 3 attempts was recorded. A 2 min rest period was allowed between efforts. Hands were placed on the hips during the jump tests. The repeatability of the CMJ has been reported with a coefficient of variation of 1.6% [9]. 5 min later, maximal strength was measured by a half-squat 1RM (90° knee joint between femur and tibia), with competition standard Olympic style bars and weights (T-100G, Eleiko, Halmstad, Sweden). Testing was carried out using 5 kg increments and 1–2 min between each trial. 1RM was normally determined using 3–5 trials. The players were familiar with half-squats as part of their regular strength training programs, although with a much reduced load (<70% 1RM).

After the sprint, jumping and strength tests, each player warmed up for 10 additional minutes on a treadmill (Technogym, Runrace, Italy) at 50–60% of VO_{2max}, after which the treadmill speed was increased to 11 km · h^{-1} and kept there for 5 min. The average oxygen uptake (VO_2) between 4.0 and 4.5 min was used to calculate running economy (CR), as outlined previously [15]. The speed of the treadmill was then increased by 1 km·h^{-1} every minute to a level that brought the subject to exhaustion within 5–6 min. Inclination was kept constant at 5.5% throughout the treadmill test. The average of the 3 highest 10-s measurements determined VO_{2max} when a respiratory exchange ratio (RER) above 1.05 was present [3]. Immediately after the VO_{2max} determination, each subject ran for 2 min at an exercise intensity of 50–60% of VO_{2max} directly followed by another maximal intensity run, resulting in exhaustion after ~3 min. The highest heart rate (f_c) throughout the test was recorded as f_{cmax}. Heart rate was measured with short-range radio telemetry (Polar Accurex Plus, Polar Electro, Kempele, Finland). VO_2, minute ventilation (V_E) and breathing frequency (f_b) were measured using a Cortex Metamax II (Cortex, Leipzig, Germany), which previously had been validated [25]. We routinely test VO_{2max} after the strength tests and find similar VO_{2max} as when performing the treadmill test on a separate day (unpublished observations).

Training protocol

After a 10-min warm-up, the aerobic training intervention consisted of interval training, comprising of 4×4 min running on a treadmill (5.5% inclination) at 90–95% of f_{cmax} for each player, separated by 3-min periods jogging at 50–60% of f_{cmax}. After a 15-min break, subjects performed the maximal strength training. This consisted of 4-repetition maximum of half-squats (90° knee joint angle) using a bar and weights in 4 series with emphasis on maximal mobilisation in the concentric phase. If 5 repetitions were managed the load was increased. Players had a 3-min rest between each series. The training sessions lasted 1 h in total.

Table 2 Overview football training in pre-season of elite professional players. Average hours training per week and (intensity in % of maximal heart rate).

warm up	2.5 h (60–80)
stretching	1.5 h
endurance running	1.5 h (90–95)
small sided games	2.5 h (85–90)
technical training	2.0 h (60–70)
strength training	1.0 h
match play	1.5 h (85–90)
total	12.5 h

The players were familiar with treadmill running and strength training as part of their regular training programs, although previously it had been carried out at lower intensities and loads. The training protocol was administered twice weekly in the mornings over an 8-week period during the pre-season. A regular week of football training consisted of six 1.5-h practice sessions plus a match, in which the emphasis was on technical and tactical match-like situations; a total of 12.5 h training per week was carried out (**Table 2**). The compliance rate of 80% was the criteria for completion of the study. Training attendance, as well as any negative side effects during the training period, such as injury, fatigue or loss of trainability was recorded by the team's physical therapists. 2 players did not perform the pre-test, and 2 other players did not perform post-test due to illness not related to training. These players are not included in the material.

Allometric scaling

Comparisons between athletes' VO_{2max} and 1RM are often made in terms of absolute measures (L · min^{-1}, kg) or relative to body weight (mL · kg^{-1} · min^{-1} for VO_{2max} or kg · kg bw^{-1} for 1RM, respectively) both of which may be functionally imprecise, especially if body mass differs or changes during the course of the study [6,14,15]. Neither the oxygen cost of running at a standard velocity nor strength (1RM) increase in direct proportion to body mass in trained individuals. Dimensional scaling suggests that comparisons between a small and a bigger individual should be expressed by kg body weight raised to the power of 0.67, as mL · kg$^{-0.67}$ · min^{-1} or kg · kg bw$^{-0.67}$ [14]. Based on descriptive data [3,6,15], comparisons of VO_{2max} should be expressed relative to body mass raised to the power of 0.75 when running. If dimensional scaling is not used, discussions of relative strength and endurance would underestimate the big athlete and overestimate the small athlete [37].

Statistical analyses

Data are presented as individual results with mean (min-max) values. Student's t-test was used to determine changes from pre- to post-test. Pearson's product-moment correlation coefficient was used to determine the relationships between selected parameters. $P<0.05$ was considered statistically significant. The number of subjects whose improvements remained below the coefficient of variance (CV) for each given dependent variable was calculated. The relationship between VO_{2max}, maximal strength and body mass was evaluated using linear regression analyses (log-log plots). Statistical power was estimated using nQuery Advisor software (Version 3.0, Statistical Solutions, Cork, Ireland). Given the standard deviation in repeated determination of VO_{2max} [3] the number of subjects studied permitted detection of a 2.7% difference between pre- and post-training ($p=0.05$, power$=0.90$).

Results

Both VO_{2max} (mL · kg^{-1} · min^{-1}) and maximal strength (squat 1RM, kg) improved by 8.6% (1.7–16.6) ($p<0.001$) and 51.7% (13.3–135.3) ($p<0.001$), respectively, during the training period (**Table 1, 3**). Body mass increased by 1.0 kg (−1.8–3.3) ($p<0.01$).

If 3 goalkeepers are excluded, the mean VO_{2max} after training was 5.27 (4.26–6.48) L · min^{-1} or 66.5 (59.4–75.5) mL · kg^{-1} · min^{-1}. At 11 km · h^{-1} fixed speed, CR improved by 3.5% (−1.2–7.7), from 0.85 (0.79–0.91) mL · kg$^{-0.75}$ · m^{-1} at pre-test to 0.82 (0.77–0.88) mL · kg$^{-0.75}$ · m^{-1} at post-test, whereas average f_c decreased from 178 (154–192) to 170 (148–189) beats · min^{-1} ($p<0.001$). Respiratory exchange ratio (RER) decreased from 1.02 (0.95–1.14) to 0.97 (0.90–1.09, $p<0.001$) and V_E decreased from 109.4 (75.8–136.4) to 102.7 (78.8–130.8) L · min^{-1} ($p<0.05$) during the experimental period. CMJ and 10-m and 20-m sprint times improved following training on average by 5.2% (0.2–12.3), 3.2% (1.1–8.8) and 1.6% (0.0–4.0), ($p<0.001$), respectively (**Table 3**). The number of subjects that remained below the CV for the improvements were in VO_{2max}: 3, 1RM: 1, CR: 4, CMJ: 6, 10-m and 20-m sprint times: 6.

VO_{2max} (L · min^{-1}) did not increase proportionally to body mass in this sample of football players. The exponent was found to be significantly less than unity, and the value was 0.70 ($r=0.66$, $p<0.001$) for VO_{2max}. Squat 1RM correlated significantly with 10-m sprint time both pre- and post-training period ($r=-0.51$ and $r=-0.46$, $p<0.05$, respectively). However, there was no linear relationship between the changes in 1RM and the changes in 10-m sprint time in the present study.

The physical therapists did not report any negative side effects from the 8 weeks intensive training period. However, the day before the post-test, the team returned from a 2-week pre-season training camp that included 1 or 2 training sessions each day and 2 matches. The players complained of stiff legs after returning from the training camp.

Discussion

The strength and endurance training intervention together with the regular football training led to considerable improvements in strength and endurance capacity, of a similar magnitude as previously reported with separate strength and endurance interventions [16,23]. The training effects in elite football players are of a similar magnitude as for lower level football players. However, due to the non-controlled design of the present study it descriptively reports changes in endurance and strength over a pre-season period. On the other hand it is an explicit trial in the exceptional population of professional elite football players.

The change in squat strength from a position with 90° between femur and tibialis was on average 61 kg (20–115) following 8 weeks of training (16 training sessions). The strength improvement from these sessions of 4×4 repetitions using 85+% of 1RM with emphasis on maximal mobilisation of force in the concentric phase, was similar to that found in a group of lower level football players [23]. The average strength improvement of 52% (13–135) took place with only an average of 1 kg (−1.8–3.3) change in body weight, supporting the neural adaptation theory [2,5,20,22,31]. Football play is dominated by acceleration and braking, and Newton's second law of motion ($F=m \cdot a$) establishes that for a given mass (the player's bodyweight), acceleration is proportional to force magnitude. This states the relationship between force and sprint and jump results. A sub-

Table 3 Maximal strength, vertical jumping height, and sprint tests of the players, pre- and post-testing.

Subject	1RM (kg)		1RM ($kg \cdot m_b^{-1}$)		1RM ($kg \cdot m_b^{-0.67}$)		CMJ (cm)		Sprint 10 m (s)		Sprint 20 m (s)	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
1	110	170	1.3	2.0	5.5	8.5	58.0	60.8	1.90	1.85	3.20	3.15
2	150	170	1.9	2.2	8.1	9.2	50.5	53.2	1.91	1.86	3.14	3.13
3	100	170	1.3	2.2	5.4	9.2	56.3	58.6	1.95	1.92	3.29	3.23
4	150	175	1.7	2.0	7.5	8.7	54.9	56.3	1.77	1.75	2.97	2.95
5	90	160	1.5	2.7	5.9	10.3	55.0	61.2	1.96	1.91	3.29	3.23
6	120	160	1.8	2.3	7.1	9.3	51.1	52.5	1.88	1.85	3.16	3.12
7	120	190	1.5	2.3	6.4	9.9	66.9	71.6	1.92	1.87	3.20	3.11
8	125	200	1.7	2.7	7.1	11.1	62.2	62.3	1.73	1.69	2.99	2.96
9	120	160	1.5	2.0	6.3	8.4	49.2	54.9	1.89	1.85	3.15	3.12
10	130	180	1.7	2.3	7.1	9.7	65.2	67.2	1.90	1.82	3.11	2.99
11	110	180	1.4	2.2	5.8	9.3	53.6	54.1	1.83	1.80	3.10	3.10
12	120	170	1.7	2.4	7.0	9.7	59.0	64.6	1.94	1.79	3.22	3.07
13	150	190	1.8	2.3	7.7	9.9	59.6	63.1	1.78	1.67	2.90	2.90
14	110	210	1.3	2.4	5.5	10.4	58.4	61.8	1.87	1.80	3.21	3.17
15	90	160	1.1	1.9	4.6	8.2	50.5	56.7	1.96	1.93	3.29	3.22
16	140	200	1.8	2.5	7.5	10.5	61.2	61.5	1.81	1.71	3.10	3.06
17	100	160	1.3	2.1	5.5	8.7	55.6	59.5	1.95	1.86	3.16	3.05
18	85	200	1.0	2.8	4.0	11.5	57.4	59.0	1.85	1.79	3.05	2.96
19	90	160	1.2	2.0	4.9	8.6	54.0	57.4	1.90	1.84	3.21	3.17
20	110	180	1.3	2.1	5.6	9.2	62.0	64.2	1.84	1.81	3.05	2.98
21	110	160	1.3	1.9	5.7	8.1	60.0	64.5	1.81	1.65	3.02	2.91
average	116	176*	1.5	2.2*	6.3	9.4*	57.2	60.2*	1.87	1.81*	3.13	3.08*
min	85	160	1.0	1.9	4.0	8.1	49.2	52.5	1.73	1.65	2.90	2.90
max	150	210	1.4	2.8	8.1	11.5	66.9	71.6	1.96	1.93	3.23	3.23

1RM: one repetition maximum half squat; m_b: body mass; CMJ: counter movement jump; Differences between pre- and post-tests: *, $p<0.001$

stantial increase in strength per kg body weight would thus be expected to increase acceleration.
The results showed a significant improvement in CMJ of 3.0 cm (0.1–6.2) or 5.2 % (0.2–10.8), in line with results from a similar intervention with World-Cup ski jumpers [22]. It is important to note that no specific jumping height training was carried out, except that implicit in the football play. Commonly used plyometrics show no comparable development in intervention experiments [26]. Similarly, highly significant improvements in 10-m and 20-m sprint times were found, and there was a significant correlation between squat 1RM and 10-m sprint time in line with previous studies [32, 36]. No specific sprint training was carried out during the intervention period other than what was implicit in football play. These improvements in 10-m have obvious practical implications in match play.
As a result of the pre-season training, CR improved on average by 3.5 % (− 1.2–7.7). This is in line with a previous study that demonstrated an average 4.7 % improvement in CR after a training intervention that involved maximal strength squat training 3 times a week for 8 weeks. This was with football players at a lower performance level than in the present study [23].
A study using a similar endurance training program to that which has been used improved CR by 6.7 % in 18-year-old football players [16]. The improvement in CR in that study can not be the simple result of substrate shift arising from improved endurance, but a result of more running practice. This is well illustrated in a study by Helgerud et al. [17]. In that study, all training groups improved CR the same, independent of changes in VO_{2max}. However, separate interventions seem to yield higher improvements in CR than the combined intervention in the present experiment.
An explanation for this might lie in a possible negative interaction of the 2 interventions. Although a more likely explanation is that the day before the post-test, the team returned from a 2-week pre-season training camp and the players complained of stiff legs, which normally influences high-velocity performance the most. However, a lack of control over some aspects of the intervention is the cost when studying elite football players.
The average 8.6 % improvement in VO_{2max} is in line with a previous study in which a similar endurance training program improved VO_{2max} by 10.8 %, in 18-year-old football players [16]. Those subjects did not perform any strength training; thus, development of VO_{2max} does not seem to be compromised by the maximal strength training carried out in the same training session over an extended period of time. This is also in line with previous studies that report the only negative interference effect is a reduced capacity to develop strength when training strength and endurance concurrently [11, 27]. However, others have clearly shown an interference effect at both whole body adaptations and molecular level [7, 8, 18, 19, 24]. Kraemer et al.'s [24] concluding remark is that the observed incompatibility of strength and endurance training may be due, at least in part, to some type of overtraining. Since the subjects in the present study are fitter than in the referred studies, they should be able to tolerate much higher intensity exercise training programs [18, 19, 24]. But the possibility of overtraining warrants further investigation.
Although data so far are sparse at the present fitness preconditions, it is tempting to suggest that concurrent maximal strength and endurance training may successfully be implemented in elite football players. It should be noted that the present improvements occurred despite the current players starting with a high initial VO_{2max} before the intervention, and they were at a far higher performance level than the above mentioned 18-year-old players [16]. The training intervention took place after a 3-week break after the termination of the previous season. During the break, the players had been carrying out voluntary endurance training to maintain capacity. The pre-test values were similar to other reports of players at this level of performance at this stage of the season [10, 21, 29]. If the goalkeepers are taken out of the analyses, the average VO_{2max} for this group is 66.5 $mL \cdot kg^{-1} \cdot min^{-1}$ at the post-test. Only one previous study has reported higher values than this for an elite football team [37]. Hoff and Helgerud [21] proposed that short term future development of football will exceed today's level of fitness and bring average team values up to 70 $mL \cdot kg^{-1} \cdot min^{-1}$ (VO_{2max}) and 200 kg (half-squat 1RM).

Limitations of the Study

Due to the uncontrolled nature of the present study, it can only be descriptive and thus report changes in endurance and strength or any negative side effects over a pre-season training period. Unfortunately, this design does not allow us to say why the subjects improved. Certainly, it could be due to the treatment, but it could also be due to other factors. On the other hand the data is novel and we do believe that researchers and coaches may benefit from a set of data based on elite football players.

Conclusions

During 8 weeks of concurrent maximal strength and high-intensity endurance training together with regular football training, this elite-level professional team achieved similar beneficial adaptations as previously only reported in groups at a considerably lower performance level.
After the training intervention, test results were equivalent to the highest values reported in the literature for a football team in terms of VO_{2max} and squat 1RM. Thus, rigorous training interventions for maximal strength and aerobic endurance may successfully be implemented in the pre-season training schedule for top-level football teams.

Acknowledgements

The authors wish to acknowledge the coaches and the football players for their contributions.

Affiliations
[1] Norwegian University of Science and Technology, Department of Circulation and Medical Imaging, Trondheim, Norway
[2] Hokksund Medical Rehabilitation Centre, Norway
[3] Telemark University College, Department of Sports and Outdoor Life Studies, Bø, Norway
[4] Medical Services F.C. Barcelona, Barcelona, Spain
[5] Institute of Cardiovascular and Medical Sciences, University of Glasgow, United Kingdom
[6] St. Olav University Hospital, Department of Physical Medicine and Rehabilitation, Trondheim, Norway

References

1 *Ali A*, *Farrally M*. A computer-video aided time-motion analysis technique for match analysis. J Sports Med Phys Fitness 1991; 31: 82–88
2 *Almåsbakk B*, *Hoff J*. Coordination, the determinant of velocity Specificity. J Appl Physiol 1996; 80: 2046–2052
3 *Åstrand PO*, *Rodahl K*. Textbook of Work Physiology. Physiological Basis of Exercise, 3rd edition. New York: McGraw-Hill; 1986
4 *Bangsbo J*, *Nørregaard L*, *Thorsøe F*. Activity profile of competition soccer. Can J Sport Sci 1991; 16: 110–116
5 *Behm DG*, *Sale DG*. Intended rather than actual movement velocity determines velocity-specific training response. J Appl Physiol 1993; 74: 359–368
6 *Bergh U*, *Sjødin B*, *Forsberg A*, *Svedenhag J*. The relationship between body mass and oxygen uptake during running in humans. Med Sci Sports Exerc 1991; 23: 205–211
7 *Chromiak JA*, *Mulvaney DR*. A review: the effects of combined strength and endurance training on strength development. J Appl Physiol 1990; 4: 55–60
8 *Coffey VG*, *Pilegaard H*, *Garnham A*, *O'Brian*, *Hawley JA*. Consecutive bouts of diverse contractile activity alter acute responses in human skeletal muscle. J Appl Physiol 2009; 106: 1187–1197
9 *Cormack SJ*, *Newton RU*, *McGuigan MR*, *Doyle TL*. Reliability of measures obtained during single and repeated countermovement jumps. Int J Sports Physiol Perform 2008; 3: 131–144
10 *Davis JA*, *Brewer J*, *Atkin D*. Pre-season physiological characteristics of English first and second division soccer players. J Sports Sci 1992; 10: 541–547
11 *Dudley GA*, *Djamil R*. Incompatibility of endurance- and strength-training modes of exercise. J Appl Physiol 1985; 59: 1446–1451
12 *Duthie GM*, *Pyne DB*, *Ross AA*, *Livingstone SG*, *Hooper SL*. The reliability of ten-meter sprint time using different starting techniques. J Strength Cond Res 2006; 20: 246–251
13 *Harriss DJ*, *Atkinson G*. International Journal of Sports Medicine – Ethical Standards in Sports and Exercise Science Research. Int J Sports Med 2009; 30: 701–702
14 *Heil DP*. Body mass scaling of peak oxygen uptake in 20- to 79-yr-old adults. Med Sci Sports Exerc 1997; 29: 1602–1608
15 *Helgerud J*. Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performances level in marathons. Eur J Appl Physiol 1994; 68: 155–161
16 *Helgerud J*, *Engen LC*, *Wisløff U*, *Hoff J*. Aerobic endurance training improves soccer performance. Med Sci Sports Exerc 2001; 33: 1925–1931
17 *Helgerud J*, *Høydal KL*, *Wang E*, *Karlsen T*, *Berg PR*, *Bjerkaas M*, *Simonsen T*, *Helgesen CS*, *Hjorth NL*, *Bach R*, *Hoff J*. Aerobic high intensity intervals improve VO_{2max} more than moderate training. Med Sci Sports Exerc 2007; 39: 665–671
18 *Hennessy LC*, *Watson AW*. The interference effects of training for strength and endurance simultaneously. J Strength Cond Res 1994; 8: 12–19
19 *Hickson RC*. Interference of strength development by simultaneous training for strength and endurance. Eur J Appl Physiol 1980; 45: 255–263
20 *Hoff J*, *Almåsbakk B*. The effects of maximum strength training on throwing velocity and muscle strength in female team-handball players. J Strength Cond Res 1995; 9: 255–258
21 *Hoff J*, *Helgerud J*. Endurance and strength training for soccer players. Physiological considerations. A review. Sports Med 2004; 34: 165–180
22 *Hoff J*, *Berdahl GO*, *Bråten S*. Jumping height development and body weight considerations in ski jumping. In: Müller E, Schwameder H, Raschner C, Lidinger E (eds). Science and Skiing II. Hamburg: Verlag Dr. Kovac; 2001; 40–41
23 *Hoff J*, *Helgerud J*. Maximal strength training enhances running economy and aerobic endurance performance. In: *Football (Soccer). New Developments in Physical Training Research*, Hoff J, Helgerud J. Trondheim, Norway: Norwegian University of Science and Technology; 2003; 37–53
24 *Kraemer WJ*, *Patton JF*, *Gordon SE*, *Harman EA*, *Deschenes MR*, *Reynolds K*, *Newton RU*, *Triplett T*, *Dziados E*. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol 1995; 78: 976–989
25 *Larsson PU*, *Wadell KM*, *Jakobsson EJ*, *Burlin LU*, *Henriksson-Larsen KB*. Validation of the Metamax II portable metabolic measurement system. Int J Sports Med 2004; 25: 115–123
26 *Lees A*, *Graham-Smith P*. Plyometric training: a review of principles and practice. Sports Exerc Injury 1996; 2: 24–30
27 *Nelson AG*, *Arnall DA*, *Loy SF*, *Silvester LJ*, *Conlee RK*. Consequences of combining strength and endurance regimens. Phys Therapy 1990; 70: 287–294
28 *O'Donoghue P*. Time-motion analysis of work rate in elite soccer. In: Tavares HMF (ed). IV World Congress of Notational Analysis of Sport. Lisbon, Portugal; 2001; 65–70
29 *Reilly T*. Physiological profile of the player. In: Ekblom B (ed). Football (Soccer). London, Blackwell; 1994; 78–94
30 *Rienzi E*, *Drust B*, *Reilly T*, *Carter JEL*, *Martin A*. Investigation of the anthropometric and work-rate profiles of elite South American international soccer players. J Sports Med Phys Fitness 2000; 40: 162–169
31 *Sale DG*. Neural adaptations to strength training. In: Komi PV (ed). Strength and Power in Sport. London, Blackwell; 1992; 249–265
32 *Schmidtbleicher D*. Training for power events. In: Komi PV (ed). Strength and Power in Sport. London, Blackwell; 1992; 381–395
33 *Støren Ø*, *Helgerud J*, *Støa EM*, *Hoff J*. Maximal strength training improves running economy in distance runners. Med Sci Sports Exerc 2008; 40: 1089–1094
34 *Valquer W*, *Barros TL*, *Sant'anna M*. High intensity motion pattern analyses of Brazilian elite soccer players. In: Tavares HMF (ed). IV World Congress of Notational Analysis of Sport. Lisbon, Portugal; 1998; 80
35 *Withers RT*. Match analyses of Australian professional soccer players. J Hum Mov Stud 1982; 8: 159–176
36 *Wisløff U*, *Castagna C*, *Helgerud J*, *Jones R*, *Hoff J*. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. Br J Sports Med 2004; 38: 285–288
37 *Wisløff U*, *Helgerud J*, *Hoff J*. Strength and endurance of elite soccer players. Med Sci Sports Exerc 1998; 30: 462–467