
The role and development of sprinting speed in soccer

Doctoral thesis

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Faculty of health and sport science

2014

Doctoral thesis at University of Agder (nr. 80)

ISSN: 1504-9272

ISBN: 978-82-7117-759-1

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Printed by the Printing Office, University of Agder

Kristiansand

Abstract

Purpose: The overall objective of this thesis was to investigate the role and development of sprinting speed in soccer. Six original studies plus a published review have been completed towards with this objective.

Valid and reliable measurement of sprint times is a prerequisite to reliably detect true changes in sprinting performance. Therefore, the purpose of study I was to quantify potential sprint time differences between single beamed (SB) and dual beamed (DB) timing systems. The aim of study II was to compare different sprint start positions and generate correction factors between popular timing triggering methods on 40 m sprint. The results from these two methodological studies secured a fundamental platform for interpretation of further sprint data in the thesis. The purpose of studies III and IV was to use a large database of soccer athlete sprint and countermovement jump (CMJ) tests collected under highly standardized conditions over 15 years to estimate generalizable differences in sprinting speed and jumping height as a function of: 1) athlete playing level, 2) field position, and 3) age. Additionally, we also evaluated the evolution of sprint and CMJ ability among male professionals and female elite players in Norwegian soccer over a 15 year period. The purpose of study VI was to investigate the effect of training at 90% sprint speed on maximal and repeated sprinting performance in soccer. The aim of study VII was two fold: 1) To compare the effects of training at 90 and 100% sprint speed on maximal and repeated sprint performance, and 2) to compare the effects of directly supervised sprint training versus unsupervised training on maximal and repeated sprint performance.

Methods: In study I, two recreationally active participants cycled as fast as possible through a 40 m sprint track 25 times each with a 160 cm tube (18 cm diameter) vertically mounted in front of the bike. Using this protocol, SB and DB timing systems should ideally generate 50 pairs of identical times. Then, 25 junior elite track & field athletes (19 ± 1 years, 67 ± 10 kg) performed two 40 m sprints each in order to quantify the magnitude and incidence of time differences between SB and DB under normal sprint conditions. In study II, track & field athletes ($n=25$, 18 ± 4 years, 67 ± 10 kg) performed two sets of three 40 m sprints in randomized order: A) Start from block, measured by Brower audio sensor and Dartfish video timing, B) 3-point start, measured by hand release pod and Dartfish video timing, and C) standing start, measured by both photo cell start, floor pod foot release plus Dartfish video timing. In study III and IV, 939 male (22 ± 4 years, 77 ± 8 kg) and 194 female (22 ± 4 years, 63

±6 kg) soccer players, including national team players, tested 40 m sprint with electronic timing and CMJ on a force platform at the Norwegian Olympic Training Center between 1995 and 2010.

Study VI and VII were randomized controlled trials. The control group in study VI completed regular soccer training according to their teams' original training plans while the training group replaced one of their weekly soccer training sessions with a repeated sprint training session performed at 90% of maximal sprint speed. In study VII, the control group completed regular soccer training according to their teams' original training plans, while 3 training groups replaced one of their weekly soccer training sessions with a repeated sprint training session performed at A) maximal intensity, B) 90% of maximal sprint speed with direct supervision or C) 90% of maximal sprint speed without direct supervision. Results from CMJ, repeated 20 m sprints (including best sprint time, mean sprint time, stride length, stride frequency, lactate and peak heart rate) and endurance tests (VO_{2max} /Yo-Yo Intermittent recovery 1 in study VI and Yo-Yo Intermittent recovery 2 in study VII) were compared before and after the interventions. The nine week intervention period in study VI took place in the last part of the soccer season, while the seven week intervention period in study VII took place in the off-season.

Results: Simultaneous measurements with SB and DB timing revealed that coefficient of variation (CV) was 0.4 and 0.7% for 0-20 m and 20-40 m sprint times, respectively, while SEM was 0.01 s for both distances when arm and leg motion was controlled for (study I, phase 1), During normal sprint action (study I, phase 2), CV increased to 1.4 and 1.2% for 0-20 m and 20-40 m splits, respectively, while SEM was 0.02 s for both distances. During normal sprint action, absolute time differences for 0-20 m sprint times ranged from -0.05 to 0.06 s between SB and DB timing. Compared to block starts reacting to gunfire, hand release, standing photo cell start and foot release start yielded 0.17 ± 0.09 , 0.27 ± 0.12 and 0.69 ± 0.11 s faster times respectively over 40 m (study II). In study III and IV, data from a large sample of athletes tested under identical conditions demonstrated small to large differences in sprinting times across playing standards. CMJ performance was practically identical among male national teams and 1st-2nd division players. Forwards were faster than defenders, midfielders and goalkeepers, respectively. Sprint performance peaked in the age range 20-28 years for male professional players, while no differences in sprinting velocity were observed among female age categories. Furthermore, the data revealed a small but significant positive development in sprint performance among male professionals and female elite soccer players

over a 15 year period of testing, while no significant changes in CMJ ability were observed. In study VI and VII, no significant between group differences for any of the performance parameters were observed, and effect magnitudes were trivial or small. In the control groups, we observed ± 0.06 and 0.04 s absolute variation in mean sprint time between the pre- and post tests for study VI and VII participants, respectively. Typical variation for repeated 20 m sprint time was 0.025 s for all groups (CV 0.8-1.0%).

Conclusions: The present thesis revealed that accurate 0-20 m sprint performance monitoring is complicated by timing errors up to ± 0.06 s between SB and DB systems. At worst, this error source alone represents three times the value of the smallest worthwhile performance enhancement for this variable in team sports. DB timing is therefore required for scientists and practitioners wishing to derive accurate and reliable short sprint results. Moreover, time differences among commonly used start positions and triggering methods can exceed 0.6 s, a substantially larger difference than the typical gains made from specific training, or even the variance between superior and mediocre sprinters. For internal comparisons of performance in a training monitoring setting, changing timing methods is unacceptable. Our retrospective analysis of data reveals that sprinting velocity is a crucial performance factor in soccer. Linear sprinting skills distinguish players from different standards of play and positions. There has been a small but positive development in sprinting velocity among male professionals and female elite players over time. While these data are collected on Norwegian players only, we hypothesize that they reflect a general trend in elite soccer. Finally, our intervention studies showed that weekly repeated sprint training at sub-maximal or maximal intensity was not sufficient to improve maximal or repeated sprint performance over 20 m. However, we observed weekly absolute variations in sprint times considerably higher than the typical variability. If improvement of sprinting skills is the primary goal for certain players, future studies should explore whether it is more effective to structure the players' weekly soccer training rather than introducing an additional physical conditioning regime. Our findings add further support to the notion that sprinting skills over short distances are hard to improve within the constraints of overall soccer conditioning.

Acknowledgements

This work has been carried out on behalf of the Norwegian Olympic Sports Program through the University of Agder, Faculty of Health and Sport Sciences.

The story behind this thesis started already at the end of 1994 when I was hired as a testing instructor for the Norwegian Olympic Training Center in Oslo. At the same time I was a bachelor student and mediocre sprinter in athletics, allowed to practice in one of the most successful sprint groups in Europe at that time. My poor sprinting career is not worth mentioning, but the practical knowledge gained through these years has been very useful for me later. By observing, assisting and participating in Norwegian athletics through the developing of several world class sprinters, I have gained valuable practical knowledge. I will therefore start by thanking sprint coach Leif Olav Alnes and his sprinting group for inclusion, inspiration and sharing wisdom.

As the years went by and computers became widespread, thousands of testing results were performed and stored in databases at the Norwegian Olympic Training Center. Without knowing it, I have been working on my PhD for the last sixteen years. I will therefore thank the leadership in the Norwegian Olympic Sports Program for financing and providing me the opportunity to accomplish this project. A special thank to my boss and co-supervisor, Espen Tønnessen, for facilitating and assistance through the whole process. I owe you my largest gratitude for support and encouragement.

I would like to express my appreciation especially to professor Stephen Seiler at the University of Agder. Stephen, I would never have reached the finish line without your help. Your scientific knowledge is world class, and it has been an honor to have you as my main supervisor. I hope our research corporation can continue for many years further.

Thanks also to my colleagues in Department of Training for all support. Because of you, I am looking forward to every working day. A special thanks to Ida, for all your help with literature, statistics and language. I also want to thank Jonny Hisdal, for constructive feedback in the final stage.

Finally, I wish to express my deepest gratitude to the persons closest to me; my wife Mona, for patience and love through the entire process, and my children, Malin & Sander, for providing me energy and inspiration. Because of you, I could realize my PhD dream.

List of papers

This thesis is based upon seven studies, which will be referred to in the text by their Roman numerals.

- I. Haugen T, Tønnessen E, Svendsen I, Seiler S. Sprint time differences between single beamed and dual beamed timing systems. *J Strength Cond Res.* 2014; Feb 12 [E-pub ahead of print].
- II. Haugen T, Tønnessen E, Seiler S. The difference is in the start: impact of timing and start procedure on sprint running performance. *J Strength Cond Res.* 2012; 26: 473-79.
- III. Haugen T, Tønnessen E, Seiler S. Anaerobic performance testing of professional soccer players 1995-2010. *Int J Sport Physiol Perform.* 2013; 8: 148-56.
- IV. Haugen T, Tønnessen E, Seiler S. Speed and countermovement jump characteristics of elite female soccer players 1995-2010. *Int J Sport Physiol Perform.* 2012; 7: 340-49.
- V. Haugen T, Tønnessen E, Hisdal J, Seiler S. The role and development of sprinting speed in soccer. *Int J Sport Physiol Perform.* 2013; Aug 27 [E-pub ahead of print].
- VI. Haugen T, Tønnessen E, Leirstein S, Hem E, Seiler S. Not quite so fast: Effect of training at 90% sprint speed on maximal and repeated sprint ability in soccer players. Submitted to *Int J Sport Physiol Perform.* 2014; Feb.
- VII. Haugen T, Tønnessen E, Øksenholt Ø, Haugen FL, Paulsen G, Enoksen E, Seiler S. Improving sprinting skills in soccer: Effect of training at different sprint speed intensities and direct supervision. Submitted to *PLOS ONE* 2014; Feb.

The first two papers are methodological studies related to timing procedures in sprint testing. Paper III and IV are cross-sectional studies built on descriptive data that have been collected over two decades of sprint and vertical jump testing on soccer players, including national team for men and women. Paper V is a published review of the present thesis. The last two papers are intervention studies (randomized controlled trials) involving repeated sprint training in soccer players.

Abbreviations

ANCOVA = analysis of covariance

ANOVA = analysis of variance

BLa⁻ = blood lactate concentration

CG = control group in study VI

CI = confidence interval

CMJ = countermovement jump

CON = control group in study VII

CV = coefficient of variation

DB = dual beamed timing system

HR = heart rate

HR_{max} = maximum heart rate

HR_{peak} = peak heart rate

NOC-timing = the timing system at the Norwegian Olympic Training Center

RER = respiratory exchange ratio

RSA = repeated sprint ability

SB = single beamed timing system

SL = stride length

SF = stride frequency

SEM = standard error of measurement

TG = training group in study VI

VO_{2max} = maximal oxygen uptake

Yo-Yo IR1 = Yo-Yo Intermittent Recovery 1 test

Yo-Yo IR2 = Yo-Yo Intermittent Recovery 2 test

90SUP = training group in study VII who performed repeated sprint training at 90% intensity with direct supervision

90UNSUP = training group in study VII who performed repeated sprint training at 90% intensity without supervision

100UNSUP = training group in study VII who performed repeated sprint training at 100% intensity without supervision

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1 Introduction

1.1 Rationale for the thesis

Soccer is the world's most popular sport. According to the International Federation of Association Football (2014^A), approximately 265 million players and 5 million referees and officials are actively involved. This is equivalent to 4% of the world's population. The game is intermittent in nature and involves multiple motor skills such as running, dribbling, kicking, jumping and tackling. Performance depends upon a variety of individual skills and their interaction and integration among different players within the team. Technical and tactical skills are considered to be predominant factors, but physical capabilities must also be well developed in order to become a successful player. The sum of all individual skills determines the team's potential. These skills must be correctly balanced across playing positions in order to solve various tasks during play. Accordingly, coaches try to organize their team in order to utilize the strengths of each individual player, as well as camouflage possible weaknesses. The key skills must be maximized, while other capabilities merely need to meet a minimum requirement (Reilly et al., 2000^A). For example, Bradley et al. (2013) reported that pass completion, frequency of forward and total passes, balls received and average touches per possession were higher in the Premier League compared to lower standards. On the other hand, aerobic endurance capacity is not a clearly distinguishing variable separating players of different standard (Bradley et al., 2013; Tønnessen et al., 2013). Conditioning experts have to balance their training methods and exercises in order to optimize these different skills in relation to their contribution to overall soccer performance.

Numerous studies have investigated the physical demands and training of soccer players. While the physiology, metabolism, match activity and fatigue mechanisms have been well explored from an aerobic perspective (Bangsbo 1994; Reilly et al. 2000^A; Krustup et al., 2005; Mohr et al., 2005; Stølen et al., 2005; Bangsbo et al., 2006 and 2007; Krustup et al., 2010; Bradley et al., 2013; Haugen et al. 2013; Tønnessen et al., 2013), there is less information available regarding anaerobic demands and training methods in elite or professional soccer. Therefore, the overall objective of the present thesis is to explore the role and development of sprinting speed in soccer.

1.2 Literature search

The purpose of the introduction is to summarize the research that has been undertaken so far and highlight those areas that require further and more detailed investigation regarding the

role and development of sprinting speed in professional soccer. Another important aspect of this part is to identify methodological limitations and concerns associated with these studies. The databases of PubMed and SPORTDiscus were used to search for literature. For scientific studies, only peer-reviewed articles written in English were included. Regarding demands and training of sprinting skills, the search was conducted in two levels; type of sport and type of athlete. Regarding the first level, the terms “soccer” and “football” were used. In order to narrow the search, studies including the terms “American football”, “Australian football”, “Australian Rules football”, “Gaelic football”, “rugby” and “futsal” were excluded. Secondly, to ensure that the involved players were of a reasonably high playing standard, the search was restricted to >16 years athletes categorized as “elite”, “professional”, “high level”, “top class”, “first division”, “upper division”, “top level”, “high class”, “high standard” or “national team”. Only studies investigating the role or development of sprinting skills in soccer were included. In addition, the reference lists and citations (Google Scholar) of the identified studies were explored in order to detect further relevant papers. To ensure updated sprinting demands, test results reported before the year 2000 were excluded. In order to restrict the total number of references, only the most recent studies were referred when multiple investigations reported identical findings.

1.3 Sprinting demands during match play

A large number of soccer players from the best European soccer leagues have been analyzed according to motion during match play. Data are commonly generated by either semiautomatic video analysis systems or global positioning systems. The analyses show that both male and female outfield soccer players cover 9-12 km during a match (Burgess et al., 2006; di Salvo et al., 2007; Rampinini et al., 2007^{A and B}; Gabbett & Mulvey, 2008; Vigne et al., 2010). Of this, 8-12% is high intensity running or sprinting (Burgess et al., 2007; Rampinini et al., 2007^A; Gabbett & Mulvey, 2008; Vigne et al., 2010). Wide midfielders and external defenders perform more high intensity running and sprinting compared to the other playing positions (di Salvo et al., 2007; Rampinini et al., 2007^A). Reported peak sprint velocity values among soccer players are 31-32 km·h⁻¹ (Rampinini et al., 2007^{A and B}). Sprint frequencies in the range 17-81 per game for each player have been reported (Burgess et al., 2007; di Salvo et al., 2007; Vigne et al., 2010). Mean sprint duration is between 2 and 4 s, and the vast majority of sprint displacements are shorter than 20 m (Burgess et al., 2007; Gabbett & Mulvey, 2008; Vigne et al., 2010). The broad range in frequency estimates of sprints reported is likely due to varying intensity classifications, as different running velocities (18-30

km·h⁻¹) have been used to distinguish sprint from high speed running. It is important to note that running speed in the range 20-22 km·h⁻¹ is equivalent to the mean velocity in male elite long distance running, and mediocre sprinters reach peak speeds >35 km·h⁻¹ (Mero & Komi, 1986; Mero et al., 1992). Therefore, definitions based upon absolute velocity are methodologically problematic in terms of validity and reliability, in addition to limiting comparisons across studies. Furthermore, absolute velocity values exclude short accelerations from analysis. Players perform 8 times as many accelerations as reported sprints per match, and the vast majority of these accelerations are too short in duration to cross the high-intensity running threshold (Varley & Aughey, 2013). Thus, high intensity running and sprinting load may be underestimated (Osgnach et al., 2010; Varley & Aughey, 2013). Measuring methods that capture accelerations independent of peak velocity would markedly strengthen game analyses.

To date, no full game analyses have quantified the movement patterns of intense actions across playing level or positions in terms of sharp turns, rotations, change of direction, etc. with and without the ball. However, Faude et al. (2012) have used visual inspection to analyze videos of 360 goals in the first German national league. They reported that the scoring player performed a straight sprint prior to 45% of all analyzed goals, mostly without an opponent and without the ball. In comparison, frequencies for goals immediately preceded by jumps and change-in-direction sprints were 16 and 6%, respectively. Straight sprinting was also the most frequent action for the assisting player, mostly conducted with the ball.

Previously published match analyses indicate that well developed sprinting speed might be an advantage in professional soccer. However, games are impossible to standardize, and precise measurements of short sprint actions in games are complicated by methodological challenges, equipment cost and availability. As an alternative, many coaches and scientists perform soccer specific sprint testing of players in order to explore the physical demands and evaluate the training process.

1.4 Testing of sprint performance

Sprint performance differences that separate the excellent from the average are relatively small on an absolute scale, and the effects of training interventions are even smaller. Thus, valid and reliable timing and test procedures are critical to detect true changes in sprinting performance. Practically all soccer related studies have used testing distances in the range 5-40 m. A review of published studies monitoring speed performance reveals considerable

variation and/or insufficient information regarding timing methods, hardware manufacturers, testing procedures and method of reporting (i.e. best sprint vs. mean sprint time of several trials). It is therefore important to describe the methodological sprint test approach as detailed as possible.

Fully automatic timing systems used in international athletics have been considered the gold standard to accurately and reliably quantify sprint performance, as this includes photo finish analysis with high resolution digital line-scan cameras. Unfortunately, such timing equipment is expensive and impractical, so other alternatives have been used by practitioners and scientists over time. Clearly, electronic timing is superior to handheld stopwatch timing (Hetzler et al., 2008; Mayhew et al., 2010). Greater accuracy of dual beam (DB) versus single beam (SB) photocell timing systems has been reported (Yeadon et al., 1999; Earp, 2012), as SB systems can be triggered early by lifted knees or swinging arms. Many scientists and practitioners continue to use SB systems, most likely due to lower cost and greater availability. No studies have so far quantified potential sprint time differences between SB and DB timing systems. Such information would be of benefit to practitioners and scientists wishing to derive accurate and reliable results, while identifying the most appropriate measurement system for use.

In theory, recording gun smoke and sprinters passing the finish line with a single video camera should give enough information for valid sprint time analysis when captured into a computer video analysis program. While this timing method represents a practical “gold standard” for validation of other methods, it has so far not been reported in the literature. The Brower Timing System (Draper, USA) has been used in the majority of studies involving sprint testing of soccer players, but specific start procedures and hardware approaches to timer initiation have varied. Electronic timing is influenced by differences in timer activation methods and the starting position of athletes (Duthie et al., 2006). These variables can generate substantial differences in performance times that may complicate comparison of results from different studies or estimation of the effect magnitude of training interventions.

Duthie et al. (2006) examined the reliability and variability of different starting techniques on 10 m sprinting speed and reported that different sprint start techniques are associated with small typical errors (< 1%). They concluded that repeated measures on individuals are necessary to provide performance changes resulting from speed oriented training. Buchheit et

al. (2012) claim that two or three 10 m intervals are required to guarantee an accurate evaluation of maximal sprinting speed when using timing gates.

In summary, very few electronic timing systems have been validated, and correction factors between popular timing triggering methods are so far not generated. Such information would facilitate more meaningful comparisons of published sprint performance results.

1.5 Sprinting characteristics of soccer players

Soccer related sprinting skills can be categorized as straight line sprinting, agility and repeated sprint ability (RSA). Straight line sprinting is commonly further categorized as acceleration, maximal running velocity, and deceleration (Mero et al., 1992). Agility was originally defined by Clarke (1959) as “speed in changing body positions or in changing direction”. More recently, Sheppard & Young (2006) defined agility as “a rapid whole-body movement with change of velocity or direction in response to a stimulus,” based on the conception that agility has relationships with both physical and cognitive components. Repeated sprint ability is the ability to perform repeated sprints with brief recovery intervals (Dawson et al., 1993). In recent years, RSA has received increasing attention as a central factor in most field-based team sports. Within the RSA term, Girard et al. (2011) have defined intermittent sprint exercise as repeated short sprints (≤ 10 s) with long recovery periods (60-300 s), while repeated sprint exercise is interspersed with brief recovery periods (≤ 60 s).

1.5.1 Straight line sprinting skills

Game analyses have shown that more than 90% of all sprints in matches are shorter than 20 m (Vigne et al., 2010), indicating that acceleration capabilities are most important for soccer players in this context. However, the importance of peak velocity increases when sprints are initiated from a jogging or non-stationary condition. It is also important to keep in mind that 80-90% of maximal sprint velocity is achieved already after 2-3 s (Chelly & Denis, 2001; Graubner & Nixdorf, 2011). Mendez-Villanueva et al. (2010) reported a strong relationship between sprint test performance and peak velocities reached in games. A small number of studies have reported sprint times for high-level soccer players with sufficient information to compare results across studies. Dupont et al. (2004) reported that 22 male French professionals achieved a mean 40 m time of 5.35 ± 0.13 s. Rebelo et al. (2013) reported group mean 30 m sprint times of 4.31 ± 0.18 s for goalkeepers ($n = 9$), 4.29 ± 0.08 s for central defenders ($n = 13$), 4.23 ± 0.18 for full-backs ($n = 14$), 4.30 ± 0.15 s for midfielders ($n = 38$)

and 4.27 ± 0.13 s for forwards ($n = 21$) among Portuguese U19 elite players. A standing start with Brower timing gates placed at the start line was used in both studies, but the authors reported mean sprint times of mixed playing standard or position categories. To date, no studies have presented the range of speed performance among high-level soccer players. What is the difference in sprinting velocity between the fastest and slowest elite players? How fast do the fastest players run, i.e. compared to sprinters in athletics? Despite the importance of running speed in soccer, there is almost no published data available regarding the level of sprinting velocity among professionals at an international competitive level.

Some studies have reported that elite players run faster than non-elite players, while others do not show a clear trend (Reilly et al., 2000^B; Cometti et al., 2001; Gissis et al., 2006; Vaeyens et al., 2006; Rebelo et al., 2013). Sporis et al. (2009) and Boone et al. (2012) concluded that forwards were faster than defenders, midfielders and goalkeepers, respectively, while Taskin (2008) did not observe significant differences in straight sprinting speed by playing position. The literature remains unclear and inadequate regarding potential sprint performance changes within the typical competitive age range (Mujika et al., 2009^A; Vescovi et al., 2011). Most previous investigations are weakened by small simple size and do not adequately represent variation in performance level or age. No studies have so far examined performance development of linear sprinting among elite soccer players over time.

1.5.2 Agility

The vast majority of agility tests in soccer are designed to evaluate the physical qualities of the players, without cognitive (i.e. choice reaction) challenges. Zig zag runs, 90-180° turns, shuttle runs, sideways, and backwards running with maximal intensity are commonly used drills. Agility patterns may vary as a function of playing role, and Sporis et al. (2010) suggested different tests for different positions. Published agility tests do not reflect the nature of deceleration and turning performed during elite soccer matches. In fact, the vast majority of turning movements are initiated from a stationary or jogging condition while change-in-direction within sprinting movements rarely occur (Bloomfield et al., 2008).

Marcovic (2007) reported a poor relationship between strength and power qualities and agility performance. Little & Williams (2005) and Vescovi & McGuigan (2008) concluded that straight sprint, agility and vertical jump capabilities are independent locomotor skills. This is demonstrated on a YouTube video of Cristiano Ronaldo racing against the Spanish 100 m champion, Angel David Rodriguez (<http://www.youtube.com/watch?v=hZqEj-Qyg6U>).

Ronaldo lost by 0.3 s over 25 m straight sprint, but won by 0.5 s when running in a zig zag course over the same distance.

Several studies have reported that professionals or elite players have better agility skills compared to players of lower standard (Reilly et al., 2000^B; Vaeyens et al., 2006; Kaplan et al., 2009; Rebelo et al., 2013). However, Rösch et al. (2000) observed no differences across a broad range of playing standard. The literature is equivocal regarding agility performance across playing positions (Taskin, 2008; Sporis et al., 2010; Boone et al., 2012). Interestingly, midfielders perform relatively better in agility tests compared to linear sprint tests. The literature also suggests that when change-of-direction is preceded by braking from a nearly full sprint, the agility difference across position categories shrinks. In classical mechanics, the kinetic energy of a non-rotating object of mass (m) travelling at a speed (v) is $0.5m \cdot v^2$. Thus, faster players with more body mass must counteract a larger kinetic energy during sharp turns while sprinting. Since midfielders in general have lower body mass and lower peak sprinting speed (Sporis et al., 2009), it is reasonable to expect that this group also demonstrates smaller performance differences in certain agility tests compared to linear sprint tests.

Timing of ground reaction forces, body configuration and center of gravity placement are crucial biomechanical elements when changing direction while sprinting. By lowering the center of gravity while changing direction, the involved lower extremity muscles can work under more optimal conditions. By leaning the upper body towards the intended direction during turns, combined with foot placement in the opposite intended running direction away from the vertical center of gravity-line during ground contact, more kinetic energy can be counteracted. Correct technique during change-in-direction movements is also important from an injury prevention perspective.

1.5.3 Repeated sprint ability

Numerous field tests have been developed to evaluate RSA. Sprint distances of 15-40 m x 3-15 repetitions have been used in elite or professional soccer, and the majority of tests have included 15-30 s recovery periods between sprints (Table 1). Several tests have combined agility and repeated sprints (Bangsbo, 1994; Ferrari Bravo et al., 2008; Impellizzeri et al., 2008^A; Rampinini et al., 2009; da Silva et al., 2010).

Table 1: Repeated sprint field test protocols (repetitions x distance) used on elite or professional soccer players >16 years ranged according to total sprinting distance (TSD) during the test. Recovery (Rec.) is reported as time between each sprint.

Study	Subjects	Protocol	Rec. (s)	TSD (m)	Mean time (s)	Equipment / setup & starting procedures
Krustrup et al., 2010	23 sr. females	3x30m	25	90	4.86 ±0.06	Time IT (SWE) / not reported
Gabbett, 2010	10 sr. females	6x20m	<15	120	3.48 ±0.08	Not reported / not reported
Aziz et al., 2007	37 jr. males	6x20m	20	120	3.08 ±0.09	Swift Perf. (AUS) / standing start 0.4 m behind gate
Wong et al., 2012	18 sr. males	6x20m	25	120	Not reported	Brower (USA) / standing start 0.5 m behind gate
Aziz et al., 2008	13 U23 males	8x20m	20	160	3.08 ±0.08	Swift Perf. (AUS) / standing start 0.4 m behind gate
Mujika et al., 2009 ^B	28 U17-18 males	6x30m	30	180	4.42 ±0.14	Alge-Timing (AUT) / standing start 0.3 m behind gate
Dellal & Wong, 2013	8 sr. males	10x20m	25	200	2.96 ±0.08	Microgate (ITA) / not reported
Chaouachi et al., 2010	23 sr. males	7x30m	25	210	4.46 ±0.16	Brower (USA) / standing start 0.5 m behind gate
Meckel et al., 2009	33 jr. males	6x40m	~ 25	240	5.85 ±0.25	Alge-Timing (AUT) / standing start 0.3 m behind gate
Meckel et al., 2009	33 jr. males	12x20m	~ 17	240	3.23 ±0.06	Alge-Timing (AUT) / standing start 0.3 m behind gate
Impellizzeri et al., 2008 ^A	30 sr. males	6x20+20m	20	240	7.12 ±0.17	Micogate (ITA) / not reported
Tønnessen et al., 2011	20 jr. males	10x40m	60	400	5.32 ±0.17	Biorun (NOR) / standing start from floor pod
Little & Williams, 2007	6 sr. males	15x40m	~ 8-12	600	5.73 ±0.07	Brower (USA) / not reported
Little & Williams, 2007	6 sr. males	40x15m	~ 20-30	600	2.59 ±0.05	Brower (USA) / not reported

Primarily two measures have been used to quantify RSA; total time and/or deterioration in performance. Total time or mean sprint time have been used as performance indices, and results from RSA tests have been shown to differentiate professionals from amateur players (Rampinini et al., 2007^B; Aziz et al., 2008; Impellizzeri et al., 2008^A; Rampinini et al., 2009). Deterioration in performance, calculated as sprint decrement, has generally been used to quantify the ability to resist fatigue during such exercise (Glaister, 2005). Fatigue resistance depends upon a wide range of physiological factors, mostly related to aerobic metabolism, and athletes with higher maximal oxygen uptake (VO_{2max}) have smaller performance decrements during repeated sprint exercise (Aziz et al., 2007). This is most likely explained by the linear relationship between phosphocreatine resynthesis rate and mitochondrial capacity within muscle (Paganini et al., 1997). A full review of the physiological mechanisms related to RSA is beyond the scope of this thesis, but this topic is well described elsewhere (Spencer et al., 2005).

The interpretation and usefulness of repeated sprint tests has been questioned over the years (Spencer et al., 2006; Oliver, 2009). Insufficient timing information and variations in testing protocols complicate comparisons across studies. Based on the short recovery periods between each sprint, most RSA test protocols simulate the most intensive game periods, leading to a possible overrating of the aerobic demands. Pyne et al. (2008) reported that total time in a RSA test was highly correlated with single sprint performance and concluded that RSA was more related to sprinting speed than endurance capacity. In order to detect the “sprint endurance” component, repeated sprint test protocols with higher total volume are perhaps required. According to Balsom et al. (1992), it is more difficult to detect detrimental effects with shorts sprints (15 m) compared to slightly longer sprints (30-40 m). Medical data derived from American football indicate that extensive sprint testing/training without prior gradual progression increases the risk of hamstring injuries (Elliott et al., 2011). This constraint perhaps explains why most repeated sprint test protocols are designed with a relatively small total volume of sprinting.

1.5.4 Sprint and vertical jump relationship

The importance of vertical jump abilities in soccer players is heavily debated. According to Rampinini et al. (2007^A), the utility of assessing vertical jump performance is questionable as such skills have little relevance to soccer play. In contrast, Faude et al. (2012) reported that jumps are one of the most frequent actions prior to goals, both for the scoring and assisting

player. Based on these observations, they concluded that jumping (in addition to sprinting) should be included in fitness testing and training, as such actions are important within decisive situations in professional soccer. Stølen et al. (2005) claim that well-developed strength in lower limbs is important for soccer players, as this basic quality influences power performance and skills like sprinting, turning and change of direction. Wisløff et al. (2004) reported a strong correlation between maximal strength, sprint performance and vertical jump height, while Salaj & Markovic (2011) concluded that jumping, sprinting and change of direction speed are specific independent variables that should be treated separately. Taken the arguments and observations together, it is likely that individuals with poor leg extension power relative to sprint performance should prioritize power development more compared to their counterparts in order to enhance sprint performance. Quantifying vertical jump performance alongside sprint performance may facilitate a more correct interpretation of sprint data.

Countermovement jump (CMJ) is the most frequently reported vertical jump test among soccer players. Differences in testing procedures (i.e. with or without arm swing), equipment (i.e. contact mats vs. force platforms) and software complicate comparisons across studies. Most studies have reported mean CMJ height without arm swing in the range 37-42 and 26-33 cm for male and female elite performers, respectively (Cometti et al., 2001; Arnason et al., 2004; Rampinini et al., 2007^A; Rønnestad et al., 2008; Mujika et al. 2009^A; Sedano et al., 2009; Sporis et al., 2009; Castagna & Castellini, 2012). Some authors have reported differences in CMJ performance as a function of competitive level (Arnason et al., 2004; Gissis et al., 2006; Rebelo et al., 2013), while other studies have not identified such differences (Rösch et al., 2000; Cometti et al., 2001; Castagna & Castellini, 2012; Sedano et al., 2009). Boone et al. (2012) and Rebelo et al. (2013) reported differences in CMJ performance across playing positions, while Sporis et al. (2009) did not. The literature also shows conflicting results regarding vertical jump performance development within the typical competitive age range or during the course of the training year and competition season (Casajus et al, 2001; Mujika et al., 2009^A; Vescovi et al., 2011). Previous investigations do not adequately represent variation in performance level, playing position or age. No studies have examined the development of vertical jump performance in relation to sprint performance among elite soccer players over time.

1.6 Training to improve sprint performance

1.6.1 Soccer related intervention studies

If we look to track and field age-group statistics (Norwegian Athletics Association, 2014) and the experience of practitioners (Miller, 1984), the picture suggests that sprint performance is quite resistant to training enhancement. However, numerous intervention studies have been performed over the years in order to enhance sprint performance in soccer players. The resulting research literature suggests that positive outcomes can be achieved using different training approaches, leading to the assumption that all kinds of training can improve sprinting performance among soccer players not specialized in sprinting. While publication bias towards studies reporting positive outcomes may be involved, another plausible explanation is the lack of a control group in many studies, as the results might have been affected by learning effects or overall soccer conditioning in the intervention period. Furthermore, the majority of published studies have been performed on young players (16-18 years). Less exposure to specialized training provides more potential for stimulating positive effects. A well-trained professional soccer player may be essentially untrained in terms of sprint training. When evaluating research literature, it is important to keep in mind that successful interventions vary in terms of training time investment, as time consuming interventions will probably be rejected by team coaches. A great deal of knowledge can be gathered from non-successful conditioning programs as well, which so far are underrepresented in research journals. With these considerations in mind, we have tried to identify criterions for success in order to improve soccer related sprinting skills. Future research regarding dosing strategies should be designed to validate these recommendations.

1.6.2 Principles of sprint training in soccer

1.6.2.1 Specificity

A review of published sprint intervention studies on soccer players confirms the principle of specificity. Linear sprint training improves linear sprinting skills (Tønnessen et al. 2011), but not performance in sprints with changes of direction (Shalfawi et al., 2013; Young et al., 2001). Agility training improves the specific agility task performed during practice (Shalfawi et al., 2013). Repeated sprinting improves RSA (Ferrari Bravo et al., 2008; Tønnessen et al., 2011). The superiority of resisted or assisted sprint training compared to normal sprinting has so far not been clearly established (Spinks et al., 2007; Upton, 2011).

Several “less specific” training forms have also been explored in order to improve sprinting skills of soccer players. Contrast training (combination of strength, power and sport specific drills) has elicited positive effects on soccer-specific sprint performance (Polman et al., 2004; Mujika et al., 2009^C), but twice weekly training sessions do not seem to be more beneficial than one weekly session (Alves et al., 2010). Plyometric training interventions appear to have limited effects on soccer players` sprint performance (Impellizzeri et al., 2008^B; Thomas et al., 2009; Sedano et al., 2011). Furthermore, heavy strength training does not consistently improve sprinting capabilities (Jullien et al., 2008; Lopez-Segovia et al., 2010; Loturco et al., 2013). Sedano et al. (2011) claimed that improved explosive strength can be transferred to acceleration capacity, but a certain time is required for the players in order to transfer these improvements. Kristensen et al. (2006) recommend normal sprinting over other training forms in order to obtain short distance sprinting improvement in a short period of time.

At least one laboratory has reported that a combination of high-intensive interval training and heavy strength training enhances sprinting performance in soccer players (Wong et al., 2010; Helgerud et al., 2011). These interventions are extensive and time consuming, as they include at least 4 weekly training sessions. Other studies recommend high-intensive aerobic interval training (80-90% of VO_{2max}) in addition to repeated sprint in order improve RSA (Dupont et al., 2004; Spencer et al., 2005; Bishop et al., 2011). However, Ferrari Bravo et al. (2008) demonstrated that repeated sprint training was superior to high-intensity aerobic interval training in terms of aerobic and soccer specific training adaptations. Tønnessen et al. (2011) showed that elite soccer players were able to complete repeated sprints with intensity closer to maximum capacity after repeated sprint training once a week, without additional high-intensive intervals. Even though the principle of specificity is clearly present, sprinting skills in soccer may be improved in several ways, and no specific training method has emerged as superior.

1.6.2.2 Individualization

Unfortunately, most interventions in sport science are limited to answering typical one-dimensional questions, more specifically whether certain types of training are generally more effective than others, based on group-wise responses. In practice, however, coaches are concerned with three dimensions; 1) what kind of training should be performed, 2) by which individuals, 3) at what time point in the season. Similar to medical consultations, a broad range of performance factors may need to be tested and evaluated before optimal treatment is

prescribed. The principle of individualization is well established in resistance training in order to maximize outcomes (Fleck & Kraemer, 1997).

Capacity profiles are essential in order to diagnose each individual and develop training interventions that target the major limiting factors. Logistically, individualized training of physical capacity is difficult to organize in a team sport setting. This is probably a greater problem in high-level female and youth soccer, where team staff is smaller compared to male professional teams. In such cases, most soccer coaches are constrained to perform similar training for all outfield players within the team, despite large individual differences in capacity profiles. However, it is unlikely that similar training doses lead to similar responses for players belonging to opposing extremes. Surprisingly, there has been little research about how individual capacity profiles can be developed in team sports.

1.6.2.3 Familiarization, progression and periodization

Sprinting is the most frequent mechanism associated with hamstring injuries, and age/previous injuries are the most important risk factors (Ekstrand et al., 2011). About 17% of all injuries in soccer are hamstring injuries, and more than 15% of all hamstring injuries are re-injuries (Ekstrand et al., 2011). Players that have not been fully rehabilitated following sprint-related injury, or who have had such injuries during the previous weeks, should be particularly cautious. Many hamstring injuries occur during the short pre-season, and Elliott et al. (2011) ascribe this to the deconditioning that occurs in the off-season. Thus, during the initial weeks of a sprint training program there should be a gradual familiarization, both in terms of intensity and the number of sprint repetitions. We have not identified progression or periodization models regarding sprint training in the research literature.

The classic linear periodization model in strength training is characterized by high initial training volume and relatively low intensity. During the training cycle, volume gradually decreases and intensity increases (Stone et al., 1982; Fleck, 1999). This makes it tempting to propose a similar training model for sprinting. Anecdotal evidence in support of this is observed in the sprint training philosophy developed by athletic sprint pioneer coach Carlo Vittori in the mid-1970s (Vittori, 1996). Pre season conditioning for his athletes was initiated with short sprints at low intensity. As training progressed, the intensity and/or total volume gradually increased in order to improve alactic capacity. To the author's knowledge, Vittori first published the repeated sprint training-method (at that time termed "speed endurance training"). He was national team sprint coach and personal coach to Pietro Mennea, Olympic

gold medalist in 1980 and former world record holder for the 200 meter. Recently, Tønnessen et al. (2011) performed a sprint training intervention with a similar progression model. The authors reported positive and time-efficient effects on sprinting skills. Further studies are warranted in order to establish progression and periodization models for sprint development.

1.6.2.4 Integration of sprint training

According to acknowledged practitioners in soccer, physical conditioning of players must be integrated with the remaining soccer-specific training (Verheijen, 1998). It is important to keep in mind that playing soccer is an important contribution to the overall fitness level of the players. For example, Sporis et al. (2011) reported that starters developed sprinting skills to a higher level compared to non-starters. Successful off-field interventions will not automatically be accepted by the soccer coaches. It is therefore essential that the small amount of time available for physical training is used effectively. Hoff et al. (2002) demonstrated how aerobic endurance training can be integrated into soccer specific training, and a similar approach should also be used in order to improve sprinting skills.

1.6.2.5 Physical coaching expertise

Sprint velocity is a function of stride length (SL) and stride frequency (SF). Previously published studies indicate that SF is a main limiting performance factor in elite athletic sprinting, while SL is more limiting among athletes of lower sprint standard (Armstrong et al, 1984; Mero et al, 1992; Mero & Komi, 1986). A wide range of SL and SF combinations are observed in athletes with similar sprint velocities, with several possible sources of a negative interaction (Hunter et al, 2004). The importance of feedback during practice is well established in motor skill learning (Schmidt & Wrisberg, 2008), and continuous presence of a sprint conditioning expert probably increases the odds for more successful training outcomes in soccer. Coaching centers to a larger degree on continually evaluating and making adjustments to the training process. In research related intervention studies, such opportunities are limited due to issues of standardization and validation. Mazzetti et al. (2000) and Coutts et al. (2004) showed that the presence of a training expert was beneficial for maximal strength development over time. To the authors' knowledge, the effect of direct supervision of sprint training sessions in soccer players has so far not been investigated.

1.6.3 Essential training variables

1.6.3.1 Distance

Previously, we have observed unaltered 0-20 m sprint performance, but improved 20-40 m speed as a result of weekly repeated 40 m sprints over ten weeks (Tønnessen et al., 2011). This suggests that players are more disposed to adaptations over somewhat longer but less soccer-specific sprint distances. Soccer players perform a high number of accelerations during training and games, and it is possible that they have achieved much of their 0-20 m sprint potential during regular soccer conditioning. Spinks et al. (2007) reported enhanced 0-15 m performance as a result of two weekly short sprint (5-20 m) sessions, but the positive outcomes may have been affected by additional strength training during the intervention period. Prolonged sprints (≥ 30 s) seem to have limited effects on acceleration or peak velocity (Gunnarson et al., 2012).

1.6.3.3 Intensity

Essentially all studies involving sprint training interventions for soccer players make no other recommendations than that sprint velocity should be maximal throughout. Available evidence in endurance training and strength training demonstrates that high, but sub-maximal intensity loading effectively stimulates adaptation through the interaction between high intensity and larger accumulated work that can be achieved before onset of fatigue, compared to maximal efforts (Kraemer et al., 2002; Seiler et al., 2013). Anecdotal evidence in support of this is observed in the sprint training philosophy by sprint pioneer coach Carlo Vittori (Vittori, 1996). His athletes performed repeated sprint training sessions with an intensity as low as 90% of maximal sprint intensity during the initial pre-season conditioning. The lowest effective sprinting intensity for stimulating adaptation is so far not established in the research literature, and no randomized controlled trials have so far compared the impact of different sprinting intensities.

1.6.3.2 Sets and repetitions

Repeated sprinting is primarily classified as an anaerobic exercise, but the contribution of aerobic metabolism increases with repetitions (Balsom et al., 1992). Sets and repetitions must be related to distance and intensity when designing a sprint conditioning program (Little & Williams, 2007). Protocols ranging from 40x15 m to 20x40 m have been used in repeated sprint training sessions of professional soccer players (Dupont et al., 2004; Little & Williams,

2007; Tønnessen et al., 2011), representing a total distance of 600-800 m sprint with maximal intensity per session.

1.6.3.3 Recovery duration

Recovery duration between repetitions and sets is one of the most important variables in manipulating training intensity. Shorter recovery time forces lower intensity per sprint repetition. The longer the recovery duration, the more repetitions can be completed at a high intensity (Little & Williams, 2007). Spencer et al. (2005) assert that the recovery intervals used during repeated sprint training should be representative of the most intensive periods during a game, rather than the average of the game as a whole. However, this may lead to an over-emphasis on aerobic endurance aspects of the adaptive signal from a resulting training regime and under-emphasis on acceleration and sprint “quality”. Balsom et al. (1992) observed that when soccer players ran 15x40 m at maximal intensity, separated by 30 s recovery, the acute performance decline was 10%. However, when the same training was performed with either 60 or 120 s recovery, the performance drop-off was reduced to 3 and 2%, respectively. In strength training research, long-term studies have shown greater maximal strength improvements with long (2-3 min) versus short (30-40 s) recovery periods between sets (Robinson et al., 1995; Pincivero et al., 1997). Low-intensity, active recovery seems to be beneficial in reducing performance decline during repeated sprint (Signorile et al., 1993).

1.6.3.4 Sprint training frequency

Recent sprint training regimes conducted on elite soccer players have shown positive effects following sprint training as little as once a week (Tønnessen et al., 2011; Shalfawi et al., 2014). The question remains whether even greater effects could be stimulated in this population with more frequent training sessions. No studies have so far compared the adaptive effects of different sprint training frequencies. If a doubling of sprint training frequency per week results in only marginally better training effects, it is likely that the majority of soccer coaches would choose to implement only one session per week, and reduce the risk of injury, while freeing up more time for soccer-specific training.

1.6.3.5 Training related constraints

Sprint performance is adversely sensitive to other training forms. Nakamura et al. (2012) observed a substantial 0-15 m decline (0.10-0.15 s) after endurance running or plyometric training two days per week for three weeks. Ross & Leveritt (2001) suggest that the outcome

of sprint training is best following a period of rest or reduced training, as this leads to appropriate contractile adaptations. Sprinting is therefore difficult to combine with other forms of training, and constraints to overall soccer conditioning are important aspects of assessing the practical efficacy of training interventions. Dupont et al. (2004) reported positive training effects after repeated sprint training in-season. Other studies have shown positive outcomes when the sprint training has been performed in the off-season or early pre-season (Tønnessen et al., 2011; Shalfawi et al., 2013 and 2014). To the authors' knowledge, no studies have compared sprint training effects across different phases of the season. Recently, we aborted an intervention study performed during the transition from pre-season to season start due to drop-out issues caused by injuries. Future intervention studies should report the number of injuries sustained during the intervention period, along-side any observed positive training effects, as these results are equally important in soccer.

In summary, total load and fatigue in sprint training is determined by the interaction of exercise mode, distance, intensity, sets x repetitions, recovery duration, recovery type and session frequency, in addition to training status/overall conditioning and external conditions (i.e. wind, running surface, footwear and altitude). Depending on the manipulation of these variables, different repeated sprint protocols can induce almost opposite physiological adaptations, making it possible for scientists to discover what they want to see. Coaches and training experts must take into account the demands of the sport and each athlete's capacity when designing a conditioning program.

2 Aims and hypotheses of the thesis

The overall objective of this thesis was to investigate the role and development of sprinting speed in soccer. To elucidate the main issue in a comprehensive manner, six original studies and a published review were conducted.

Sprint performance differences that separate the excellent from the average are relatively small on an absolute scale. Very high validity and reliability is therefore important if we are to detect meaningful changes in sprinting performance with confidence. To contribute to this end, the purpose of study I was to quantify potential sprint time differences between SB and DB timing systems. This information will be of benefit to practitioners and scientists wishing to derive accurate and reliable results, while identifying the most appropriate measurement system for use. To facilitate informed comparisons of times derived from different timing methods, the purpose of study II was to compare different sprint start positions and generate correction factors between popular timing triggering methods on 40 m sprint. Test validity, test-retest reliability of sprint testing and correction factors derived from study I and II will strengthen the methodological platform for interpretation of further data in the thesis. We hypothesized that starting method and timing system used can combine to generate large absolute differences in sprint time.

Limited information in research literature is available regarding concrete demands on sprinting skills in soccer. Fundamental aspects regarding the role and development of sprinting skills in soccer can be characterized by a retrospective analysis of data over a significant timeframe and by access to a large representative cross-section of sprint performance in soccer players. The Norwegian Olympic training center is a standard testing facility for a large number of teams at different performance levels, including national squads. A database of sprint and CMJ results that has been collected over 15 years provides the potential for addressing several different questions related to the role and development of sprinting speed in soccer. We chose to include CMJ test results in our next studies, as we believe that such available information will strengthen the interpretation of sprint data. Therefore, the purpose of study III and IV was to use a large database of soccer athlete sprint and CMJ tests collected under highly standardized conditions over 15 years to estimate generalizable differences in sprinting speed and jumping height as a function of athlete playing level, field position and age. Additionally, we wanted to evaluate the evolution of sprint and CMJ ability among male professionals and female elite players in Norwegian soccer over a 15 year period. To the extent that Norwegian soccer developments mirror

international developments, these results have international relevance. We hypothesized that sprinting skills distinguish groups from different playing standard and positions, and that professional players have become faster over time.

Study V is a published review of the research that has been undertaken so far and “holes therein” regarding our understanding of the role sprinting speed has in soccer and how best to stimulate its development in team sport athletes. Research questions for the last two studies regarding sprint training of soccer players emerged and were developed from this review.

The vast majority of studies involving sprint training interventions for soccer players make no other recommendations than that sprint velocity should be maximal throughout. Available evidence in endurance training and strength training demonstrates that high, but sub-maximal intensity loading effectively stimulates adaptation through the interaction between high intensity and larger accumulated work that can be achieved before onset of fatigue, compared to maximal efforts. Anecdotal evidence in support of this is observed in the sprint training philosophy developed by athletic sprint pioneer coaches. Therefore, the purpose of study VI was to investigate the effect of training at 90% sprint speed on maximal and repeated sprinting performance in soccer. We hypothesized that a relatively large repetition load of sprints at 90% of maximal velocity would improve soccer related sprinting skills.

No previous studies have compared the effects of sprint training at different intensities. Furthermore, the effect of sprint technique supervision has so far not been investigated in soccer players. Therefore, the purpose of study VII was two fold: 1) To compare the effects of training at 90 and 100% sprint speed, and 2) compare the effects of directly supervised sprint training versus unsupervised training on maximal sprint performance, repeated sprint ability and gait characteristics in young soccer players. We hypothesized that sprinting at 90 and 100% of maximal velocity would improve soccer related sprinting skills to a similar degree, and that directly supervised training would enhance sprint performance compared to unsupervised training.

3 Methods

3.1 Experimental approach to the problems

3.1.1 Sprint time differences between single beamed and dual beamed systems (study I)

Sprint times measured by DB and single beamed SB photocell systems were compared on a sprint track at the Norwegian Olympic Training Center. Each system contained its own separate trigger, with photocells placed at the start (0.5 m after the start line), 20 m and 40 m splits. Data was collected in two phases. The purpose of phase 1 was to compare the timing systems under ideal conditions. To eliminate the potential effects of the sensor beams being broken prematurely by swinging limbs, two recreationally active participants cycled as fast as possible through the 40 m track 25 times each with a 160 cm tube (18 cm diameter) vertically mounted in front of the bike. Using this protocol, the two systems should ideally generate 50 pairs of identical times. Deviations from this expectation were quantified. The purpose of phase 2 was to quantify the incidence and magnitude of time discrepancy between SB and DB under normal running sprint conditions. Twenty-five (15 females, 10 males) well-trained junior elite track & field athletes with at least two years of training background performed two 40 m sprints each.

3.1.2 Validation of timing systems and start procedures (study II)

Data in study II was collected in two phases. The purpose of phase 1 was to establish the validity of times determined using the following timing systems:

- Brower Timing Systems, a popular wireless and portable timing system, with audio speaker sensor.
- Dartfish video timing, a software program for video analysis.

These systems were compared with the Omega Scan`O`Vision system during national competitions at Bislett stadium in Oslo, an internationally certified athletics venue. Timing was initiated by gunfire, and the athletes ran from set start block (4-point stance) position. Times of 48 different heat winners (60-400 m running events) were determined using all 3 systems simultaneously.

Phase 2 data collection was designed to quantify the impact of several popular timer triggering/start position combinations in a group of 25 track & field athletes. In addition, to assess test-retest reliability, repeated trials for each of the three starting methods were

compared. In each series, the athletes performed three sprints over 40 m in randomized order under the following conditions:

- Start from standard sprinter blocks with gunfire, measured by both Brower Timing System with audio speaker sensor and Dartfish video timing.
- 3-point start with fingers placed on a timer touch pad at the start line, measured by both Brower Timing System and Dartfish video timing.
- Standing rocking start leaning back prior to sprinting, measured by both Brower Timing System, Dartfish video timing, and a dedicated indoor system used by the Norwegian Olympic Training Center employing an imbedded pressure sensor below the track surface (NOC-timing).

The different timing methods and starting positions are summarized in Table 2. Rest between each of the three sprints in a series was 6 minutes. Pause duration between the two series was 20 min.

Table 2. Timing methods and starting position during phase 2 data collection in study II.

System Method	Brower Timing System			Dartfish video timing			NOC-timing
<i>Start device</i>	Audio sensor	Hand pod	Photo cells	Video camera	Video camera	Video camera	Floor plate
<i>Initiating by</i>	Gunfire	Pressure release	Move-ment	Move-ment	Move-ment	Move-ment	Pressure release
<i>Reaction time</i>	Yes	No	No	Yes	No	No	No
<i>Stop device</i>	Photo cells	Photo cells	Photo cells	Video camera	Video camera	Video camera	Photo cells
<i>Start position</i>	Block 4-point	3-point stance	Standing	Block 4-point	3-point stance	Standing	Standing
Used in run	A	B	C	A	B	C	C

NOC-timing= the timing system at the Norwegian Olympic Training Center

3.1.3 Database categorization (study III and IV)

Thousands of 40 m sprint and vertical jump tests have been performed at the Norwegian Olympic Training Center over the last two decades. System setup and procedures have remained consistent throughout the entire period. An excel-database has been developed in order to store all test results, providing the opportunity to quantify performance demands and estimate generalizable differences in sprinting speed and CMJ height as a function of athlete

playing level, field position, age and development across time epochs. For the playing level analyses, soccer players were categorized as: Senior national team, 1st division, 2nd division, 3rd-5th division, junior national team and junior players. Senior national team soccer players ($n=134$) were defined as individuals who represented Norway in Olympic Games, World Cup, Euro Cup, qualifying matches or training matches. Junior national team players ($n=116$) had represented Norway in the U20 and/or U23 age group. First division soccer players ($n=372$) represented clubs from the highest division level in the Norwegian soccer league system, while 2nd ($n=187$) and 3rd-5th ($n=175$) division athletes were playing in the corresponding lower divisions. The junior players ($n=169$) were playing in the highest junior division for different clubs in Norway. Due to the smaller sample size for females, the following four categories were created: Senior national team, 1st division, 2nd division and junior elite. Male national team and 1st-2nd division players were professional players, while female national team and 1st division players were categorized as elite athletes in this thesis.

Player positions were identified for each athlete by their coaches or by self-report as: Goalkeepers, defense players, midfielders or forwards. Athlete age was calculated from date of birth and testing date. Male subjects were categorized as: <18, 18-19, 20-22, 23-25, 26-28 and >28 years. The female soccer players were categorized as: <18, 18-19, 20-22, 23-25, and >25 years. To quantify the development of sprinting velocity and CMJ ability over time, the database was divided into three time epochs: 1995-1999, 2000-2005 and 2006-2010. The rationale behind the age and time epoch categorization was sample size distribution and best possible equal splits.

Playing position, age and time epoch analyses for the male players were restricted to professionals (national teams and 1-2nd division players) at the time of testing. All female players were included in the playing level, position and age analyses, but the time epoch analysis was restricted to members of the national team at the time of testing. The analyses of 40 m sprint and CMJ performances were based on best individual result. In some cases best sprint and CMJ test results occurred on different testing days. Data from a single athlete was only included in one category for each analysis. That category was the athlete's affiliation on the day of their best result.

3.1.4 Repeated sprint training of junior soccer players (study VI and VII)

Study VI was a randomized controlled trial where the control group (CG) completed regular soccer training according to their teams` original training plans while the training group (TG) replaced one of their weekly soccer training sessions with a repeated sprint training session performed at 90% of maximal sprint speed. The nine week intervention period took place from mid August to mid October, corresponding to the last part of the Norwegian soccer season. Results from soccer specific physiological test results were compared before and after the intervention period.

Study VII was a randomized controlled trial where the participants were randomly assigned to four different treatment conditions. A control group (CON) completed regular soccer training according to their teams` original training plans. Three training groups replaced one of their weekly soccer training sessions with a repeated sprint training session performed at either maximal intensity (100UNSUP), 90% of maximal sprint speed with direct supervision (90SUP) or 90% of maximal sprint speed without direct supervision (90UNSUP). The seven week intervention period took place from mid October to mid December, corresponding to off-season in the Norwegian soccer season. Results from soccer specific physiological test results were compared before and after the intervention period.

3.2 Subjects

In total, 1208 soccer players and 98 track & field athletes contributed data to this program of research (Table 3). Twenty-five junior elite track & field athletes participated in study I. Five senior national team sprinters in study II had represented Norway in Olympic Games, European or World championships, individually or in 4x100 m relay while the remaining track & field athletes ($n=20$) in the study were among the best Norwegian juniors in sprint or hurdle events. The soccer players in study III and IV represented a broad range of playing standard, from national team to amateur players in lower divisions. Since 1995, the Norwegian female squad has won gold and bronze in the Olympic Games, gold in World Cup and silver medal in the Euro Cup. The male squad has been ranked among the top 10 several times in the official FIFA ranking (International Federation of Association Football, 2014^B). Considering the performance level of male 1st division teams, Norway has been ranked between 10th and 20th place in UEFA`s country ranking during the time period 1995-2010 (Unions of European Football Associations, 2014).

Twenty-five soccer players (13 male and 12 female), aged 16-19 years, volunteered to participate in study VI. They were all students at a local sports high school/academy which included a soccer specialization program and recruited from the Oslo region. All athletes were playing in the highest junior division level for a number of different clubs in Norway. Gender and age information were used to pair match subjects for gender and grade level. Subject pairs were then randomized to either TG or CG by a co-author not directly involved in testing or the training intervention. Two participants from TG and one from CG dropped out due to acute knee or ankle injuries sustained during soccer practice or matches. Thus, 22 of 25 subjects completed the study. The final group sizes were 13 in the TG and nine in the CG.

Fifty-two male soccer players, aged 16-19 years, volunteered to participate in study VII. None of these athletes participated in study VI. The athletes were playing in the highest junior division level for four different clubs in Norway. To eliminate the influence of varying overall soccer conditioning, the participants were initially paired for clubs and then randomly assigned to one of the four intervention conditions by a co-author not directly involved in testing or the training intervention. The subjects in the three training groups were required to complete at least six out of seven training sessions during the intervention period in addition to all performance tests in order to be included in further analyses. CON subjects were required to perform at least 80% of planned sessions and complete all pre- and post tests. One participant each from CON, 100UNSUP, and 90SUP dropped out due to illness during training or testing. Two participants from 90SUP and one from 90UNSUP dropped out due to injuries sustained outside of the sprint training intervention. A final player from 90SUP group dropped out due to Achilles tendon strain, possibly associated with the sprint intervention. Thus, 45 of 52 subjects completed the study with the following sample sizes: CON=9, 100UNSUP=13, 90UNSUP=13 and 90SUP=10. For more information regarding the participants, the reader is referred to the separate papers.

Table 3: Participant characteristics across studies

	n=	Age	Body mass	Type of athlete
Study I	2	32 ±7 yrs	76 ±10 kg	Recreationally active
Study I	25	19 ±1 yrs	67 ±10 kg	Junior elite track & field athletes
Study II	48	15 ±4 yrs	-	Male and female 60-400m sprinters and hurdlers
Study II	25	18 ±4 yrs	65 ±9 kg	National team and junior elite track & field athletes
Study III	939	22 ±4 yrs	77 ±9 kg	Male soccer players from a broad range of performance levels
Study IV	194	22 ±4 yrs	63 ±6 kg	Female soccer players from a broad range of performance levels
Study VI	22	17 ±1 yrs	65 ±7 kg	Male and female junior soccer players
Study VII	45	17 ±1 yrs	69 ±8 kg	Male junior soccer players

Age and body mass are stated as mean and SD

3.3 Ethical considerations

Informed consent was obtained from all participants in study I. The first data collection in study II was performed during different national athletics meets in order to validate timing systems. Results from 48 heat winners were included for analysis. The athletes signed up and participated voluntarily for these competitions on the basis of being timed, thus no informed consent was obtained. Approvals from meet organizers to set up extra timing systems were obtained in advance. In the second phase of data collection, twenty-five athletes participated in the study at the Norwegian Olympic Training Center. Informed, written consent was obtained in advance from each subject prior to participation.

Data from studies III and IV were preexisting data from the quarterly, semiannual, or annual testing that soccer teams performed for training purposes. The current investigations became pertinent several years after the soccer players were tested, and the athletes were not aware of being part of a research program at the time. In practice, it was impossible to contact more than 1100 formerly or still active soccer players in order to obtain informed consent.

According to the National Research Ethics Committee for Social Sciences and Humanities, exception from the general rule of obtained informed consent is possible provided that the information being processed is not sensitive and the research has a value that clearly exceeds any possible disadvantages to the individuals involved. No health data were collected from any of the subjects. The Norwegian Olympic Sports Program approved the use of these data, provided that individual test results remained confidential.

In study VI and VII, all participants gave their written voluntary informed consent. Parental consent was obtained for <18 years athletes. All studies were approved by the ethics committee from the Faculty of Health and Sport Sciences, University of Agder.

3.4 Apparatus

3.4.1 NOC-timing (study I-IV, VI and VII)

All sprint tests with NOC-timing were performed on a dedicated indoor 40 m track with 8 mm Mondo track FTS surface (Mondo, Conshohocken, USA) and electronic timing equipment. A 60x60 cm start pad was placed under the track at the start line. The clock was initiated when the front foot stepped off the pad. The athletes' center of gravity was therefore ~ 0.5 m in front of the start line when the timer was initiated. Split times were recorded at 10 m intervals. Infrared photocells with transmitters and reflectors were placed in pairs on each side of the

running course with 1.6 m transmitter-reflector spacing. The infrared beam was split to reduce the possibility of arm swings triggering the cells. Transmitters were placed 140 cm above the ground and reflectors for the split beam were placed 130 and 150 cm above the floor. Both beams had to be interrupted to trigger the timer stop. Electronic times were transferred to dedicated computer software (Biorun, made in MatLab by Biomekanikk AS, Oslo, Norway).

The timing system at the Norwegian Olympic Training Center was upgraded in 2011. All timing gates were replaced by dual beamed photo cells placed 130 and 150 cm above the floor. Both beams had to be interrupted to trigger the photo cell. The floor pod was replaced with a single beamed timing gate placed 60 cm in front of the start line 30 cm above floor level. The athletes' center of gravity was therefore ~ 0.5 m in front of the start line when the timer was initiated by the leg during the first stride. The old system was used in study II-IV, while the upgraded system was used in study I, VI and VII.

3.4.2 Omega Timing System (study II)

Omega's Scan`O`Vision photo finish timing system was used as "gold standard" for validation of all other timing systems. Timing is initiated by an electronic gun, sending current through an attached wire to a separate console in a control room that triggers all timing devices. Trial gunshots, also called "zero shots," were fired before each competition start to ensure exact timing initiating. Scan`O`vision Star cameras were installed at the finish. They take up to 2000 images per second with a resolution of 2048 pixels per vertical line. The Omega system splices thousands of scans together, forming a composite image of the contestants. Corresponding time is displayed for each picture, providing the photo finish judge enough information to estimate time within ± 0.0005 s (Swiss Timing, 2014).

3.4.3 Brower Timing System (study II)

The Brower Timing System (Draper, USA) is the most commonly used timing system in speed-related studies and employs three different time initiating devices:

- 1) An audio sensor that captures gunfire and start the timer, in principle equivalent to athletics timing where reaction time is included. This method of timing initiation was used in both data collection phases in study II.
- 2) A small hand pod (12x5 cm) placed at the start line was also used in the second data collection phase, measuring athletes starting from a 3-point stance with feet split and one

hand on the pad. The timer starts when hand pressure against the pod is released. The time difference between 3-point stance and block start by gunfire is the net effect of including reaction time and the possible benefits of start blocks.

3) A pair of infrared Brower photo cells (model TRD-T175, Draper, USA) was also used as time triggering in the second data collection. An infrared transmitter with corresponding reflector was placed on each side of the running course 1 m above the ground at the start line. In this test, athletes stood with front foot on the start line, and were allowed to lean backward before rolling forward into the timer initiation infrared beam.

Single beamed infrared photo cells captured the 40 m finish line for all Brower timing methods. In order to minimize false signals caused by swinging arms, we adjusted the finish line transmitter and corresponding reflector to head level for each runner instead of the normally used chest level.

3.4.4 Dartfish video timing (study II)

Video recordings by Sony HD camera (HDR-HC9E, Tokyo, Japan) were analyzed in Dartfish 5.0 (Fribourg, Switzerland) to estimate sprint times during both data collection phases in study II. For all block starts, each video clip captured both gun smoke from the starter's pistol and the athletes passing the finish line. There are 0.02 s between each video frame in the Dartfish analyzer window. To ensure best possible accuracy, two independent analyzers assessed the size of the smoke plume in the first frame where smoke was visible. For a small smoke plume, the start was set 0.01 s back on the timeline (cue in). When a large plume was visible in the first "smoke frame", the start was set 0.02 s back on the timeline. Similar procedures were used to set video cue in for 3-point starts and standing starts. If the hand or foot left the pod or floor plate between two frames, the start time was set between these two timeline values. Finish time (cue out) was set the same way. If the athlete passed the finish line between two frames, the finish time was set between these two timeline values. Time of each athlete's run was calculated by subtracting cue in from cue out. Mean values were taken from the times determined by two independent observers.

3.4.5 Force platform (study III, IV, VI and VII)

The force platform at the Norwegian Olympic Training Center was used in study III, IV, VI and VII. All CMJ tests were performed on AMTI force platform; model OR6-5-1 (Watertown, USA). Jumping height was determined as the center of mass displacement

calculated from force development and measured body mass. The system setup was in accordance to the guidelines recommended by Street et al. (2001). Force data were sampled at 1000 Hz for 5 s with a resolution of 0.1 N. The data were amplified (AMTI Model SGA6-3), digitized (DT 2801), and saved to a special made computer software (Biojump, Oslo, Norway). All athletes were registered with full name, date of birth, testing date, age, playing level, position in field, body mass and CMJ height. The force platform has been assessed for accuracy and reliability (Enoksen et al., 2009).

3.4.6 $\text{VO}_{2\text{max}}$ test apparatus (study VI)

A 200x70 cm ELG Woodway treadmill (Woodway GmbH, Weil am Rhein, Germany) routinely calibrated for speed and incline was used for the maximum oxygen uptake ($\text{VO}_{2\text{max}}$) testing. Treadmill inclination was 3° (5.25%) for all tests. During the test, subjects breathed into a Hans Rudolph two-way breathing valve (2700 series; Hans Rudolph Inc, Kansas City, USA) connected to metabolic gas analyzers. Gas exchange and ventilatory variables were continuously sampled in a mixing chamber with 30 s averaging. Oxygen uptake was measured using an Oxycon Pro™ metabolic test system (Jaeger-Toennis, Wurtzburg, Germany). The test equipment underwent a standard calibration procedure before each test. Several studies of Jaeger's Oxycon Pro™ system with mixing chamber have reported high overall validity and stability across a range of ventilations exceeding 200 L·min⁻¹ when using the Douglas bag method as reference standard (Rietjens et al., 2001; Carter & Jaekendrup, 2002; Foss & Hallén, 2005). Heart rate was measured continuously during the test (Polar RS400, Kempele, Finland).

3.5 Testing procedures

3.5.1 40 m sprint test (study I-IV, VI and VII)

The participants in study II conducted standing starts, block starts and 3-point starts. The starting positions and triggering methods employed are illustrated in Figure 1, panels A-D. For the start block condition, the athletes followed the instructions and commands according to the competition rules of the International Athletics Association Federation (2014^A). This method includes reaction time to the starter's pistol. In the 3-point condition, athletes placed the fingers from their front hand on the pod immediately behind the starting line. During standing starts, timing was initiated in two ways; via release of pressure from the front foot on the sub-surface triggering plate, and via breaking a photocell beam 1 m above the starting line. Athletes were instructed not to lean into the photo beam prior to the start. After a ready

signal was given by the test operator, athletes started on their own initiative. In the 3-point and standing start conditions, no start command was given and reaction time was not included in the total time. All subjects in study II were familiar with the different starting positions through training sessions with their clubs, relays and competitions.

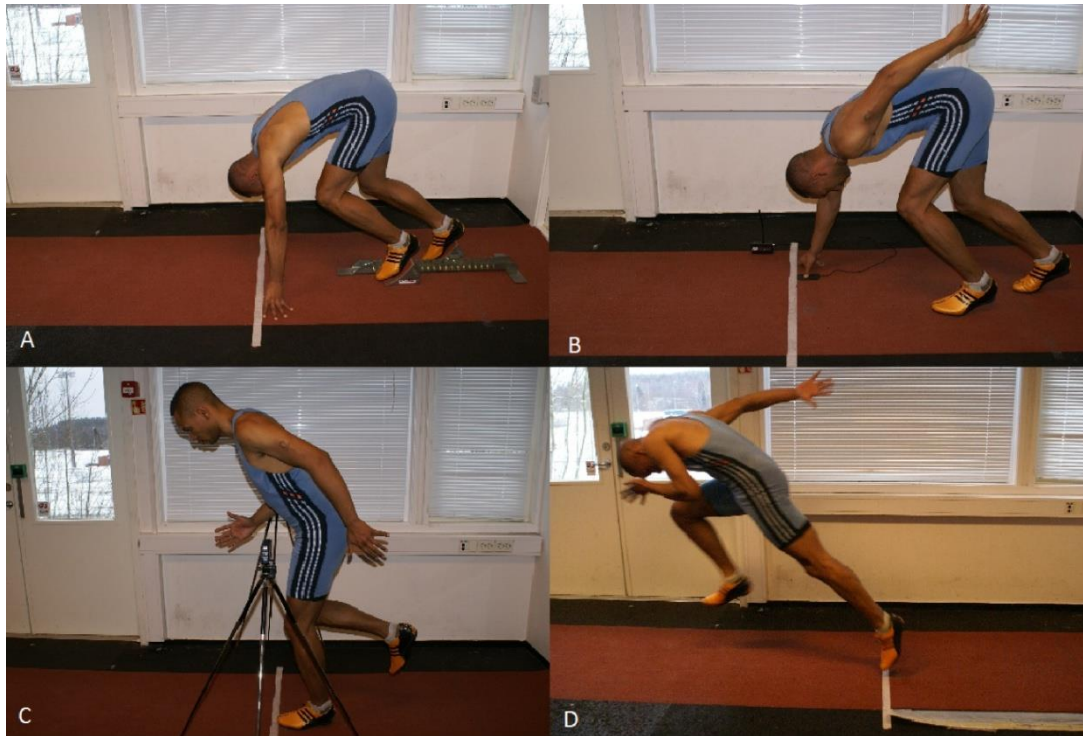


Figure 1. A: Body position at timer triggering for block start. B: Three-point start with hand release. C: Standing start with photo cell trigger. D: Standing start with floor sensor trigger below front foot.

The participants in study I, III and IV performed 40 m sprint tests from a standing start position (Figure 1, panel D). In study III and IV, new trials were performed every 3-5 min until evidence of peak performance was observed. The best sprint result for each player was retained for analysis. In practice, 80% of all athletes achieved their best performance within two trials. A total of 2078 sprint tests formed the basis for studies III and IV. All subjects underwent identical testing procedures and conditions, including equipment setup and running surface, during the 15 year data collection period.

3.5.2 CMJ test (study III, IV, VI and VII)

Each athlete was weighed on the force platform for system calibration before testing. After warm up, the subjects underwent 1-2 easy trial jumps to assure testing procedure familiarization. In study III and IV, the soccer players performed repeated jumps with ~ 60 s recovery between each trial until jump height stabilized. In study VI and VII, each participant

performed 3 trials with similar recovery time. To isolate the test to leg extensor muscles and minimize technical elements, jumps were performed with hands placed on the hips. The subjects were required to bend their knees to approximately 90 degrees and then rebound in a maximal vertical jump. Best result for each player was retained for analysis. A total of 1293 CMJ tests formed the basis for study II and III.

3.5.3 Repeated sprint testing (study VI and VII)

The participants in study VI and VII performed a repeated sprint test over 20 m with start each 60 s prior to and after the intervention period. Distance and recovery were chosen in line with mean frequency and typical distance of all-out sprints reported from match analyses (Chapter 1.3). Since maximal sprinting is the most frequent situation associated with hamstring injuries (Ekstrand et al., 2011), we restricted the number of sprints to 12 in study VI and increased the number to 15 sprints in study VII. The athletes were asked to run as fast as possible on each sprint. Starting procedures were similar to the standard sprint test (Figure 1, panel D). Mean time and best sprint was retained for analysis. Heart rate was measured continuously during the test (Polar RS400, Kempele, Finland). A blood sample was acquired via finger stick to quantify the blood lactate concentration (BLa-) immediately after the last sprint (LactatePro LT-1710, Arkay KDK, Kyoto, Japan).

All sprint tests were video captured from start to finish (Sony HDR-HC9E). Video recordings were analyzed in ProSuite, version 5.5 (Dartfish, Switzerland) to determine stride count and derive average stride length. For precision, the digital ruler in the analyzer window was used to interpolate the last step across the finish line. For example; if the 13th and 14th ground contact occurred 0.8 m in front of and 1.2 m beyond the finish line, respectively, the recorded number of strides was registered as 13.4. Mean SL was calculated by dividing the number of steps by the distance (in this case: $20 \text{ m} \cdot 13.4^{-1} = 1.49 \text{ m}$). Mean SF was calculated from mean velocity and mean SL. Prior to the study, we validated this measurement method by rolling out thin paper at the finish line area in order to measure the distance between the visible spike shoe marks from competitive sprinters. The absolute difference across twenty sprint comparisons never exceeded 0.1 steps. Thus, the maximal margin of error for stride counts over 20 m is 0.7-0.8% for athletes using 13-15 steps.

3.5.4 VO_{2max} test (study VI)

The participants in study VI performed a VO_{2max} test 80-90 minutes after the repeated sprint test. Each subject completed a standardized 15 minute warm up on a treadmill prior to testing. The warm up consisted of 10 min low intensity running (50-70% of HR_{peak}) followed by 2-3 short bouts (~ 30 s) performed at the average expected velocity of the VO_{2max} test (13-14 km·h⁻¹ for females and 15-16 km·h⁻¹ for males). The testing procedure was a stepwise increase in running velocity every minute until volitional exhaustion after 5-8 minutes. Starting velocities were 9 and 12 km·h⁻¹ for females and males, respectively. The velocity was increased by 0.5 or 1 km·h⁻¹·min⁻¹ until evidence of VO₂ leveling off was seen, with the last velocity step maintained for at least 1 min. Athletes were continuously updated on all relevant variables during testing to enhance motivation to full voluntary exhaustion. The test was terminated before volitional exhaustion if VO₂ values leveled off or decreased despite increasing workload and ventilation and respiratory exchange ratio (RER) exceeded 1.10. VO_{2max} was defined as the highest average of two consecutive 30 s measurements. HR_{peak} was defined as the highest 5 s HR average. Test results with peak RER below 1.05 were excluded. The reliability and validity of our testing procedures are supported by Midgley et al., (2008).

3.5.5 Yo-Yo Intermittent recovery tests (study VI and VII)

The Yo-Yo Intermittent Recovery test 1 (Yo-Yo IR1) and 2 (Yo-Yo IR2) was used in study VI and VII, respectively. The rationale for using different tests was due to gender distribution among participants, as study VII only consisted of male athletes. The tests were performed indoors on artificial turf. Prior to the test, participants performed a standardized warm up consisting of 10 min easy jog, followed by the initial 90-120 s of the IR1 test or 60-90 s of the IR2 test. The test set-up and procedures were in accordance with the guidelines by Krustup et al. (2003). The standardized audio files for Yo-Yo IR1 and 2 were played from a HP Pavilion g7 Notebook PC (Palo Alto, CA, USA) connected to Creative 265 speakers (Singapore). Two test leaders supervised the tests. The athletes were divided in consecutive groups, such that each supervisor was responsible for ≤ 4-5 athletes during the test.

For more detailed information regarding the testing procedures, the reader is referred to the separate papers.

3.6 Intervention programs (study VI and VII)

During all training sessions in study VI, TG performed repeated 20 m sprints at 90% intensity with start each 60 s. All training sessions were performed outdoor on an artificial turf soccer pitch. Outside air temperature ranged from 5 to 20° C. Twenty sprints were performed in the first training session, while 25 sprints were performed in the remaining eight training sessions. All sprint training sessions in study VII were performed indoors (air temperature ~ 20° C) on an 8 mm Mondo FTS surface (Mondo, Conshohocken, USA). 100UNSUP performed 15x20 m maximal sprints with start each 60 s once a week. Groups 90SUP and 90UNSUP performed one weekly training session consisting of a larger dose of 30x20 m sprints at 90% of maximal sprint velocity with start each 60 s.

In the absence of previously published studies, we estimated a 1:2 repetition ratio between 100% and 90% sprinting based on both anecdotal and experimental evidence from strength training and endurance training studies comparing interventions where similar intensity ranges were utilized. For example, within endurance training, elite athletes accumulate about twice as much duration when performing intervals at 90% of HR_{max} as when performing at $\geq 95\%$ of HR_{max} (Seiler et al., 2013). In order to compare the two repeated sprint training sessions used in study VII, session rated perceived exertion (RPE) was recorded for all athletes after the repeated sprints performed in pre test and first training session. Written and verbal instructions regarding its use were provided in advance (Foster et al., 1998). Heart rate was measured continuously during the first training session for all athletes who ran at 90% sprint intensity, in addition to BLa^{-} immediately after their last sprint. Mean SL and SF for this session were calculated by identical procedures as for the pre- and post tests. Finally, all training group athletes in study VII performed 3x20 m maximal sprints with start each 60 s 48 hours after the first training session in order to quantify performance recovery. The mean time for these three sprints was compared with the corresponding sprints from the pre test.

Two sprint training experts, with extensive national level coaching experience, supervised the 90SUP group during the intervention. Three key sprint-technical elements and corresponding verbal instructions were emphasized during the training sessions:

- *Optimize upper body angle* relative to the ground during the initial steps in order to create higher horizontal propulsive forces through more effective utilization of hip and knee extensors (Harland & Steele, 1997; di Prampero et al., 2005): The athletes were instructed

to assume a start position with forward leaned upper body and lowered centre of gravity, and to gradually become more upright throughout the acceleration.

- *Minimize horizontal braking forces* (Harland & Steele, 1997): Athletes with apparently too high braking forces were encouraged to assume a more favourable configuration at the point of ground contact with the foot plant closer to the perpendicular line from the centre of mass. This can be achieved by hitting the ground with a bent knee (relevant during acceleration) or with the centre of mass at a large vertical distance above the ground (relevant during maximal sprinting).
- *Produce a stiff rebound during ground contact* in order to minimize degeneration of horizontal propulsive forces (Chelly & Denis, 2001; Kuitonen et al., 2002; Girard et al., 2011): Identified “heal runners” were encouraged to pre activate dorsiflexion muscles prior to foot plant and stiffen the ankle joint during ground contact, allowing them to utilize the elasticity in the plantar flexors for greater force development. These instructions were emphasized during the warm up drills.

After video analysis of the first training session, the two sprint training experts prepared an individual capacity profile for all participants in the 90SUP group. Each athlete was presented one technical task at a time, in accordance with general feedback principles (Schmidt & Wrisberg, 2008). Players with obvious technical limitations were provided more verbal instructions than technically well-performing athletes.

Electronic timing was always used in study VI and VII to control running speed and adjust intensity according to each player’s “target time”. Target time was based on best sprint time achieved during preliminary testing by multiplying mean velocity over the 20 m distance by 0.9. No feedback other than sprint time information was provided after each run for TG in study VI and 90UNSUP/100UNSUP in study VII. More than 90% of all sprints were completed with intensity between 87 and 93% of maximal sprint velocity for TG, 90UNSUP and 90SUP. The sessions were performed at the same time and day for each training group in study VI and VII throughout the intervention period.

3.7 Statistics

Sprint time comparisons in study I and validation of the timing systems in study II were determined based on mean difference, Pearsons R correlation, standard error of measurement (SEM), and coefficient of variation (CV). A paired samples t-test was used to identify

significant differences between SB and DB in study I, and timing discrepancies are presented as a frequency distribution. In study II, the General Linear Model with Repeated Measures followed by Bonferroni adjustment for multiple comparisons was used to compare results from the three time initiating methods. Test-retest differences in performance were compared using the paired samples t-test. Dartfish video timing was used for reliability measurements. Mean difference, SEM and 95% confidence interval (95% CI) for differences between block starts (reference starting position) and the other starting methods are presented.

In study III and IV, mean and 95% CIs were calculated to each group or category for the analyzed performance split times. One-way Analysis of Variance (ANOVA) followed by Tukey's post hoc test where necessary, were used to identify differences in 20 m sprint times and CMJ performance across groups or categories.

In study VI and VII, the General Linear Model with Repeated Measures followed by Bonferroni adjustment for multiple comparisons was used to examine RSA development (mean sprint time) for 100UNSUP across tests and training sessions. Same model was used for 90SUP and 90UNSUP to compare effort related variables in maximal and sub-maximal sprinting. A paired samples t-test was used to examine within group changes in central location (mean). Analysis of Covariance (ANCOVA) adjusting for pre-test value and stratification factor (club) was used to examine between group changes in central location. The differences were judged by using Estimated Marginal Means (EMM). Bonferroni corrections were used to adjust *p*-values for multiple testing. Unadjusted effect size (Cohen's *d*) was calculated to evaluate the meaningfulness of the difference between category means.

The first 6 sprints from pre test were used to calculate typical variation for sprint time, SL and SF in study VI and VII. Effect size of the within group changes for mean sprint time were based on change in central location (mean) and typical variation. Pearson's R was used to quantify the relationships among anthropometric and physical parameters. Effect magnitudes were interpreted categorically according to the scale presented by Hopkins et al. (1999). The results are expressed as mean \pm SD, and 95% CIs was calculated for all measures.

Significance was accepted at the $p < 0.05$ level in all studies. All sprint times are reported to the nearest 0.01 s. PASW Statistics 16.0 or 18.0 (SPSS, Chicago USA) was used for all statistical analyses. For more information regarding the statistics, the reader is referred to the separate articles.

4 Results

4.1 Timing of sprint performance (study I and II)

4.1.1 Sprint time differences between SB and DB timing systems (study I)

When arm and leg motion was eliminated as a source of timing variation (tube mount bicycle sprint, Phase 1), CV was 0.4 and 0.7% for 0-20 m and 20-40 m sprint times, respectively, while SEM was 0.01 s for both distances. During normal sprint action (Phase 2), CV increased to 1.4 and 1.2% for 0-20 m and 20-40 m splits, respectively, while SEM was 0.02 s for both distances. No bias was observed for 20-40 m sprint times, but SB timing generated 0.02 s slower 0-20 m sprint times than DB timing ($p < 0.01$). During normal sprint action, absolute time differences for 0-20 m sprint times ranged from -0.05 to 0.06 s between the two timing devices.

4.1.2 Correction factors across timing systems and start methods (study II)

Concurrent measurements of athletics events using the Omega timing system, Brower audio triggering and Dartfish based video analysis demonstrated that the two later measurement methods were valid to the limits of precision of the instruments.

Table 4 reports differences in performance time associated with the three starting positions compared, all based on Dartfish video analysis. The impact of starting position on 40 m performance time was statistically significant and much larger than the typical variation from test to test.

Table 4: Correction factors across starting positions (block start to gunfire as reference)

Starting positions compared to block start with reaction time (n= 25)	Mean (s)	SD (s)	95% CI	
			Lower	Upper
3-point (fingers leave hand pod) faster by	0.17*	0.09	.11	.22
Standing start (body passes photo cell) faster by	0.27*	0.12	.20	.33
Standing start (front foot leaves foot pad) faster by	0.69*	0.11	.63	.75

* $p < 0.01$ vs. block start

4.2 Sprinting demands in soccer (Study III and IV)

4.2.1 Sprint performance by playing standard

Figure 2 shows the relationship between playing level and sprint performance. Overall, 95% CIs for 0-20 m sprinting time trended predictably across playing standard. In contrast, no predictable trend across playing levels was observed for CMJ performance.

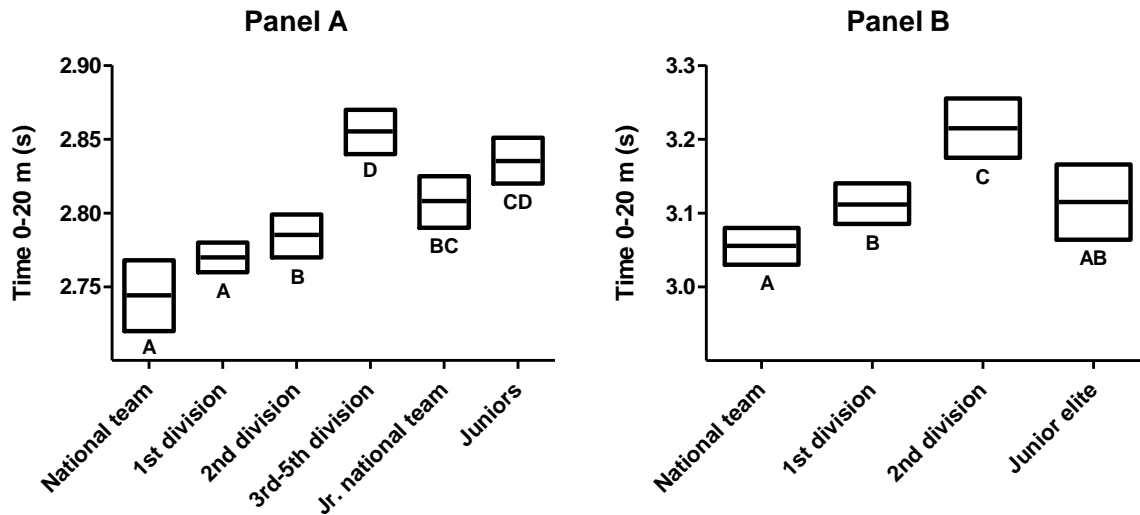


Figure 2: 95% confidence intervals for 0-20 m sprint time as a function of male (Panel A) and female (Panel B) playing level. Differing letters indicate significant differences among groups.

4.2.2 Sprint performance by playing position

Figure 3 shows the relationship between sprint performance and playing position. Forwards were the fastest players, ahead of defenders, midfielders and goalkeepers, respectively.

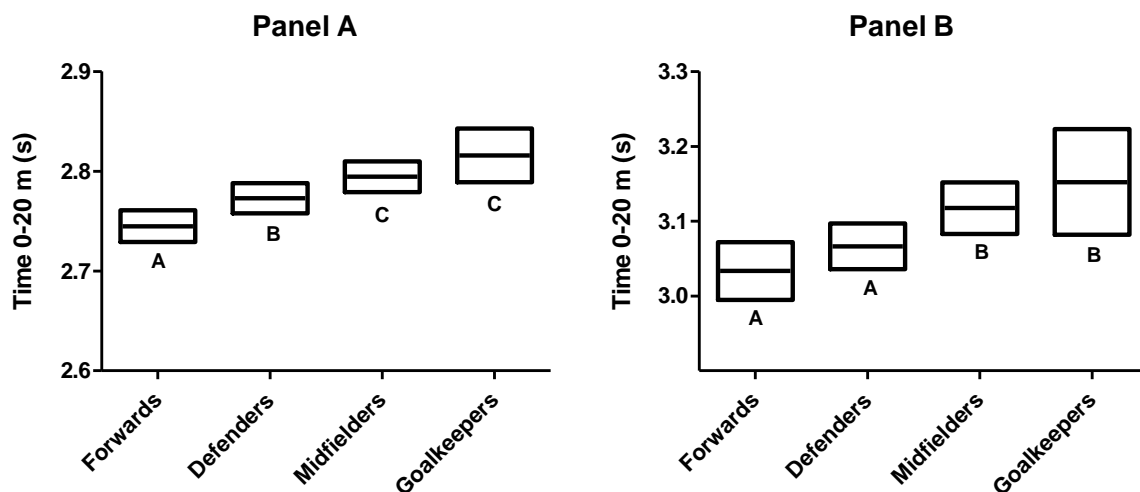


Figure 3: 95 % confidence intervals for 0-20 m sprint time as a function of playing position for male (Panel A) and female (Panel B) players. Differing letters indicate significant differences among groups.

Male midfielders demonstrated poorer jumping performance than the other playing positions, while no differences in CMJ height were observed among playing positions for females.

4.2.3 Sprint performance by age

Figure 4 shows the development of sprint performance through different age stages. Sprint performance peaked in the age range 20-28 years for men, while no differences in 0-20 m sprint times were observed across the female categories. No differences in CMJ height were observed across male and female age categories.

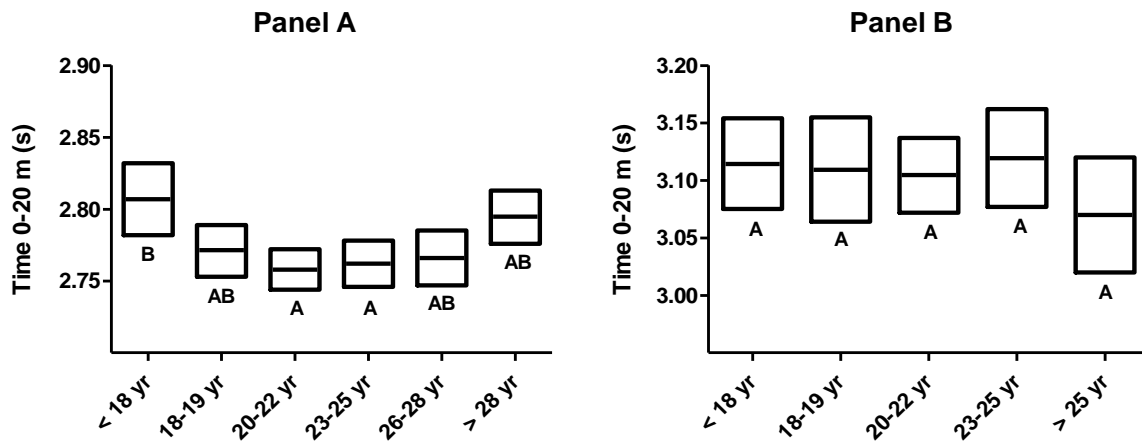


Figure 4: 95% confidence intervals for 0-20 m sprint time as a function of male (Panel A) and female (Panel B) age groups. Differing letters indicate significant differences among groups.

4.2.4 Sprint performance by time epochs

Figure 5 shows the development of sprint performance through different time epochs. Overall, the 95% CIs demonstrate a slight trend towards faster soccer players over time.

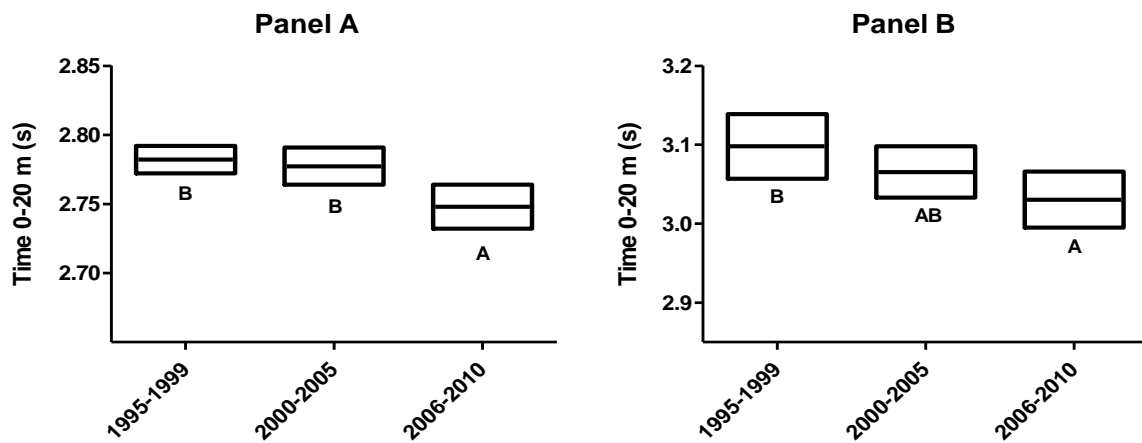


Figure 5: 95% confidence intervals for 0-20 m sprint time as a function of time epoch for male professional players (Panel A) and female national team players (Panel B). Differing letters indicate significant differences among groups.

No significant differences in CMJ performance were observed for neither male nor female players across the epochs.

4.2.5 Percentiles

Percentiles of sprint times, peak velocity and CMJ for male professional and female elite players are presented in Table 5.

Table 5: Percentiles (PCTL) of split times, peak velocity (PV) and countermovement jump (CMJ) for male professionals and female elite soccer players

PCTL	Males						Females					
	10m (s)	20m (s)	30m (s)	40m (s)	PV (m.s ⁻¹)	CMJ (cm)	10m (s)	20m (s)	30m (s)	40m (s)	PV (m.s ⁻¹)	CMJ (cm)
99	1.40	2.58	3.65	4.69	9.71	52.1	1.55	2.86	4.10	5.30	8.55	41.0
95	1.42	2.61	3.70	4.77	9.43	47.0	1.57	2.90	4.13	5.34	8.33	37.3
90	1.44	2.64	3.75	4.84	9.30	45.2	1.59	2.93	4.15	5.41	8.20	35.4
75	1.48	2.70	3.82	4.92	9.10	42.0	1.64	3.00	4.29	5.54	7.94	32.7
50	1.52	2.76	3.91	5.04	8.81	38.7	1.69	3.08	4.37	5.69	7.65	29.4
25	1.56	2.83	4.00	5.17	8.55	35.7	1.72	3.16	4.53	5.86	7.40	26.8
10	1.60	2.89	4.08	5.26	8.36	33.3	1.79	3.23	4.64	6.02	7.19	24.5

Note: For the sprint tests, a floor pod placed on the start line was used for time initiation.

4.3 Repeated sprint training effects (study VI and VII)

No differences in RPE were observed between the two repeated sprint sessions in study VII. The athletes were also equally recovered 48 hours after the respective sprint training sessions. Sprinting at 90% velocity was accompanied with reduced HR_{peak} (17%; very large effect; $p < 0.001$), BLa⁻ (55%; large effect; $p < 0.001$) and SF (11%; very large effect; $p < 0.001$) compared to maximal sprinting. While heart rate plateaued after ~ 10th repetitions during the 30x20 m 90% sprint training sessions, heart rate increased progressively throughout the 15x20 m 100% sprint sessions.

Figure 6 shows individual changes in mean sprint time from pre- to post test. Typical variation for sprint time was 0.025 s for both groups (CV 0.8-1.0%). In study VI, TG improved 12x20 m mean sprint time and Yo-Yo IR1 performance ($p < 0.05$). In study VII, 90SUP group improved Yo-Yo IR2 performance from pre- to post-test ($p < 0.01$). No significant between group differences for the performance parameters were observed. 90SUP improved Yo-Yo IR2 performance by a moderate margin compared to the other groups. All other effect magnitudes between or within groups were trivial or small. We observed ± 0.06 and ± 0.04 s absolute variation in mean sprint time between pre- and post tests for CG and CON, respectively. Moreover, weekly group mean changes in repeated sprint performance up to 0.05 s were observed for 100UNSUP.

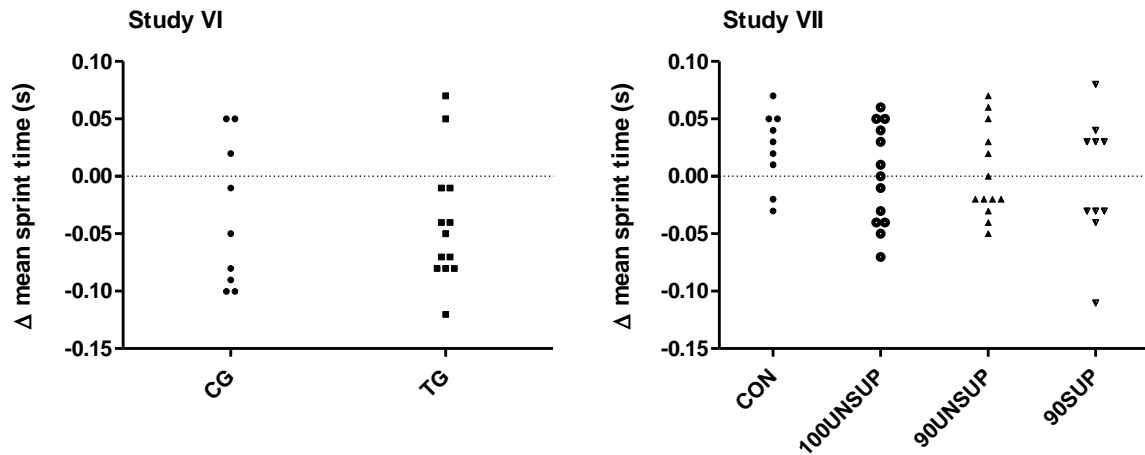


Figure 6: Individual changes in mean sprint time from pre- to post test.

No significant between group differences in anthropometric, physiological and biomechanical variables were observed from pre to post-test in study VI, and effect magnitudes were trivial to small. In 100UNSUP, significant differences from pre- to post test were observed for BLa^- ($p < 0.001$), SL ($p = 0.020$) and SF ($p = 0.019$). A significant difference between 100UNSUP and CON was observed for BLa^- ($p = 0.008$). No other within or between group differences in anthropometric, physiological and biomechanical variables were observed in study VII.

Changes in mean sprint time were moderately correlated with changes in BLa^- from pre- to post-test. Changes in best sprint time showed a very large to nearly perfect correlation with changes in mean sprint time.

5 Discussion

This thesis showed that accurate sprint performance monitoring can be complicated by timing errors as large as ± 0.06 s when using SB instead of DB systems. More strikingly, the starting method and timing system used can combine to generate up to ~ 0.7 s absolute differences in sprint time. Our retrospective analysis of sprint test data revealed that sprinting performance distinguishes groups from different performance levels and positions. While sprint velocity for males peaks in the age range 20-28 years, with small but significant declines in velocity thereafter, female soccer players struggle to improve their sprinting skills after their teens. These cross-sectional data also suggested positive development in sprinting velocity among elite performers over a 15 year period of testing. Weekly repeated sprint training sessions at either maximal or 90% maximal sprint speed were not sufficient to improve performance outcomes for soccer related sprinting performance, when compared to a matched control group assumed to maintain a constant training pattern. Finally, no differences in performance outcomes were observed between supervised and unsupervised sprint training groups training at 90% maximal sprinting velocity.

5.1 Timing of sprint performance (study I and II)

5.1.1 Sprint time differences between SB and DB timing systems (study I)

The time variation observed with single beam and double beam systems was negligible when arm and leg motion interference was eliminated. Concurrent measurements of two participants cycling as fast as possible with a tube vertically mounted in front of the bike demonstrated that SB and DB were valid to the limits of precision of the instruments. During normal sprint action involving rotating limbs, absolute time differences ranged from -0.05 to 0.06 s for 0-20 m splits. The significantly slower SB sprint times (0.02 s) compared to DB are most likely explained by swinging arms breaking the SB beam before the torso at start. No significant bias was observed for 20-40 m sprint times, and absolute time differences were somewhat smaller compared to 0-20 m times. The greater error in the 0-20 m split is likely attributable to the differing start position mechanics and forward-lean of athletes during acceleration contributing to an earlier obstruction of the SB gate compared to the more upright position during maximum speed sprinting.

Study I demonstrated that a true 0-20 m sprint time of 2.75 s at worst could be quantified as 2.70 or 2.81 s by SB. Up to 0.06 s error based on timing equipment is a very big difference for short sprint distances. Among male soccer players, this represents the difference between the

75th and 25th percentile among Norwegian football players (Table 5). We believe that ± 0.06 s probably represents the upper limit of the magnitude of time differences between SB and DB timing, as there are anthropometric limitations regarding how far in front of the torso arms or lifted knees can be while sprinting. However, signal to noise ratio decreases with decreasing running distance, and higher CV / lower correlations for 10 m splits compared to 20 m splits were observed in study III. Such aspects are of particular significance when coaches and athletes are interested in measuring running speed over very short distances.

5.1.2 Correction factors across timing systems and start methods (study II)

Study II revealed no systematic variation between Omega, video and Brower speaker sensor timing. That is, for practical purposes the Brower audio sensor/photo cell timing system and Dartfish video analysis give identical results to Omega photo timing to a precision of ± 0.01 s.

The starting method and timing system used can, however, combine to generate large absolute differences in “sprint time”. Table 4 shows that 40 m times triggered by hand release from a 3-point stance, breaking a photocell beam from a standing start, and releasing the front foot from the ground during a standing start generate 0.17, 0.27 and 0.69 s faster times respectively compared to block starts with a timer triggered by gunfire. At the extreme, a seemingly outstanding 40 m sprint time of 4.4 s measured from a standing start with triggering via floor sensor below the front foot is equivalent to a 40 m sprint time of ~ 5.1 s measured from starting blocks with time initiated by a starter’s gun. This large time difference is explained by three main components:

1. Reaction time is included in block starts, not standing starts.
2. ~ 1 m difference in center of gravity placement at time triggering.
3. Horizontal center of gravity velocity at time triggering.

The method of sprint timing used can result in much greater differences in sprint time than observed sprint performance range in soccer players (Table 5). These differences are essentially absolute. Therefore, their impact on the interpretation of shorter sprint distance performances would be even greater. The young athletes in this study were not all sprint specialists, but were experienced with block start conditions as well as the other starting conditions employed. While the absolute differences observed might vary somewhat with the experience of the athletes being tested, we believe the correction factors quantified here provide a reasonable framework for comparing sprint performances across timing methods.

5.2 Sprinting demands in soccer (study III and IV)

5.2.1 Sprint performance by playing standard

The 95% CIs in Figure 2 show that sprinting velocity trends predictably across performance level. To our knowledge, these are the first studies to demonstrate that linear sprinting ability is a performance distinguishing factor in male and female soccer. Previous studies have either involved players that did not adequately represent variation in playing standard or included small sample size. All category differences observed in the present study were larger than test-retest reliability (CV ~ 1%) for the same timing system and starting procedures, as reported in study II.

Based on the present findings, it is tempting to claim that improved sprinting skills can make a football player more effective, and therefore more valuable. Faster players are probably able to utilize their technical and tactical skill better than slower players with otherwise identical skills. The chance of dribbling an opponent out of position, or successfully defending an attack, increases with improved sprinting skills. Soccer athletes must develop multiple qualities, and coaches should take sprinting velocity into account within the larger skill set of soccer. According to Reilly et al. (2000^B), sprinting skills are one of several important criteria in talent identification and selection processes in early junior stages. Several authors have reported that elite youth or selected players around puberty tend to be faster than non-elite youth and non-selected players (Vaeyens et al., 2006; Gil et al., 2007; le Gall et al., 2010). Thus, selection of players, testing, and physical conditioning of the athletes should be reflected by the importance of speed.

This study did not demonstrate a clear relationship between CMJ height and soccer performance level. Male senior national team, 1st-2nd division and junior national team players jumped on average ~ 39 cm in the CMJ test (Study III). This is similar to the values achieved by Portuguese U19 elite players, Italian National team and elite players, and French elite players (Cometti et al., 2001; Rampinini et al., 2007^A; Castagna et al., 2012; Rebelo et al., 2013). The female national team players in the present study jumped on average ~ 31 cm. This is similar to the values reported for female Spanish elite players and Italian national team players (Castagna et al., 2012; Mujika et al., 2009^A). Taken together, the present findings and those of other studies do not provide enough evidence to claim that CMJ ability is a performance distinguishing factor in soccer. According to Rampinini et al. (2007^A), such tests

have little relevance to soccer play. It may be that a certain minimum of vertical jump ability is required, and our data indicate that mean CMJ values in the range 38-40 and 30-32 cm are sufficient to perform at an elite level in male and female soccer, respectively. This does not mean that CMJ height beyond this level is not beneficial. Several studies have reported improved sprint or agility skills as a result of increased power in lower limb muscles (Alves et al., 2010; Wong et al., 2010; Helgerud et al., 2011; Loturco et al., 2013).

5.2.2 Sprint performance by playing position

Velocity differences across playing positions ranged from small to large in the present investigation. Forwards were the fastest players ahead of defenders, while midfielders and goalkeepers were slowest (Figure 3). All differences observed were larger than test-retest reliability revealed in study II. The internal ranking by player position is in accordance with the findings by Boone et al. (2012) and Sporis et al. (2009), while other studies have reported a more unclear relationship between sprint performance and playing position (Taskin, 2008; Rebelo et al., 2013). Physical characteristics may vary across clubs and nations, depending on tactical dispositions and differences in the athlete selection process over time. Gil et al. (2007) reported physical differences related to playing positions among 241 Spanish juniors, suggesting selection processes in early junior stages as a possible explanation for the rank of speed pattern among playing positions. Coaches may select the fastest players for attacking positions due to the belief that team success depends primarily on the forwards. Buchheit et al. (2010) and Mendez-Villanueva et al. (2010) claim that the impact of physical capacities on game physical performance is position dependent.

Sprinting ability must be seen in relationship to the physical demands of the different positions on the field. Our playing position categorization is somewhat limited, but forwards and defenders are probably the fastest players because they are involved in most decisive duels during match play (Rampinini et al., 2007^B). Thus, these players should perhaps spend more time on sprint training compared to the other playing positions. Midfielders cover the longest distance during games, indicating physical qualities other than sprinting velocity may be more important for this position (Vigne et al., 2010). Taken together, the present findings and previous published studies indicate that players in different positions should prioritize different physical conditioning regimes to solve different tasks during play.

Our data showed that male midfielders had lower vertical jump capacity compared to the other positions (study III). This is in contrast to Sporis et al. (2009) who reported no CMJ

height differences across positions among 270 Croatian elite soccer players. Goalkeepers performed better in CMJ than sprinting relative to the other position groups in study III, which is in accordance to Boone et al. (2012). Goalkeepers were also the tallest players, supporting the logical expectation of explosive range as an important performance factor for goalkeepers. No significant differences in CMJ height were observed across playing positions for the female players in study IV. However, the results show a similar trend as for men.

Despite significant differences, the physical differences across playing positions in Norwegian soccer seem relatively small in practical terms. It seems illogical that goalkeepers have similar vertical jump ability and only $\sim 5 \text{ mL} \times \text{min}^{-1} \times \text{kg}^{-1}$ lower $\text{VO}_{2\text{max}}$ values than midfielders (Tønnessen et al., 2013). This indicates that mostly all players within the same team perform similar physical training.

5.2.3 Sprint performance by age

Our data show that sprint velocity for men peaked in the age range 20-28 years with small but significant decreases in velocity thereafter (Figure 4, panel A). No studies have so far carefully examined velocity and power characteristics across age among male soccer players. Mujika et al. (2009^A) reported no significant differences in 15 m sprint times between juniors and seniors representing a Spanish soccer club. Nominees to the FIFA world player of the year since 1995 ($n=48$) had a mean age of 26 ± 3.6 years, indicating that peak sprinting performance may occur at the same age as when male soccer players were on top of their career (International Federation of Association Football, 2014^C). Athletics statistics show that the world top 50 sprinters achieved their best performances at a mean age of 25 ± 3.1 years (International Athletics Association Federation, 2014^B). No further cross-sectional improvement in sprint velocity was observed after the age 20-22 years in our study. Thus, peak sprinting performance within the larger skill set of soccer peaks 3-4 years earlier compared to when sprint optimization is the only training goal. This stagnation may be considered in the context of match program and specific training. It is possible that extensive soccer training, including 1-3 hrs. running with varying intensity 5-6 days per week, inhibits sprinting performance.

No differences in CMJ ability were observed across the male age categories. This finding reinforces the notion that vertical jump performance is less important than sprinting ability in soccer. No age related differences in sprint and CMJ performance were observed among the

female players in the present study (Figure 4, panel B). Previous studies indicate that peak performance in speed and vertical jump is achieved in the mid-teens for female soccer players. In a study of 414 female athletes (12-21 years), Vescovi et al. (2011) reported an increase in sprint and CMJ ability up to 15-16 years before stabilizing. Mujika et al. (2009^A) found differences in CMJ height, but not 15 m sprint time, between Spanish junior and senior female elite players.

Female soccer players struggle to improve their sprinting velocity and vertical jump ability as seniors beyond the level achieved as juniors. Similar patterns are seen in available statistics from Norwegian athletics as for the girls in this study. Female sprinters and long jumpers improved their performance level from 13 to 17 years of age before plateauing, while corresponding male athletes achieve their peak performance level several years later (Norwegian Athletics Association, 2014). Speed and vertical jump stagnation in the mid-teens is not only a challenge for women`s soccer, but for female sport in general. Players in the age group 18-19 years were heavier than the <18 years category (Paper III). Increased body weight might contribute to the failure of continued training to result in improved sprint velocity and power performance. According to the Norwegian elite series team coaches, primarily their very best players continue participating in soccer after 23-24 years of age. This selection bias may mask a small decline in sprinting and power performance occurring already in the mid 20s among females.

5.2.4 Sprint performance by time epoch

This study demonstrates a small but positive development in sprinting velocity for Norwegian soccer players over time based on cross-sectional comparison of 5-year time cohorts (Figure 5). No studies have so far monitored a large number of soccer players` physical characteristics longitudinally. The time epoch analysis was restricted to male professionals and female National team athletes, and all of these players were tested as part of routine testing procedures. The female National team players and three male elite series teams tested at least once a year throughout the entire period, and the development of sprinting velocity for these teams demonstrated a positive trend. Therefore the difference observed cannot be explained by a selection bias. Instead, we hypothesize that this provides some evidence for the contention that Norwegian professional players have become faster over time. To the extent that Norwegian soccer developments mirror international developments, these results have

international relevance. This reinforces the assumption that sprinting skills are becoming more and more important in modern soccer.

Interestingly, our data showed no development in CMJ height during the corresponding time epochs. We are not aware of studies reporting development in short sprinting distances without development in CMJ ability. Our results remained consistent even when only players who performed both sprint and CMJ testing were considered. These findings indicate that sprint and vertical jump are specific and independent qualities.

5.2.5 Sprint time comparisons

Sprint time comparisons across studies based on available correction factors for time initiating/starting procedures (Table 4), wind (Linthorne, 1994), footwear (Haugen, unpublished material) and running surface (Stafilidis & Arampatzis, 2007) indicate that male professional players from the best European soccer leagues sprint slightly faster than the professional soccer players in study III (Dupont et al., 2004; Rebelo et al., 2013). We calculate that the fastest soccer players are ~ 0.6 s slower than the world's fastest sprinters over 40 m (Graubner & Nixdorf, 2011). However, individual test results from study II and III shows that the very fastest male soccer players may achieve 40-m sprint times on par with 60-m sprint finalists from national athletics championships.

In practical terms, individual differences in sprinting skills are even more critical than mean differences among groups of players. Our database material from the Norwegian Olympic Training Center, including 40 m sprint tests of 628 male and 165 female elite players between 1995 and 2010, shows that the 75th -25th percentile difference is 0.13 and 0.16 s over 20 m sprint for male and female players, respectively (Table 5). Based on average velocity over the distance, the fastest quartile is at least 1 m ahead of the slowest quartile over 20 m. Similarly, the 90th -10th percentile difference over 20 m sprint is equivalent to more than 2 m.

Furthermore, the 10% fastest players run 1 m further than the 10% slowest players for each second during peak sprinting (Table 5). Thus, peak velocity is decisive in longer sprint duels. Even though this thesis has focused on 0-20 m sprinting skills, the results in paper III and IV demonstrates almost identical trends for maximum sprinting skills as a function of playing level, position and development over time. This stands in contrast to the opinion of many coaches who believe that sprinting skills only over very short distances are important in soccer. While short sprints (<20 m) occur more frequently in games, the longest sprints are probably more decisive.

According to Hopkins et al. (2000), the smallest worthwhile performance enhancement/change in team sport is 0.2 of the between-subject standard deviation. Based on the database material in study III and IV, this corresponds to 0.02 s over 20 m sprint. In practical settings, a 30-50 cm difference (~ 0.04-0.06 s over 20 m) is probably enough in order to be decisive in one-on-one duels by having body/shoulder in front of the opposing player. Thus, the ability to either create such gaps as an attacker or close those gaps as a defender can be fundamental to success in elite level soccer. The chance of dribbling an opponent out of position, or successfully defending an attack, increases with greater acceleration and sprinting ability.

5.3 Repeated sprint training effects (study VI and VII)

5.3.1 Effort matched sprint training

A 1:2 ratio for sprint repetitions between 100UNSUP (15x20 m) and the two sub-maximal sprint training groups (30x20 m) was used in study VII. These two training sessions were equally rated in terms of session RPE. Furthermore, no differences in sprint performance were observed between the three initial pre test sprints and the 3x20 m sprints performed 48 hours after the first training session for the maximal and sub-maximal training groups, respectively, indicating similar recovery status two days after the sprint training sessions used. Based on these observations, we conclude that the two repeated sprint training sessions were effort matched. However, heart rate values demonstrated a “steady state” condition during repeated 20 m sprints at 90% intensity, and corresponding lactate values were below what has been considered “lactate threshold intensity” (BLa^- between 2.5 and 4.0 mmol·L⁻¹) in endurance training (Tokmakidis & Piliandis, 1998). In contrast, repeated sprinting at maximal intensity induced a progressive increase in heart rate, as well as BLa^- at or above the typical lactate threshold range described for endurance athletes. Even though BLa^- values obtained from sprint and endurance training are not directly comparable, the data suggest a marked difference in skeletal muscle glycolytic metabolism between 90% and maximal sprinting.

5.3.2 Effect of training at maximal and sub-maximal intensity

Study VII revealed only trivial and non significant changes in soccer related sprinting skills from pre- to post test for 100UNSUP (Figure 6). Previously, we have observed unaltered 0-20 m sprint performance, but improved 20-40 m speed as a result of weekly repeated 40 m sprints at maximal or near maximal intensity over ten weeks (Tønnessen et al., 2011). Taken together with track and field age-group statistics (Norwegian Athletics Federation, 2014), age-group analyses from large retrospective data collections in soccer players (Figure 4) and

the experience of practitioners (Miller, 1984), it becomes increasingly evident that short sprint performance is quite resistant to training enhancement.

While sprint performance remained unchanged in 100UNSUP, SL and SF changed significantly from pre- to post test. This change was higher than the observed typical variation. We suspect that 100UNSUP unconsciously shortened SL and increased SF in the chase of velocity enhancement, as this provides a subjective feeling of running faster. According to Mero & Komi (1986) and Mero et al. (1992), high level sprinters should strive to improve performance by increasing SF while maintaining SL. In contrast, SL is considered a more limiting factor among athletes of lower sprint standard (Armstrong et al., 1984). We can only speculate if supervised coaching would have ensured a more optimal combination of SL and SF in 100UNSUP. The correlation values for SL ($r = 0.60$) and SF ($r = 0.63$) across the present tests were surprisingly low when all groups were pooled together (study VII). This indicates that identical sprint performance can be achieved with varying locomotion efficiency among athletes of lower sprint standard, which is in accordance with observations made by Hunter et al. (2004).

Based on the findings in study VI and VII, we cannot conclude that training at 90% sprint speed is a sufficient sprinting intensity for stimulating adaptation over short sprint distances (Figure 6). The concept of training at slightly sub-maximal sprinting intensity is derived from coaching practice in track and field athletics, where competitive distances are 60 m and longer (Vittori, 1996). It is possible that sub-maximal sprint training is more appropriate for typical athletic sprinting distances (100-200 m) compared to 0-20 m accelerations. In strength- and endurance training, reduced training intensity can be compensated for with substantially increased accumulated work to enhance performance (Kraemer et al., 2002; Seiler et al., 2013). In these training situations, the physiological energy demand is controlled using heart rate or oxygen consumption for endurance training, or external load for strength training, such that percentage work intensity is linearly related to the objectively measured change in workload up to 100% of VO_{2max} , or 100% of 1RM. However, 20 m sprints are comprised of high to maximal acceleration from a resting state and continuing through the timed distance. In this condition, energy demands during the acceleration phase greatly exceed those at peak velocity (di Prampero et al., 2005). These calculations are complex, but a relevant simplification is to compare the change in kinetic energy that must be achieved at maximal and 90% of maximal acceleration. The change in kinetic energy ($0.5m \cdot v^2$) is proportional to the square of the change in velocity, such that the 90% sprint condition is associated with a

nearly 20% reduction in kinetic energy change (and by extension, muscular energetic demand) compared to maximal sprinting velocity. Due to this non-linearity, a 5% reduction in short sprint velocity during repeated sprint training over short distances would correspond to 90% workloads in strength training and endurance training, and might give a more optimal balance of stress, injury risk reduction and adaptive signal retention. This possibility remains to be explored.

5.3.3 Effect of supervised training

Study VII revealed no significant training effects when supervised and unsupervised sprint training at 90% sprint speed were compared (Figure 6). However, the 90SUP group improved Yo-Yo IR2 performance by a moderate margin compared to the other groups, indicating that sub-maximal sprint locomotion efficiency had improved. The lack of effects on maximal and repeated sprint ability may have been affected by the possibility that sprint training at 90% sprint speed is below the lowest effective sprinting intensity for stimulating adaptation. Future studies should therefore explore the effect of directly supervised training with a gradual increase in intensity from sub-maximal to maximal sprint velocity.

Mazzetti et al. (2000) and Coutts et al. (2004) showed that the presence of a training expert was beneficial for maximal strength and power development over time. In contrast to study VII, the training experts in those studies were allowed to adjust the total training load during the interventions. Based on these observations, one could speculate that the effect of expert supervision during training is optimized when combined with greater flexibility in the day-to-day training prescription.

5.3.4 Constraints to overall soccer conditioning

The within-subject typical variation for 20 m sprint time was 0.025 s over the first 6 sprints, or < 1%, demonstrating excellent reliability of the criterion measure. In CG and CON, we observed ± 0.06 and 0.04 s absolute individual variation in mean sprint time between the pre- and post tests, respectively. More important, weekly changes in group mean values up to 0.05 s (nearly 2%) were observed in 100UNSUP, despite consistent frequency and volume of games and training sessions during the intervention period. This weekly or seasonal variation is considerably higher than the observed typical variation during a single sprint testing session. Our findings emphasize the need for more detailed information about overall conditioning load, accepting that intensity and structuring of training are challenging variables

to control in a large group of players from different teams. If improvement of sprinting skills is the primary goal for certain players in-season, future studies should explore whether it is more effective to structure the players' weekly soccer training rather than introducing an additional physical conditioning regime. A “perfectly designed” conditioning program for certain capabilities may limit other important qualities and vice versa. Coaches and conditioning experts have to balance their training methods and exercises in order to optimize different skills in relation to their contribution to overall soccer performance.

More sprint training sessions per week or a longer intervention period could increase the potential for developing faster players. Based on session RPE (Foster, 1998), the participants perceived each sprint session as “somewhat hard” (study VII). Unfortunately, most of their respective team coaches were not willing to “sacrifice” further soccer training sessions, even in the off-season or early pre-season. Our interventions were shaped by several training-related constraints within the overall soccer training program. We argue that these constraints are indeed an important aspect of assessing the practical efficacy of training interventions in team sport.

5.3.5 Correlations across analyzed parameters

We observed a significant relationship between individual changes in sprint performance and corresponding changes in BLa^- immediately after the repeated sprint tests in both intervention studies. Accepting the limitations of interpreting muscle energetics from blood lactate concentration, there was a moderate trend towards lower individual “lactate production” with reduced repeated sprint performance, and vice versa. Since individual sprint performance depends upon the ability to fully activate fast twitch motor units with maximal firing frequency (Ross & Leveritt, 2001), we speculate that increased BLa^- during sprinting could reflect enhanced neural activation on an individual level.

Moreover, the results revealed a very large to nearly perfect correlation between changes in best sprint time and changes in mean sprint time during repeated 20 m sprints from pre- to post test (study VI and VII). This finding strongly supports the conclusion of Pyne et al. (2008), who reported that RSA is more strongly correlated with maximal sprinting velocity than endurance capacity. Even when the recovery time between each 20 m sprint is reduced to 25 s, the difference between mean time and best time remain small (Dellal & Wong, 2013). Balsom et al. (1992) observed that it is more difficult to detect detrimental effects with short sprints compared to slightly longer sprints. Our results support this observation, as the

absolute time difference between best and mean sprint time was only 2 x the typical variation calculated from pre-testing (Table 3).

Changes in sprint performance were only moderately correlated with changes in CMJ performance among the players in study VII, while this relationship was non-significant in study VI. Wisløff et al. (2004) reported a strong correlation between maximal strength, sprint performance and vertical jump height, based on low sample size. Salaj & Markovic (2011) concluded that jumping, sprinting and change of direction speed are specific independent variables that should be treated separately. According to Thomas et al. (2001), variables should be considered specific and independent of each other when the coefficient of determination is less than 0.50. The findings in study VI are in accordance with the trends over time analyses in study III and IV, namely that development in short sprinting distances may occur without development in CMJ ability at a group level.

6 Conclusions and practical applications

The present thesis revealed that accurate 0-20 m sprint performance monitoring is complicated by timing errors of ± 0.06 s between SB and DB systems. This error source alone represents three times the value of the smallest worthwhile performance enhancement for this variable in team sports. The observed magnitude and incidence of time differences must be taken into account when selecting timing system. Single beam timing is not recommended for scientists and practitioners wishing to derive accurate and reliable sprint time results.

Moreover, starting method and timing system used can combine to generate large absolute differences in “sprint time”. Times triggered by hand release from a 3-point stance, breaking a photocell beam from a standing start, and releasing the front foot from the ground during a standing start generated 0.17, 0.27 and 0.69 s faster times respectively compared to block starts with a timer triggered by gunfire. Comparison of sprint timing results without consideration of the specific start configuration and timing methods can make for a lot of confusion. For internal comparisons of performance in a training monitoring setting, changing timing methods is unacceptable. The present investigation provides useful correction factors that should improve the validity of performance comparisons across research studies.

Moreover, our cross-sectional studies demonstrated a clear relationship between average sprinting speed and standard of play, supporting the assumption that speed is a crucial performance factor in soccer. Sprint performance varies as a function to playing position. Forwards are the fastest players ahead of defenders, midfielders and goalkeepers. While sprint velocity for males peaks in the age range 20-28 years, with small but significant decreases in velocity thereafter, female soccer players struggle to improve their sprinting skills after their teens. We also observed a positive development in sprinting velocity among elite performers over a 15 years period of testing, indicating that sprinting skills are becoming more and more important in modern soccer. Soccer athletes have lots of qualities to develop, and coaches should take sprinting velocity into account within the larger skill set of soccer. Selection of players, testing, and physical conditioning of the athletes should be reflected by the importance of speed.

Our intervention studies showed that weekly repeated sprint training sessions at maximal or sub-maximal sprint speed were not sufficient to improve performance outcomes for soccer related sprinting performance. Furthermore, no significant differences in performance outcomes were observed between supervised and unsupervised sprint training groups training at 90% maximal sprinting velocity. More frequent training sessions or longer interventions

are obviously required, perhaps in combination with other training forms, increasing the risk of training-related constraints to the overall soccer conditioning. Future studies should explore whether it is more effective to structure the players` weekly soccer training rather than introducing an additional physical conditioning regime. In the absence of evidence supporting the choice of specific training methods at the group level, we suggest that it is essential to diagnose each individual and develop training interventions that target their key physiological and technical weaknesses. Future research should focus more on the relationship between physical demands of the game, capacity profiles among players, and consequences for long term planning of individual fitness programs in soccer.

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SPRINT TIME DIFFERENCES BETWEEN SINGLE- AND DUAL-BEAM TIMING SYSTEMS

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ABSTRACT

Haugen, TA, Tønnessen, E, Svendsen, IS, and Seiler, S. Sprint time differences between single- and dual-beam timing systems. *J Strength Cond Res XX(X)*: 000–000, 2014—Valid and reliable measures of sprint times are necessary to detect genuine changes in sprinting performance. It is currently difficult for practitioners to assess which timing system meets this demand within the constraints of a proper cost-benefit analysis. The purpose of this investigation was to quantify sprint time differences between single-beam (SB) and dual-beam (DB) timing systems. Single-beam and DB photocells were placed at 0, 20, and 40 m to compare 0–20 and 20–40 m sprint times. To control for the influence of swinging limbs between devices, 2 recreationally active participants cycled as fast as possible through the track 25 times with a 160-cm tube (18 cm diameter) vertically mounted in front of the bike. This protocol produced a coefficient of variation (CV) of 0.4 and 0.7% for 0–20 and 20–40 m sprint times, respectively while SEM was 0.01 seconds for both distances. To address the primary research question, 25 track and field athletes (age, 19 ± 1 years; height, 174 ± 8 cm; body mass, 67 ± 10 kg) performed two 40 m sprints. This protocol produced a CV of 1.2 and 1.4% for 0–20 and 20–40 m, respectively while SEM was 0.02 seconds for both distances. The magnitude of time differences was in the range of ± 0.05 – 0.06 seconds. We conclude that DB timing is required for scientists and practitioners wishing to derive accurate and reliable short sprint results.

AU5 AU4 KEY WORDS timing, sprint monitoring

INTRODUCTION

Valid and reliable timing is critical for effective monitoring of sprinting performance. Fully automatic timing systems used in international athletics have been considered the gold stan-

dard to accurately and reliably quantify sprint performance, as this includes photo finish analysis with high-resolution digital line-scan cameras. Unfortunately, such timing equipment is expensive and impractical for most practitioners. According to the competition rules of the International Athletics Association Federation (IAAF), time shall be taken to the moment at which any part of the body of an athlete (i.e., torso, as distinguished from the head, neck, arms, legs, hands, or feet) reaches the vertical plane of the nearer edge of the line (7). Greater accuracy of dual-beam (DB) versus single-beam (SB) photocell timing systems has been reported (2,8), because SB systems can be triggered early by lifted knees or swinging arms. Many scientists and practitioners continue to use SB systems (5), most likely because of lower cost and greater availability.

The purpose of this investigation was to quantify potential sprint time differences between SB and DB timing systems. This information will be of benefit to practitioners and scientists wishing to derive accurate and reliable results, while identifying the most appropriate measurement system for use.

METHODS

Sprint times measured by DB and SB photocell systems **AU6** were compared on a sprint track at the Norwegian Olympic Training Center. Each system contained its own separate trigger, with photocells placed at the start (0.5 m after the start line), 20 m, and 40 m splits. For simplicity, we defined the first split as 0–20 m, even though the distance between the photocells was 19.5 m. Single-beam measures were taken using the Brower Timing System (TC, **AU7** Brower Timing Systems, USA), which is a commonly used and previously validated system (5). These photocells were mounted 1 m above floor level, which is the maximal height of the manufacturer's standard tripods. The DB system was developed by Biomekanikk AS, Norway, with photocells mounted on separate tripods 1.10/1.30 m above the ground at the start and 1.30/1.50 m above ground level at 20 and 40 m, with the trigger criterion being the first occurrence of both beams being broken. Neither timing system incorporated **AU8** on-board timing, and the 2 systems did not interfere each other (Figure 1). **F1**

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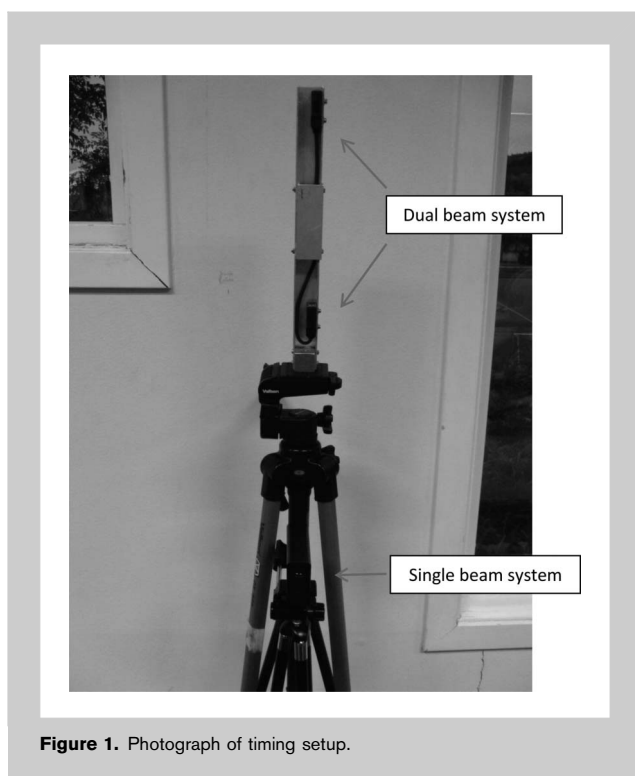


Figure 1. Photograph of timing setup.

AU9 Data was collected in 2 phases. The purpose of phase 1 was to compare the timing systems under ideal conditions. To eliminate the potential effects of the sensor beams being broken prematurely by swinging limbs, 2 recreationally active participants cycled as fast as possible through the 40-m track 25 times each with a 160-cm tube (18 cm diameter) vertically mounted in front of the bike. Using this protocol, the 2 systems should ideally generate 50 pairs of identical times. The purpose of phase 2 was to quantify the magnitude and incidence of time differences between SB and DB under normal running sprint conditions. Twenty-five (15 women and 10 men) well-trained junior elite track and field athletes in the age range 18–20 years (age, 19 ± 1 years;

height, 174 ± 8 cm; body mass, 67 ± 10 kg) with at least 2 years of training background performed two 40-m sprints each. They started from a standing stationary position, a commonly used starting position for team sport athletes (5). Informed consent was obtained from all participants, and the study was approved by the local ethics committee at the University of Agder, Faculty of Health and Sports Science.

Sprint time comparisons of the timing systems under ideal conditions were determined based on mean difference, Pearson's R correlation, SEM , and coefficient of variation (CV). A paired samples T-test was used to identify significant differences between SB and DB. Significance was accepted at the $p \leq 0.05$ level. All sprint times are reported to the nearest 0.01 seconds. Timing discrepancies (0–20 and 20–40 m) between SB and DB are presented as a frequency distribution. PASW Statistics 18.0 (SPSS, Chicago, IL, USA) was used for all statistical analyses.

RESULTS

Table 1 presents time differences between SB and DB for both data collection phases. When arm and leg motion was controlled for (phase 1), CV was 0.4 and 0.7% for 0–20 and 20–40 m sprint times, respectively, while SEM was 0.01 seconds for both distances. During normal sprint action (phase 2), CV increased to 1.4 and 1.2% for 0–20 and 20–40 m splits, respectively, while SEM was 0.02 seconds for both distances. No bias was observed for 20–40 m sprint times, but SB timing generated 0.02 seconds slower 0–20 m sprint times than DB timing ($p < 0.01$).

Figure 2 presents the differences in 0–20 and 20–40 m sprint times between SB and DB for both data collection phases. When arm and leg motion was controlled for (phase 1), we observed identical times in 44% of the bicycle sprints, and 94% of all time comparisons were within ± 0.01 seconds for both distances (Figure 1, panels A and C). During normal running sprint action, absolute time differences for 0–20 m sprint times ranged from -0.05 to 0.06 seconds between the 2 timing devices (Figure 1, panel B). Identical times were observed in only 13% of the cases, while time discrepancies of ≥ 0.02 seconds were observed in 64% of the occasions. For this time interval, the results were positively skewed, meaning that SB timing yielded slower times on average. For 20–40 m sprint times, the absolute time differences ranged from -0.03 to 0.05 seconds (Figure 1, panel D). Identical times were observed in 30% of the cases, while time discrepancies ≥ 0.02 seconds were observed in 42% of the sprints (Figure 1).

TABLE 1. Sprint time comparisons between single-beam and dual-beam timing systems under ideal conditions.*

Single-beam vs. double-beam	n	Δ (s)	R	SEM (s)	CV (%)
Phase 1, 0–20 m	50	0.00	1.00	0.01	0.4
Phase 1, 20–40 m	50	0.00	1.00	0.01	0.7
Phase 2, 0–20 m	50	0.02 [†]	0.96	0.02	1.4
Phase 2, 20–40 m	50	0.00	0.99	0.02	1.2

* n = number of observations; Δ = mean difference; R = Pearson's R correlation; CV = coefficient of variation.

[†] $p < 0.01$ vs. single-beam.

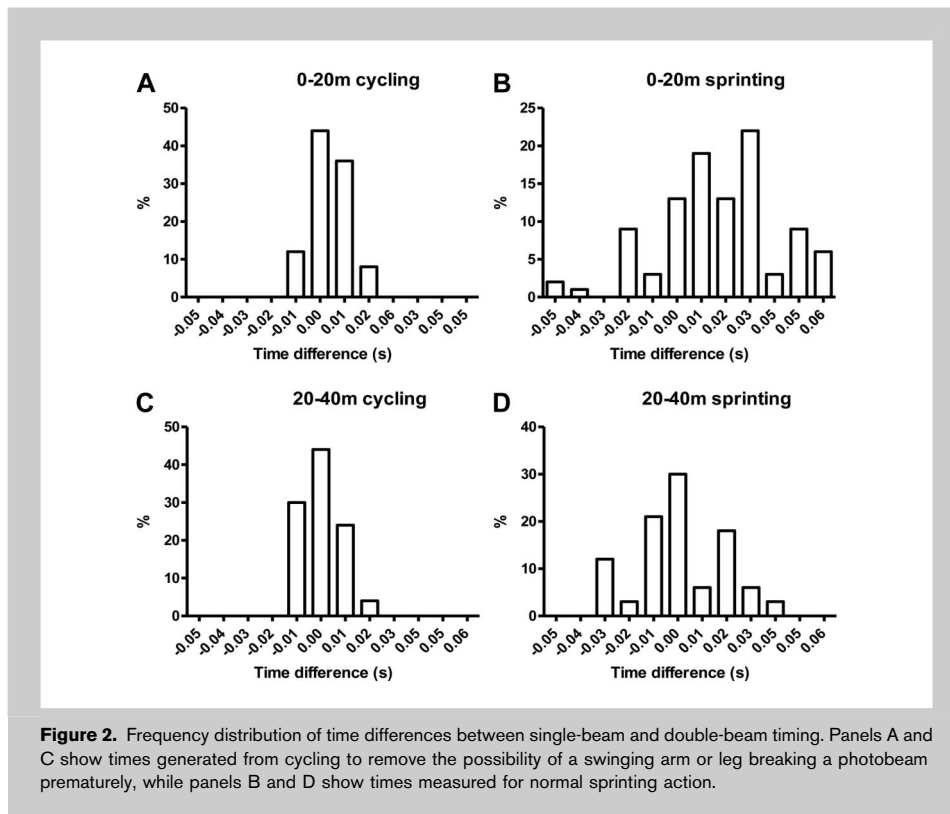


Figure 2. Frequency distribution of time differences between single-beam and double-beam timing. Panels A and C show times generated from cycling to remove the possibility of a swinging arm or leg breaking a photobeam prematurely, while panels B and D show times measured for normal sprinting action.

DISCUSSION

In the present study, the time difference measured with SB and DB systems was minimal when arm and leg motion interference was eliminated. Concurrent measurements of 2 participants cycling as fast as possible with a tube vertically mounted in front of the bike demonstrated that SB and DB were valid to the limits of precision of the instruments. Using this protocol, identical times were monitored in almost half of cases, and only 6% of all time comparisons for both distances were ≥ 0.01 seconds (Figure 1, panels A and C). However, during normal sprint action, absolute time differences ranged from -0.05 to 0.06 seconds for 0–20 m splits. The significantly slower SB sprint times (0.02 seconds) compared with DB are most likely explained by swinging arms breaking the SB beam before the torso at the start. No significant bias was observed for 20–40 m sprint times, and absolute time differences were somewhat smaller compared with 0–20 m times. The greater error in the 0–20 m split is likely attributable to the differing start position mechanics and forward-lean of athletes during acceleration contributing to an earlier obstruction of the SB gate compared with the more upright position during maximum speed sprinting.

This study demonstrated that a true 0–20 m sprint time of 2.75 seconds at worst could be quantified as 2.70 or 2.81 seconds by SB. Up to 0.06 seconds error based on timing equipment is a very big difference for short sprint distances. Among male soccer players, this represents the difference between the 75th and 25th percentile (3).

According to Hopkins et al., the smallest worthwhile performance enhancement in team sport is 0.2 of the between-subject *SD* (3), and this corresponds to ~ 0.02 seconds over 20-m sprint (4). The present results revealed that SB timing is accompanied by time differences 3 times the value of the smallest worthwhile change. We believe that ± 0.06 seconds probably represents the upper limit when it comes to the magnitude of time differences between SB and DB timing, because there are anthropometric limitations regarding how far in front of the torso arms or lifted knees can be while sprinting. However, signal-to-noise ratio decreases with decreasing running distance, and higher CV/lower correlations have been reported for 10-m splits compared with

20-m splits (4). Such aspects are of particular significance when coaches and athletes in, for example, team sports are interested in measuring running speed over very short distances.

Some limitations in the present study should be addressed. Even though the athletes were of differing heights and limb lengths, the SB gates were preset 1 m above ground level for logistical reasons. According to Cronin and Templeton (1), inappropriate height adjustments of timing gates increase the error of SB timing. Thus, if SB gates were adjusted to head or trunk height level for each athlete tested, the error may have been lower when using SB. However, this is a further potential benefit of using DB over SB. Not only is there less error, in general, associated with DB timing, but also the reliability of a static timing gate height has improved. Further research is warranted to develop standardized sprint testing procedures to minimize timing errors.

PRACTICAL APPLICATIONS

The present study revealed that accurate 0–20 m sprint performance monitoring is complicated by timing errors of ± 0.06 seconds between SB and DB systems. This error source alone represents 3 times the value of the smallest worthwhile performance enhancement for this variable in team sports. The observed magnitude and incidence of time differences must be taken into account when selecting timing system. Single-beam timing is not recommended for scientists and practitioners wishing to derive accurate and reliable sprint time results.

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THE DIFFERENCE IS IN THE START: IMPACT OF TIMING AND START PROCEDURE ON SPRINT RUNNING PERFORMANCE

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ABSTRACT

Haugen, TA, Tønnessen, E, and Seiler, SK. The difference is in the start: impact of timing and start procedure on sprint running performance. *J Strength Cond Res* 26(2): 473–479, 2012—The difference is in the start: impact of timing and start procedure on sprint running performance. The purpose of this study was to compare different sprint start positions and to generate correction factors between popular timing triggering methods on 40-m/40-yd sprint time. Fourteen female athletes (17 ± 1 years), personal best 100 m: 13.26 (± 0.68) seconds and 11 male athletes (20 ± 5 years), personal best 100 m: 11.58 (± 0.74) seconds participated. They performed 2 series of 3 40-m sprints in randomized order: (a) start from the block, measured by means of Brower audio sensor (BAS) and Dartfish video timing (DVT), (b) 3-point start, measured by using hand release pod (HR) and DVT, and (c) standing start, triggered by both photocell across starting line (SFC), and foot release (FR) plus DVT. Video analysis was performed by 2 independent observers and averaged. Simultaneous measurements at national athletics competitions demonstrated that DVT and BAS were equivalent to Omega Timing within the limits of precision of video timing (± 0.01 seconds). Hand and floor timer triggering showed small but significant biases compared with movement captured from video (0.02–0.04 seconds), presumably because of sensitivity of pressure thresholds. Coefficient of variation for test-retest timing using different starting positions ranged from 0.7 to 1.0%. Compared with block starts reacting to gunfire, HR, SFC, and FR starts yielded 0.17 ± 0.09 , 0.27 ± 0.12 , and 0.69 ± 0.11 second faster times, respectively, over 40 m (all $p < 0.001$) because of inclusion or exclusion of reaction time, plus momentum, and body position differences at trigger moment. Correction factors

for the conversion of 40 m/40 yd and 40 yd/40 m were 0.92 and 1.08, respectively. The correction factors obtained from this study may facilitate more meaningful comparisons of published sprint performances.

KEY WORDS 40 yd, 40 m, correction factor, reliability, validity

INTRODUCTION

The difference between “average” and “fast” is a few tenths of a second in a 40-m sprint. Valid and reliable timing is therefore critical for the effective monitoring of sprinting performance. In published studies of sprinting performance, electronic timing is advisable because of the importance of small variations in timing (5,7). Although theoretically more precise, electronic timing is influenced by the differences in timer activation methods and the starting position of athletes. These variables can generate meaningful differences in performance times that may complicate comparison of results from different studies or estimation of the effect magnitude of training interventions.

Because the International Association of Athletics Federations (IAAF) mandated fully electronic timing to the hundredth of a second for running events, timing methods used in international athletics have been considered the “gold standard” for accurately and reliably quantifying sprint performance. Omega’s Scan ‘O’ Vision (Swiss Timing, Corgemont, Switzerland) fully automatic photofinish system has been used in international championship and World Cup meetings. However, like many gold standard methods, such timing equipment is expensive and impractical to use for most practitioners.

In theory, recording gun smoke and sprinters passing the finish line with a single video camera should provide enough information for valid sprint time analysis when captured into a computer video analysis program. Although this timing method represents a practical “gold standard” for the validation of other methods, it has so far not been reported in the literature. A review of published studies monitoring speed performance reveals considerable variation in timing methods and hardware manufacturers.

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26(2)/473–479

Journal of Strength and Conditioning Research

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In American football, measuring the 40-yd (36.58-m) dash performance from a 3-point stance is standard practice (2,3,6,8-10). In contrast, most sprint tests in soccer studies use a rocking start or allow leaning back before movement initiation from a standing start (1,11-14). The Brower Timing System (Draper, UT, USA) has been used in the majority of these publications, but specific start procedures and hardware approaches to timer initiation have varied. Only Duthie et al. (4) have so far evaluated the reliability of different starting techniques and their impact on measured performance time.

Therefore, the purpose of this study was to compare different sprint start positions and generate correction factors between popular timing triggering methods on the 40-m/40-yd sprint. This information should facilitate more meaningful comparisons of published sprint performance results.

METHODS

Experimental Approach to the Problem

Data were collected in 2 phases. The purpose of phase 1 was to establish the validity of times determined using the (a) Brower Timing System, a popular wireless and portable timing system, with an audio speaker sensor and (b) video recordings analyzed in Dartfish 5.0 software. These systems were compared with the Omega Scan 'O' Vision system during national competitions at Bislett stadium in Oslo, an internationally certified athletics venue. Timing was initiated by gunfire, and the athletes ran from the set start block (4-point stance) position. The times of 48 different heat winners (60- to 400-m running events) were determined by using all 3 systems simultaneously.

Phase 2 data collection was designed to the impact of several popular timer triggering and start position combinations in a group of track athletes. In addition, to assessing test-retest reliability, repeated trials for each of the 3 starting methods were compared. In each series, sprinters performed 3 sprints in randomized order under the following conditions: (a) start from standard sprinter blocks with gunfire, measured by using both Brower Timing with audio speaker sensor and Dartfish video, (b) 3-point start with fingers placed on a timer touch pad at the start line, measured by using both Brower and Dartfish, and (c) standing rocking start leaning back before sprinting, measured by using both Brower, Dartfish, and a dedicated indoor system used by the Norwegian Olympic Center (NOC) employing an imbedded pressure sensor below the track surface. The different timing methods and starting positions compared are summarized in Table 1. Rest between each of the 3 sprints in a series was for 6 minutes. The pause duration between the 2 series was 20 minutes.

Subjects

Video-based timing data against the Omega system (phase 1) were validated during different national athletic meets at Bislett Stadium in Oslo. The athletes signed up and participated voluntarily for these competitions on the basis of being timed. Approvals from meet organizers to set up

TABLE 1. Timing methods and starting position during phase 2 data collection.*

System/method	Brower		Dartfish video timing		NOC	
Start device	Audio sensor	Hand pod	Video camera	Video camera	Floor plate	
Initiating by	Gunfire	Pressure release	Movement	Movement	Pressure release	
Reaction time	Yes	No	No	No	No	
Stop device	Photocells	Photocells	Video camera	Video camera	Photocells	
Start position	Block 4-point	3-Point stance	Block 4-point	Standing	Standing	
Used in run	A	B	A	C	C	

*NOC = Norwegian Olympic Center.

TABLE 2. Characteristics of the subjects used to compare timing systems and start positions.*

Gender	N	Age (y)	Height (cm)	Weight (kg)	Personal best 100 m (s)
Female	14	17 (1)	172 (4)	59 (4.9)	13.26 (0.68)
Male	11	20 (5)	181 (6)	72 (7.5)	11.58 (0.74)

*Data are presented as mean (SD).

extra timing systems were obtained in advance. In the second phase of data collection, 25 athletes participated in the study at the NOC. The subjects had all been competing in track and field events (100- to 400-m sprint and hurdle) for at least 2 years and were currently actively training for a minimum of 5 d·wk⁻¹. Written informed consent was obtained in advance from each subject before participation. They were all healthy and free from injuries at the time of testing. Regarding nutrition, hydration, sleep, and physical activity, the athletes were instructed to prepare themselves as they would for a regular competition, including no involvement in high-intensity training the last 3–4 days before testing. All the subjects were familiar with the different starting positions

through the training sessions with their clubs, relays, and competitions. The characteristics of the subjects participating in the phase 2 are presented in Table 2.

Procedures

Starting Positions. For the start block condition, the athletes followed the instructions and commands according to IAAF

competition rules. This method includes reaction time to the starter's pistol. In the 3-point and standing start conditions, no start command was given, and the reaction time was not included in the total time. In the 3-point condition, the athletes placed their fingers from their front hand on the pod immediately behind the starting line. During standing starts, timing was initiated in 2 ways: via the release of pressure from the front foot on the subsurface triggering plate and via breaking a photocell beam 1 m above the starting line. The athletes were informed not to lean into the photobeam before the start. After the ready signal was given by the test operator, the athletes started on their own initiative. The starting positions and triggering methods employed are illustrated in Figure 1A–D.

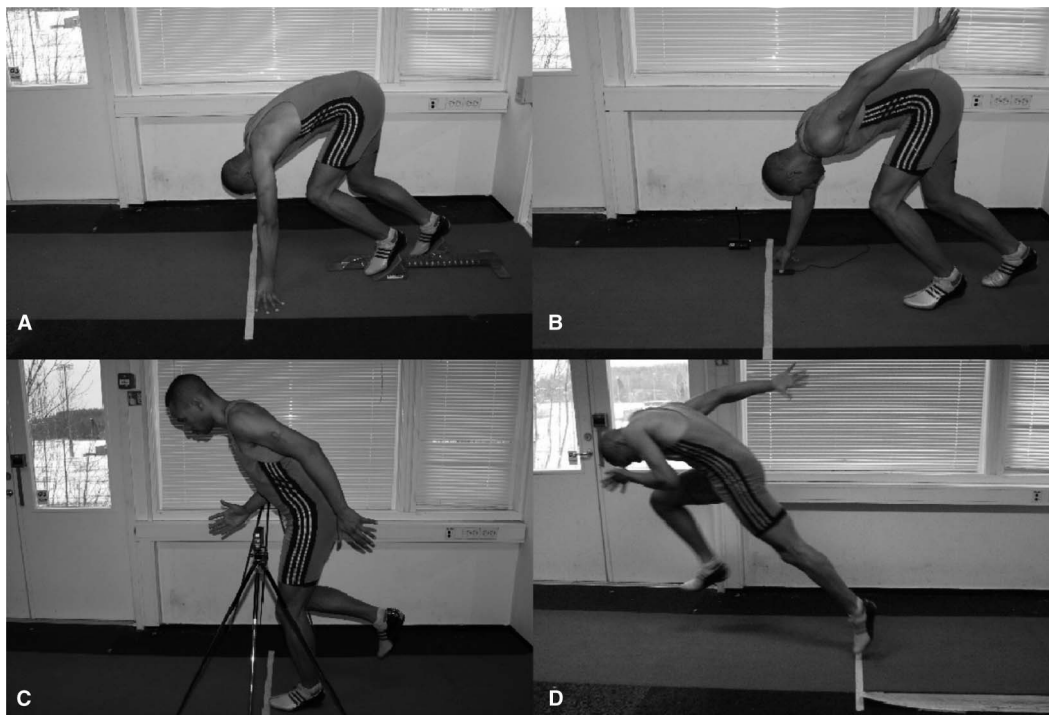


Figure 1. Body position at timer triggering for different start methods compared. (A) Block start, (B) 3-point start with hand release, (C) standing start with photocell trigger, and (D) standing start with floor sensor trigger below the front foot.

TABLE 3. Validation of timing systems.*

Timing systems	n	Δ (s)	R	SEM (s)	CV(%)	p for Δ
Omega-Video	48	0.00	1.00	0.01	0.1	0.114
Omega-Brower audio sensor	48	0.00	1.00	0.01	0.1	0.376
Video-Brower hand pod	50	0.04	1.00	0.02	0.6	<0.001
Video-NOC floor plate	50	-0.02	1.00	0.02	0.5	<0.001

*n = number of paired observations; Δ = mean difference; R = Pearson's R correlation; SEM = standard error of measurement; CV = coefficient of variation.

Timing Equipment. Omega's Scan 'O' Vision photofinish timing system was the "gold standard" for the validation of all other timing systems in this study. The timing is initiated by an electronic gun, which sends a current through an attached wire to a separate console in a control room that triggers all timing devices. Trial shots, so-called "zero shots," were fired before the start of each competition to ensure exact timing initiation. Scan 'O' vision Star cameras were installed at the finish. They can capture up to 2,000 images per second with a high resolution of 2048 pixels per vertical line. The Omega system splices thousands of scans together, forming a composite image of the contestants. The corresponding time is displayed for each picture, providing the photofinish judge with enough information to estimate the time within ±0.0005 seconds (<http://www.swisstiming.com/Athletics.495.0.html>).

The Brower Timing System (Draper) employs 3 different time initiating devices: (a) An audio sensor can capture gunfire and start the timer, in principle equivalent to athletics timing wherein reaction time is included. This method of time initiation was used in both data collection phases (Bislett Stadium and Norwegian Olympic Center). (b) A small hand pod (12 × 5 cm) placed at the start line was also used in the second session to measure athletes' performance starting from a 3-point stance with feet split and 1 hand on the pad. The timer starts when hand pressure against the pod is

TABLE 4. Test-retest reliability for 40-m sprint testing.*

Starting position	Trial n	Trial 1	Trial 2	Δ (s)	ICC	SEM (s)	CV (%)
Block	25	5.92	5.96	0.04†	0.99	0.04	0.7
3-Point	24	5.71	5.72	0.01	0.98	0.06	1.0
Standing	25	5.22	5.30	0.08†	0.97	0.05	0.9

*Δ = mean difference; ICC = intraclass correlation coefficient; SEM = standard error of measurement; CV = coefficient of variation.

†p < 0.01 vs. trial 1.

released. The time difference between 3-point stance and block start by gunfire is the net effect of including reaction time and the possible benefits of start blocks. (c) A pair of infrared Brower photocells, model TRD-T175 (Draper), were also used for time triggering in the second data collection.

An infrared transmitter with corresponding reflector was placed on each side of the running course 1 m above the ground at the start line. In this test, the athletes stood with their front foot on the start line and were allowed to lean backward before rolling forward into the timer initiation infrared beam.

Single beamed infrared photocells captured the 40-m finish line for all Brower timing methods. We adjusted the finish line transmitter and corresponding reflector to head level for each runner instead of the normally used chest level, ensuring that the sensor beam was not broken by a swinging arm 0.03–0.05 seconds before body triggering.

Dartfish Video Timing. Video recordings obtained by means of a Sony HD camera (HDR-HC9E) were analyzed in Dartfish 5.0 to estimate sprint times during both the data collection phases. For all block starts, each video clip captured both gun smoke from the starter's pistol and the athletes passing the finish line. There are 0.02 seconds between each video frame in the Dartfish analyzer window. To ensure the best possible accuracy, 2 independent analyzers assessed the size of the smoke plume in the first frame where smoke was visible. For a small smoke plume, the start was set 0.01 seconds back on the timeline (cue in). When a large plume was visible in the first "smoke frame," the start was set 0.02 seconds back on the timeline. Similar procedures were used to set video cue in for 3-point starts and standing starts. If the hand or foot left the pod or the floor plate between 2 frames, the start time was set between these 2 timeline values. The finish time (cue out) was set the same way. If the athlete passed the finish line between 2 frames, the finish time was set between these 2 timeline values. The time of each athlete's run was calculated by subtracting cue in from cue out. The mean values were taken from the times determined by 2 independent observers.

Floor Plate Triggering. Besides audio start triggering (AS), photocell start triggering (PS), and hand release (HR) start triggering (all from Brower Timer), a purpose-built foot pressure release system (FR) was also used during the second data collection session. The FR system was custom built and employed a 60 × 60-cm pressure sensitive floor plate placed under the track surface. The timer is triggered when the pressure from the front foot against the floor plate is removed.

TABLE 5. Correction factors between starting positions (block start to gunfire as reference).*†

Starting positions compared with block start with reaction time (<i>N</i> = 25)	Mean (<i>SD</i>) (s)†	95% Confidence interval	
		Lower	Upper
3 Point (fingers leave hand pod) faster by	0.17 (0.09)	0.11	0.22
Standing start (body passes photocell) faster by	0.27 (0.12)	0.20	0.33
Standing start (front foot leaves foot pad) faster by	0.69 (0.11)	0.63	0.75

*Values are given as mean (*SD*).
 †*p* < 0.01 vs. block start.

Pairs of photocells covered each fifth meter of the running distance. The infrared beam was split to reduce the possibility of arm swings triggering the cells. Transmitters were placed 140 cm above the ground, and reflectors for the split beam were placed 130 and 150 cm above the floor. Both the beams had to be interrupted to trigger the timer stop. Electronic times were transferred to a computer running dedicated software developed in MatLab (BioRun, Biomekanikk AS, Norway). Forty-yard (36.58-m) times were calculated by using the formula: time 40 yd = time 35 m + ([time 40 m – time 35 m] × 0.316).

Statistical Analyses

PASW Statistics 18.0 (SPSS, Chicago, IL, USA) was used for all the analyses. The timing systems were validated based on the mean difference, Pearson’s *R* correlation, standard error of measurement (*SEM*), and coefficient of variation (*CV*). Reliability calculations were based on the mean difference, intraclass correlation, *SEM*, and *CV*. Where a systematic bias was determined using test-retest analysis, *SEM* and *CV* were calculated after the adjustment for mean bias. All the averaged values are rounded to the nearest 0.01 second. The General Linear Model with Repeated Measures followed by Bonferroni adjustment for multiple comparisons was used to compare the results from the 3 starting positions. Test-retest differences in performance were compared using the paired samples *T*-test. Dartfish video timing provided the basis for reliability measurements. Alpha was set to ≤ 0.05 for tests of the null hypothesis. Mean difference, standard

error, and 95% confidence interval for the differences between block starts (reference starting position) and the other starting methods are presented. Finally, correction factors between 40 m and 40 yd were calculated based on the NOC timing system measurements. Residual error estimates for correction factors were calculated and expressed as typical error.

RESULTS

Concurrent measurements of athletic events using the Omega timing system, Brower audio triggering, and Dartfish based video analysis demonstrated that the 2 latter measurement methods were valid to the limits of precision of the instruments (Table 3). Table 3 also shows that both HR and FR from a subsurface pressure sensor showed a small but significant bias compared with that of video-based timing. That is, with the hand pod, timer activation actually began about 0.04 seconds before video detection of hand movement. With foot pressure activation, timer activation was delayed by 0.02 seconds compared with the detection of foot movement on video.

Test-retest reliability results are presented in Table 4. A small (~0.04 seconds), but a significant performance decline was detected when comparing the best results from series 1 and series 2, separated by only 20 minutes.

Table 5 gives the differences in performance time associated with the 3 starting positions compared, all based on Dartfish video analysis. The impact of the starting position on the 40-m

TABLE 6. Correction factors for conversion between 40 m and 40 yd.*

n	40-m mean (s)	40-yd mean (s)	Δ (s)	SD for Δ (s)	Yards to meters	Meters to yards	TE
50	5.25	4.84	0.41	0.04	1.084	0.923	0.013 s

**n* = number of simultaneous observations; Δ = mean difference; *R* = Pearson’s *R*; TE = typical error for conversion-based time estimate.

performance time was statistically significant and much larger than the typical variation from test to test. Table 6 shows correction factors for the conversion of metric to yard distances.

DISCUSSION

The analysis of phase 1 data revealed no systematic variation between Omega, video, and Brower speaker sensor timing. Table 3 shows an absolute variation of 0.01 seconds and no mean difference between Omega and the other systems. The *SEM* was 0.01 seconds for both video and Brower vs. Omega. That is, for practical purposes, the Brower audio sensor/ photocell timing system and Dartfish video analysis give identical results to Omega phototiming to a precision of ± 0.01 seconds.

Video timing was subsequently used as the validation standard during phase 2 comparisons against Brower finger pod and NOC floor plate. We detected small but significant timing biases when video detection of movement was matched with timer triggering based on sensors placed under the hand or front foot. The instrumental biases were small (0.02–0.04 seconds) and may vary across instruments depending on the calibration of pressure thresholds and other details in construction.

We observed a small (~ 0.04 seconds) but statistically significant decline in the performance from the first series of 3 sprints to the second series. The 2 series were separated by only 20 minutes. The poorer times in trials 4–6 could be explained by fatigue or a lack of mobilization. Duthie et al. (4) reported a 0.02-second mean improvement in the 10-m time for standing starts with the floor plate between 2 test sessions separated by 7 days. In our own hands, pilot measurements before this investigation revealed 0.05–0.1 second individual time variation in both directions when testing was performed on different days. Therefore, a design with a test-retest within the same day was chosen to minimize this source of variation. Table 4 shows that the CV for test-retest timing using different starting positions ranged from 0.7 to 1.0% after correction for the small systematic timing bias between trials. The block method appeared to be the most reliable in a group of athletes familiar with this start method. Under normal testing conditions, we have observed that approximately 80% of the athletes reach their best 40-m performance within 2 trials.

The key finding of this study is that the starting method and timing system used can combine to generate large absolute differences in “sprint time.” Table 5 shows that 40-m times triggered by hand release from a 3-point stance, breaking a photocell beam from a standing start, and releasing the front foot from the ground during a standing start generate approximately 0.17, 0.27, and 0.69 seconds faster times, respectively, compared with block starts with a timer triggered by gunfire (Figure 1).

These figures are not in accordance with the findings of Duthie et al. (4), who reported smaller time differences between the starting positions. These discrepancies can be

explained by several factors. First, Duthie et al. used timing equipment made by another manufacturer (Swift Performance, Australia) with a different calibration of pressure threshold and other details in the construction of the foot pod. Second, the standing start procedure in our study allowed leaning backward before rolling forward as opposed to the fixed position used by Duthie et al. Finally, Duthie et al. might have placed the photocells at the start line at a different height, allowing other body parts than the chest to trigger the beam.

At the extreme, a 40-m sprint time of 4.4 seconds measured from a standing start with triggering via floor sensors below the front foot gives a poorer performance than does 5.0 seconds measured from starting blocks with time initiated by a starter’s gun. The method of sprint timing used can result in greater differences in sprint time than obtained using several years of a conditioning training program (20). These differences are essentially absolute. Therefore, their impact on the interpretation of shorter sprint distance performances would be even greater.

The young athletes in this study were not all sprint specialists but were experienced with block start conditions and the other starting conditions employed. Although the absolute differences observed might vary somewhat with the experience of the athletes being tested, we believe that the correction factors quantified here provide a reasonable framework for comparing sprint performances across timing methods.

The sources of time differences detected include the starting device (gun, pod, and photocells), inclusion of reaction time, vertical and horizontal placement of starting device related to the start line, body configuration, and center of gravity velocity at the triggering point. The difference in performance time of 0.17 seconds between block start and 3-point start in this study can mainly be explained by the reaction time, which is identical to the mean reaction time reported by the IAAF from the last athletic championships (<http://www.iaaf.org/history/index.html>). Based on these considerations, the athletes in this study gained no positive benefits by using start blocks. However, video recordings from the 3-point starts revealed slight horizontal body movement before finger lift-off, because the athletes tried to delay lifting their hand from the timing sensor. Therefore, it is likely that a small performance advantage is achieved when using block starts in experienced performers.

The differences in performance time are larger between block starts and standing start measurements with the standing condition being consistently faster. A standing start with photocell triggering and a standing start with front foot release triggering result in 0.1- and 0.52-second better times, respectively, vs. that of the 3-point start with hand release. These differences can be explained by the body position and horizontal velocity of the center of gravity at triggering point. In the case of photocell triggering, the center of gravity is located above the start line (Figure 1C), in contrast to 3-point and block starts where the center of gravity is about

40–50 cm behind the start line (Figure 1A, B). Because the standing start allows leaning back before running, the athletes have a small horizontal movement at photocell triggering. A disadvantage with the standing photocell start is the raised upper body position to avoid early triggering. Despite this biomechanically poor stance, the horizontal speed generated from the slight flying start and the shorter effective running distance combine to yield a 0.1-second advantage vs. 3-point starts. The benefit is even more pronounced with foot release triggering. Here, the center of gravity is about 50–60 cm past the start line, and the horizontal velocity of the center of gravity is considerably higher by the time the front foot releases the triggering plate (Figure 1D). Compared with the “gold standard” block start, this start method eliminates reaction time, reduces timed running distance by about 1 m, and allows the benefit of a substantial flying start.

American athletes are often timed over 40 yd (36.58 m). Therefore, the relationship between 40- and 40-yd mean times ($n = 50$) is shown in Table 6. Based on 50 simultaneous timings of 35- and 40-m times and interpolation of 36.58-m time, a simple correction factor of 1.08 (1.084) can be used to convert 40-yd performances to comparable 40-m times. Similarly, a conversion factor of 0.92 (0.923) is appropriate to convert 40-m times to 40-yd equivalents. These correction factors might be useful when, for example, comparing speed performance in American football with familiar European team sports.

PRACTICAL APPLICATIONS

The difference between excellent and mediocre in a 40-m sprint is a few tenths of a second. Comparison of sprint timing results without consideration of the specific start configuration and timing methods can cause a lot of confusion. This study has shown that time differences among commonly used start positions and triggering methods can exceed 0.5 seconds, larger than the typical gains derived from specific training or even the difference between superior and mediocre sprinters. For internal comparisons of performance in a training monitoring setting, changing timing methods is unacceptable. Electronic triggering by hand release from a 3-point stance may represent the most practical start method with minimal momentum or distance shortening effects. However, timing methods vary from sport to sport and across investigations. Therefore, this investigation provides useful correction

factors that should improve the validity of performance comparisons across research studies and over typical “American” and “European” sprint test distances.

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Anaerobic Performance Testing of Professional Soccer Players 1995–2010

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Purpose: To compare sprint and countermovement-jump (CMJ) performance among competitive soccer players as a function of performance level, field position, and age. In addition, the authors wanted to quantify the evolution of these physical characteristics among professional players over a 15-y period. **Methods:** 939 athletes (22.1 ± 4.3 y), including national-team players, tested 40-m sprint with electronic timing and CMJ on a force platform at the Norwegian Olympic Training Center between 1995 and 2010. **Results:** National-team and 1st-division players were faster ($P < .05$) than 2nd-division (1.0–1.4%), 3rd- to 5th-division (3.0–3.8%), junior national-team (1.7–2.2%), and junior players (2.8–3.7%). Forwards were faster than defenders (1.4%), midfielders (2.5%), and goalkeepers (3.2%) over 0–20 m ($P < .001$). Midfielders jumped ~2.0 cm lower than the other playing positions ($P < .05$). Sprinting velocity peaked in the age range 20–28 y and declined significantly thereafter ($P < .05$). Players from 2006–2010 had 1–2% faster 0–20 m and peak velocity than players from the 1995–1999 and 2000–2005 epochs, whereas no differences in CMJ performance were observed. **Conclusions:** This study provides effect-magnitude estimates for the influence of performance level, position, and age on sprint and CMJ performance in soccer. While CMJ performance has remained stable over the time, there has been a small but positive development in sprinting velocity among professional players.

Keywords: sprint, vertical jump, anaerobic characteristics

Speed and power are critical performance factors in soccer. Male soccer players conduct high-intensity actions every 60 to 90 seconds during games, each lasting 2 to 3 seconds on average.^{1–3} Although sprinting and high-intensity actions represent only 8% to 12% of covered running distance, these capabilities are considered critical.^{3–6} In this decisive portion of match play, it is likely that maximal-sprint situations represent particularly critical moments. Both horizontal acceleration (sprinting) and vertical acceleration (jumping power) are involved in ball possession, repossession, defense play, corner kicks, and attack on goal.

Arnason et al⁷ reported that players at high competition level jumped higher than players at lower performance levels. However, Cometti et al⁸ and Röscher et al⁹ observed no differences in speed or jump height as a function of performance level. A few studies have investigated speed and power characteristics according to playing position.^{10–15} Davis et al¹⁰ concluded that forwards were the fastest players, ahead of defenders, midfielders, and goalkeepers. Boone et al¹¹ reported differences in speed and countermovement jump (CMJ) according to playing position. Sporis et al¹² found differences in

speed but not for CMJ, while Taskin¹³ found no speed differences as a function of position. The literature also remains unclear regarding potential sprint-performance differences across age among elite players.^{9,16} Most previously published studies were performed on semi-professional soccer players and did not include a broad range of player performance level. Many coaches claim that international soccer players are faster now than 10 years ago, but objective data supporting this claim are not available.

The Norwegian Olympic training center is a standard testing facility for a large number of teams at different performance levels, including national squads. A database of sprint and CMJ results that has been collected over 15 years provides the potential to address several different questions related to the role of sprint and vertical-jump performance in soccer. Therefore, the aim of this study was to quantify possible differences in sprinting velocity and jump height as a function of athlete performance level, field position, and age. In addition, we evaluated the evolution of sprinting velocity and CMJ height among elite performers in Norwegian soccer over a 15-year period. We hypothesized that both sprinting performance and CMJ height would distinguish the highest performance divisions from lower divisions. We also hypothesized that sprinting performance has improved over time due to increased training focus.

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Methods

Subjects

In total, 939 soccer players 16 to 37 years old (22.1 ± 4.3 y), body mass 77.2 ± 8.0 kg, representing a broad range of performance levels participated in this study. Of those, 98 players had foreign citizenship. All players were tested between 1995 and 2010. In total, 1723 sprint tests and 1003 CMJ tests formed the basis for this investigation (Table 1). For the 40-m sprint and CMJ tests, 531 of 418 players tested once, 231 of 130 tested twice, and 177 of 85 tested 3 times or more. The difference in sample size between sprint and CMJ is due to different priorities among team coaches. All tests were performed in the afternoon (between 2 and 8 PM) at the Olympic training center in Oslo. These were preexisting data from the semiannual or annual testing that these teams perform for training purposes, so no informed consent was obtained. The Norwegian Olympic Committee and Confederation of Sports approved the use of these data, provided that individual test results remained confidential. This study was approved by the ethics committee of the Faculty for Health and Sport, University of Agder.

Senior national team athletes were defined as players who represented Norway in senior World Cup, Euro Cup, qualifying matches, or training matches. Since 1995, the Norwegian squad has been ranked among the top 10 several times in the official FIFA ranking (www.fifa.com/worldfootball/ranking). The international ranking at the time this article was written (2011) was 11. The first-division athletes represented clubs from the highest division level in the Norwegian soccer league system. Considering the performance level of first-division teams, Norway has been ranked between 10th and 20th place in UEFA's country ranking (<http://www.uefa.com/member-associations/uefarankings/country/index.html>) during the time period 1995–2010. The second-division athletes were playing in the second highest division. Junior national-team players in the database had represented Norway in the U20 and/or U23 age group. The junior athletes in the database were playing in the highest division level in the Norwegian junior league system. National-team and first- and second-division players were fulltime professional performers, while the third- to fifth-division and junior players were semiprofessionals or amateurs with part or full-time jobs or educational programs in addition to their sports career.

Table 1 Sample Size, Age, Body Mass, and Height for Analyzed Categories in the Current Study

Category	Sprint, CMJ (n)	Age (y)	Body mass (kg)	Height (cm)	Body-mass index
National team	49, 21	26.8 ± 3.4^a	83.0 ± 7.8^b	184.0 ± 5.6	24.8 ± 1.8
1st division	315, 244	23.4 ± 4.3	79.0 ± 7.1^b	182.9 ± 6.2	23.6 ± 1.6
2nd division	158, 90	23.4 ± 3.7	80.1 ± 7.9^b	181.7 ± 6.0	24.3 ± 1.7
3rd–5th division	175, 93	23.0 ± 3.7	77.1 ± 8.3	—	—
Junior national team	106, 56	18.5 ± 1.8	74.9 ± 6.8	181.9 ± 6.5	22.6 ± 1.7^f
Juniors	136, 129	17.6 ± 0.9	72.8 ± 7.8	—	—
Forwards	150, 100	22.2 ± 3.9	78.7 ± 6.9	182.4 ± 5.9	23.7 ± 1.6
Defenders	210, 132	23.4 ± 4.6	80.3 ± 6.8	183.8 ± 5.5	23.8 ± 1.6
Midfielders	210, 134	22.5 ± 4.4	75.0 ± 5.8^c	179.5 ± 5.4^c	23.3 ± 1.5
Goalkeepers	58, 45	23.5 ± 4.1	86.7 ± 7.1^d	189.5 ± 4.0^d	24.2 ± 1.9
<18 y	67, 51	16.8 ± 0.4	74.3 ± 6.4^e	181.0 ± 4.7	22.6 ± 1.7^g
18–19 y	112, 62	18.5 ± 0.5	75.4 ± 7.1^e	181.8 ± 7.2	22.8 ± 1.6
20–22 y	140, 74	21.1 ± 0.8	78.2 ± 6.4	182.4 ± 6.0	23.5 ± 1.8
23–25 y	141, 99	24.0 ± 0.8	80.7 ± 7.3	182.8 ± 6.8	24.2 ± 1.7
26–28 y	92, 63	27.0 ± 0.8	81.5 ± 7.8	183.6 ± 5.2	24.2 ± 1.8
>28 y	76, 62	30.6 ± 1.6	81.5 ± 6.6	183.6 ± 5.4	24.2 ± 1.8
1995–1999	312, 113	23.0 ± 4.1	79.3 ± 7.2	182.1 ± 6.2	23.9 ± 1.6
2000–2005	155, 148	22.1 ± 4.6	78.2 ± 7.5	183.1 ± 6.3	23.3 ± 1.6
2006–2010	161, 150	23.2 ± 4.5	79.5 ± 7.5	183.3 ± 5.8	23.7 ± 1.7

Abbreviations: CMJ indicates countermovement jump.

^a National team > other performance-level categories ($P < .001$). ^b National-team and 1st- and 2nd-division players > junior national-team and junior players. ^c Midfielders were shorter and had less body mass than the other playing positions ($P < .001$). ^d Goalkeepers were taller and had more body mass than the other playing positions ($P < .001$). ^e <20-y-old players < the other age categories ($P < .001$). ^f Junior national team < national team and 2nd division ($P < .05$). ^g <18-y-old players < 23- to 25-y-old players ($P < .05$).

Instruments and Procedures

All sprint tests were monitored by electronic timing equipment (Biorun, Norway). The clock was initiated when the front foot stepped off a start pad placed under the track at the start line. CMJ tests were performed on an AMTI force platform (AMTI model OR6-5-1). The data were amplified (AMTI Model SGA6-3), digitized (DT 2801), and saved to dedicated computer software (Biojump, Norway). Each athlete was weighed on the force platform before testing. Body height was registered by self-report. All jumps were performed with hands placed on the hips. Sprint-timing equipment, force platform, and testing procedures were identical to those in the study performed by Haugen et al.¹⁷ Our procedures have remained consistent over 15 years and have recently been proven valid and reliable.¹⁸

Data Analysis and Statistics

SPSS 18 was used for all analyses. Means and SDs of each 10-m split are presented for all analyzed categories. The analyses of sprint velocity as a function of performance level, position, age, and time epoch were based on best individual 40-m-sprint test results with associated split times. Several studies show that sprint bouts during games last 2 to 4 seconds on average.^{2,6,19} For these reasons, 0- to 20-m times were chosen to represent acceleration capability in the current study. Buchheit et al.²⁰ reported maximal sprinting speed as the main determinant of the distance associated with best split among young soccer players. Expressing the data in terms of peak velocity provides a reference for game-activity analysis. Thus, we chose to use best 10-m split time as the basis for calculating peak sprint velocity.

CMJ analyses were based on best individual CMJ test results. In some cases, best sprint and CMJ test results occurred on different testing days. Data from a single athlete were only included in 1 category for each analysis. That category was the athlete's affiliation on the day of his best result. All athletes ($N = 939$) were included in the performance-level analysis. The playing position, age, and time-epoch analyses were restricted to players playing professionally at the time of testing. Player positions were identified for each athlete by their coaches or by self-report as goalkeepers, defense players, midfielders, or forwards. Athlete age was calculated from date of birth and testing date and categorized as under 18, 18 to 19, 20 to 22, 23 to 25, 26 to 28, and 28 plus. To quantify the development of sprinting velocity and CMJ ability over time, the database was divided into 3 time epochs: 1995–1999, 2000–2005, and 2006–2010.

Mean and 95% confidence intervals were calculated for each group or category. Pearson R was used to examine the relationship between CMJ and sprint ability. Best individual sprint tests formed the basis for split-time correlations. Best individual CMJ test

with corresponding sprint test during the same testing day formed the basis for correlation analyses between sprint and vertical-jump ability. One-way ANOVA followed by Tukey post hoc test where necessary was used to identify differences among groups or categories. Effect size (Cohen d) was calculated to evaluate the meaningfulness of the difference between category means. Effect magnitude was interpreted categorically as small (d 0.2–0.6), moderate (d 0.6–1.2), or large (d 1.2–2.0) using the scale presented by Hopkins et al.²¹

Results

Table 2 presents 10-m split times for the analyzed categories. Our data showed that 64% of the players increased their velocity from 30 to 40 m compared with 20- to 30-m times, 12% remained stable, while 24% of the athletes reduced their speed during the final 10 m. However, the difference between the last two 10-m splits was never more than 0.02 second for any of the categories.

Figure 1 (panel A) shows that national-team players were 1.4% faster than second-division players ($P = .046$, $d = 0.5$), 3.8% faster than third- to fifth-division players ($P < .001$, $d = 1.2$), 2.1% faster than junior national-team players ($P = .002$, $d = 0.7$), and 3.2% faster than juniors ($P < .001$, $d = 1.1$) over 0 to 20 m. First-division players were 1% faster than second-division players ($P = .038$, $d = 0.3$), 3.5% faster than third- to fifth-division players ($P < .001$, $d = 1.1$), 1.8% faster than junior national-team players ($P = .001$, $d = 0.6$), and 2.8% faster than junior players ($P < .001$, $d = 0.9$). Similar trends were observed for peak velocity (Figure 1, panel B). Figure 1 (panel C) shows that national-team players jumped 11.3% higher than juniors ($P < .001$, $d = 0.8$). First- and second-division and junior national-team players jumped 5% to 11% higher than third- to fifth-division and junior players ($P < .05$, d 0.5–0.8).

Figure 2 (panel A) shows that forwards were 1.4% faster than defenders ($P < .001$, $d = 0.5$), 2.5% faster than midfielders ($P < .001$, $d = 0.8$), and 3.2% faster than goalkeepers ($P < .001$, $d = 1.0$) over 0 to 20 m. Defenders were 1.1% faster than midfielders ($P = .002$, $d = 0.4$) and 1.8% faster than goalkeepers ($P < .001$, $d = 0.6$). Similar trends were observed for peak velocity (Figure 2, panel B). Figure 2 (panel C) shows that midfielders demonstrated 5% to 6% poorer jumping performance than forwards ($P < .001$, $d = 0.6$), defenders ($P = .003$, $d = 0.5$), and goalkeepers ($P = .016$, $d = 0.6$).

Figure 3 (panel A) shows that players under 18 years of age ran 1.8% slower than the 20- to 22-year group ($P = .007$, $d = 0.6$) and 1.4% slower than the 23- to 25-year-old players ($P = .015$, $d = 0.4$). Peak velocity among players under 18 (Figure 3 panel B) was 2.0% slower than in the 20- to 22-year group ($P = .013$, $d = 0.6$), 1.9% slower than 23- to 25-year-old players ($P = .018$, $d = 0.6$), and 2% slower than the 26- to 28-year-old group ($P = .026$, $d = 0.5$). Players in the 18- to 19-year-

Table 2 Countermovement-Jump (CMJ) Height and 10-m-Split Times for Analyzed Categories, Mean \pm SD

Category	CMJ (cm)	0–10 m (s)	10–20 m (s)	20–30 m (s)	30–40 m (s)
National team	39.4 \pm 5.2	1.51 \pm 0.05	1.24 \pm 0.04	1.14 \pm 0.04	1.13 \pm 0.04
1st division	39.0 \pm 4.6	1.52 \pm 0.06	1.24 \pm 0.05	1.15 \pm 0.07	1.14 \pm 0.07
2nd division	38.8 \pm 4.6	1.53 \pm 0.05	1.26 \pm 0.05	1.15 \pm 0.05	1.15 \pm 0.05
3rd–5th division	36.7 \pm 4.4	1.58 \pm 0.09	1.28 \pm 0.09	1.18 \pm 0.05	1.17 \pm 0.05
Junior national team	39.0 \pm 4.6	1.54 \pm 0.06	1.26 \pm 0.04	1.16 \pm 0.04	1.15 \pm 0.04
Juniors	35.4 \pm 4.2	1.55 \pm 0.06	1.28 \pm 0.05	1.19 \pm 0.05	1.17 \pm 0.06
Forwards	40.0 \pm 4.9	1.50 \pm 0.06	1.23 \pm 0.05	1.13 \pm 0.04	1.12 \pm 0.05
Defenders	39.5 \pm 5.0	1.53 \pm 0.05	1.25 \pm 0.04	1.15 \pm 0.04	1.13 \pm 0.04
Midfielders	37.5 \pm 3.7	1.54 \pm 0.06	1.26 \pm 0.04	1.16 \pm 0.04	1.15 \pm 0.04
Goalkeepers	39.8 \pm 4.2	1.55 \pm 0.06	1.27 \pm 0.05	1.18 \pm 0.04	1.17 \pm 0.05
<18 y	38.6 \pm 5.1	1.54 \pm 0.07	1.27 \pm 0.04	1.16 \pm 0.05	1.15 \pm 0.05
18–19 y	38.8 \pm 4.6	1.52 \pm 0.07	1.25 \pm 0.05	1.16 \pm 0.05	1.15 \pm 0.05
20–22 y	38.6 \pm 4.8	1.52 \pm 0.05	1.24 \pm 0.04	1.14 \pm 0.03	1.14 \pm 0.04
23–25 y	40.2 \pm 4.6	1.53 \pm 0.06	1.24 \pm 0.05	1.15 \pm 0.04	1.13 \pm 0.05
26–28 y	38.5 \pm 4.2	1.52 \pm 0.06	1.24 \pm 0.05	1.15 \pm 0.04	1.13 \pm 0.05
>28 y	38.6 \pm 4.1	1.54 \pm 0.05	1.26 \pm 0.04	1.16 \pm 0.05	1.15 \pm 0.04
1995–1999	38.4 \pm 4.5	1.53 \pm 0.05	1.25 \pm 0.05	1.15 \pm 0.04	1.14 \pm 0.04
2000–2005	39.3 \pm 4.3	1.52 \pm 0.05	1.26 \pm 0.04	1.15 \pm 0.04	1.15 \pm 0.05
2006–2010	39.2 \pm 4.9	1.51 \pm 0.07	1.24 \pm 0.05	1.14 \pm 0.04	1.13 \pm 0.05

old group were 1.6% slower than 20- to 22-year-old players ($P = .031$, $d = 0.5$) and 1.5% slower than the 23- to 25-year-old group ($P = .043$, $d = 0.4$). Players older than 28 years were 2% slower than 20- to 22-year-old players ($P = .007$, $d = 0.6$), 1.9% slower than 23- to 25-year-old players ($P = .010$, $d = 0.5$), and 2.0% slower than those in the 26- to 28-year age category ($P = .015$, $d = 0.6$). No differences in CMJ were observed across the age categories (Figure 3, panel C).

Overall, the 95% CIs demonstrate a slight trend toward faster elite players over time (Figure 4, panels A and B). Elite soccer players from the time epoch 2006–2010 had 1.4% and 1.1% higher velocity over 0 to 20 m than in the 1995–1999 ($P < .001$, $d = 0.4$) and 2000–2005 ($P = .014$, $d = 0.3$) epochs, respectively. Players from 2006–2010 had 1.4% higher peak velocity (Figure 4, panel B) than 1995–1999 players ($P = .001$, $d = 0.4$) and were 2% faster than 2000–2005 players ($P < .001$, $d = 0.5$). No significant differences in CMJ were observed across the epochs (Figure 4, panel C).

Table 3 shows correlation values between sprint and CMJ performance among analyzed categories in the current study. Overall, there was a strong correlation between CMJ height and 0- to 20-m velocity ($r = .63$, $P < .001$, $n = 633$) and between CMJ height and peak velocity ($r = .60$, $P < .001$, $n = 633$). The correlation between 0- to 20 m and peak velocity was very high ($r = .81$, $P < .001$, $n = 939$).

Discussion

In the current study, data from a large sample of athletes tested under identical conditions demonstrate moderate to large differences in sprinting velocity and moderate differences in CMJ height as a function of soccer performance level and playing position. Small to moderate differences in sprinting velocity as a function of age were observed. We also observed a small but significant positive development in 0- to 20-m sprint performance and peak velocity among professional soccer players over a 15-year period of testing, but no significant changes in CMJ ability.

Split-Time Analysis

About 64% of the players ran faster between 30 and 40 m than in the 20- to 30-m interval. Buchheit et al²⁰ reported that faster players reach peak velocity in a later stage of a sprint than slower performers. Since we have no data beyond 40 m, we might have missed peak velocity for some of the fastest players. However, the difference between the last two 10-m splits was never more than 0.02 second for any of the categories. Thus, it is reasonable to claim that sprinting velocity among the majority of male elite soccer players peaks between 20 and 40 m at 8.8 to 9.0 m/s. The apparently fast 0- to 10-m times compared with the other splits in Table 2 are explained by the time initiation with a foot-pressure-release system.¹⁷

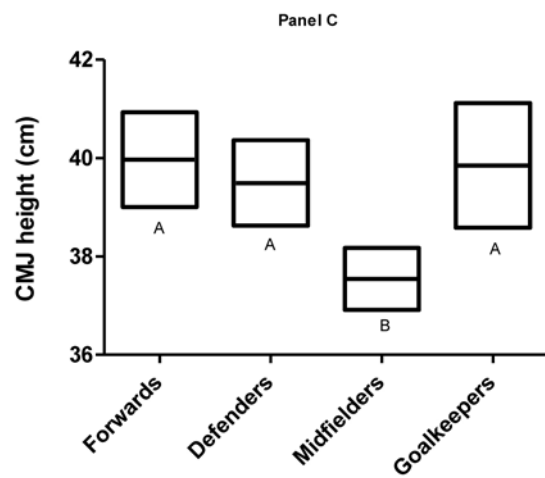
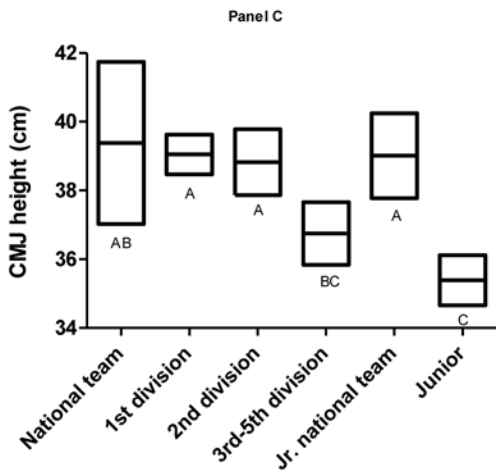
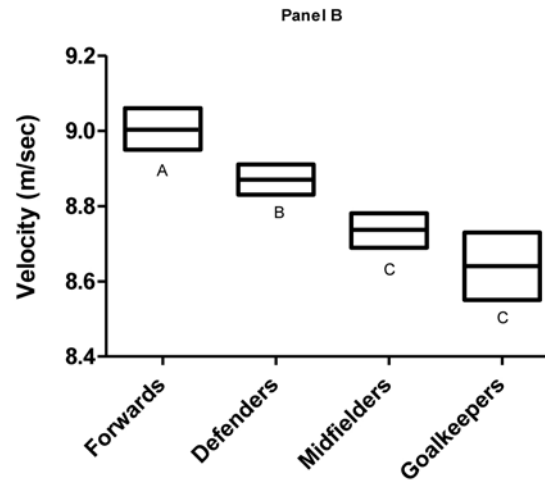
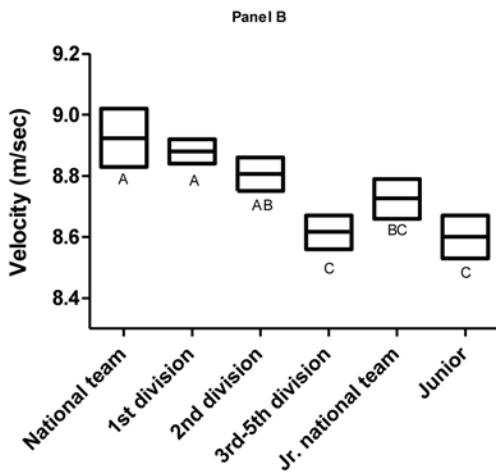
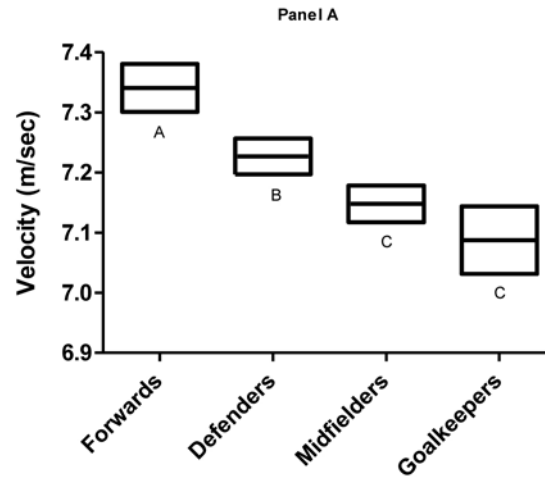
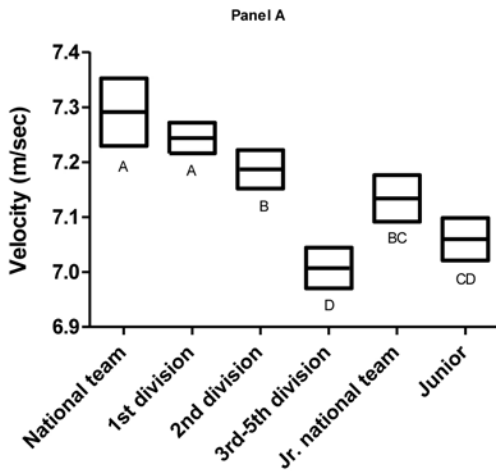


Figure 1 — 95% confidence intervals for (A) 0- to 20-m velocity, (B) peak velocity, and (C) countermovement-jump (CMJ) height as a function of performance level. Differing letters (A–D) indicate significant differences among groups.

Figure 2 — 95% confidence intervals for (A) 0- to 20-m velocity, (B) peak velocity, and (C) countermovement-jump (CMJ) height as a function of playing position. Differing letters (A–C) indicate significant differences among groups.

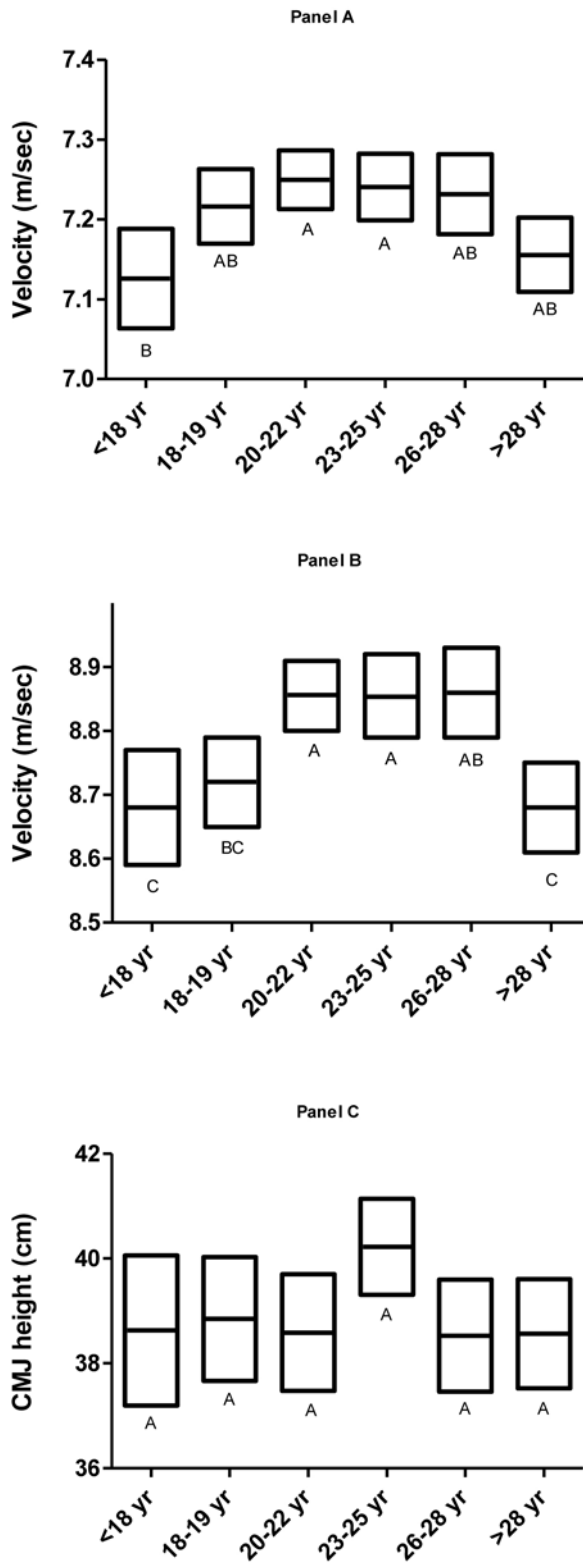


Figure 3 — 95% confidence intervals for (A) 0- to 20-m velocity, (B) peak velocity, and (C) countermovement-jump (CMJ) height as a function of age. Differing letters (A–C) indicate significant differences among groups.

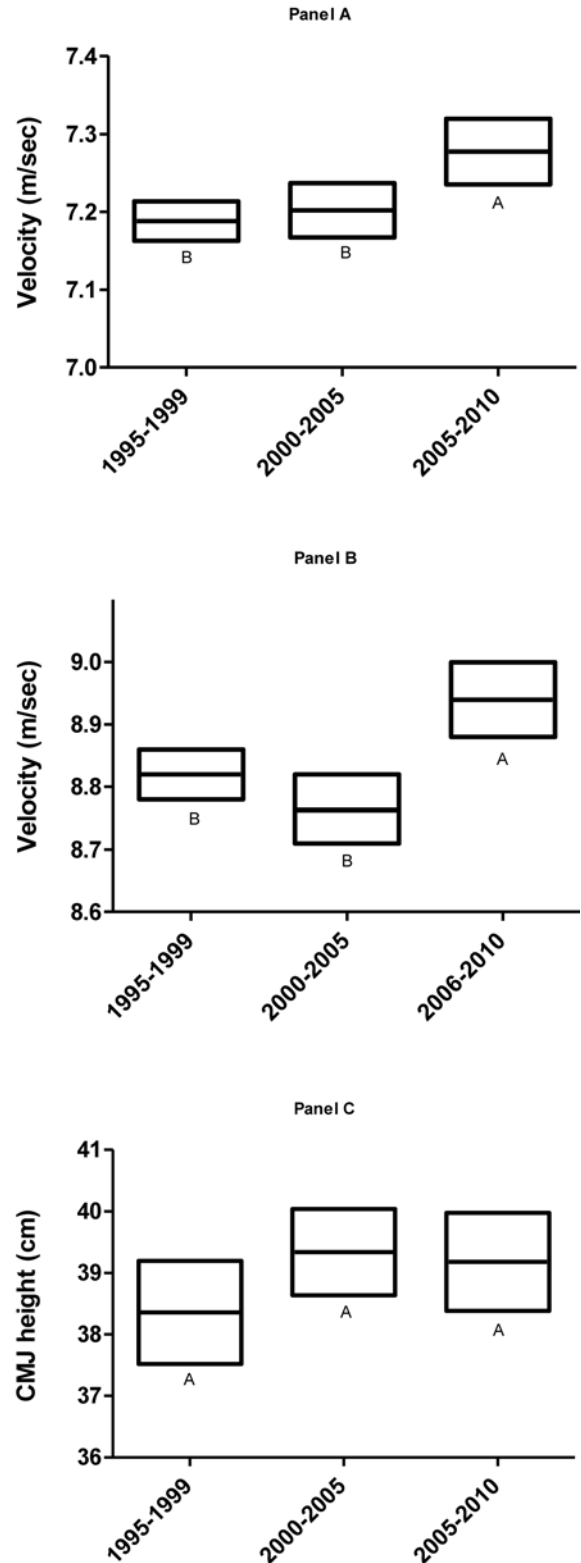


Figure 4 — 95% confidence intervals for (A) 0- to 20-m velocity, (B) peak velocity, and (C) countermovement-jump (CMJ) height as a function of time epoch. Differing letters (A–B) indicate significant differences among groups.

Table 3 Correlation Values (95% Confidence Intervals of *r*) for Sprint and Countermovement-Jump (CMJ) Performance Among Analyzed Categories

Category	CMJ vs 0- to 20-m Velocity			CMJ vs 30- to 40-m Velocity		
	Lower bound	<i>r</i>	Upper bound	Lower bound	<i>r</i>	Upper bound
National team	.18	.57	.80	.45	.74	1.00
1st division	.47	.56	.64	.46	.55	.63
2nd division	.47	.62	.73	.40	.56	.69
3rd–5th division	.39	.55	.68	.29	.47	.62
Junior national team	.51	.68	.80	.30	.52	.69
Juniors	.46	.59	.69	.36	.50	.62
Forwards	.50	.63	.74	.42	.57	.69
Defenders	.54	.65	.74	.44	.57	.68
Midfielders	.50	.62	.71	.36	.50	.62
Goalkeepers	.31	.55	.73	.39	.61	.77
<18 y	.21	.46	.65	.26	.50	.68
18–19 y	.48	.65	.77	.29	.50	.67
20–22 y	.44	.61	.74	.36	.54	.68
23–25 y	.56	.68	.77	.47	.61	.72
26–28 y	.51	.67	.79	.36	.56	.71
>28 y	.20	.43	.61	.34	.54	.70
1995–1999	.44	.58	.69	.43	.57	.68
2000–2005	.49	.60	.69	.33	.47	.59
2006–2010	.52	.63	.72	.50	.61	.70

Note: All correlations were significant ($P < .001$).

Performance Level

The 95% CIs in Figure 1 show that sprinting velocity trends predictably across performance level. To our knowledge, this is the first study to demonstrate that linear sprinting ability is a performance-distinguishing factor in male soccer. All differences observed were larger than test–retest reliability (CV ~1%) for the same timing system and starting procedures as reported by Haugen et al.¹⁸ Cometti et al.⁸ reported no speed differences over 30 m between French elite players and amateurs. However, the elite players in that study ran faster over 10 m.

This study did not demonstrate a clear relationship between jumping height and soccer performance level. No differences among the professional players and junior national-team players were observed, despite lower body-mass index among the junior national-team players (Table 1). All these performance-level categories jumped ~3 to 5 cm higher than third- to fifth-division players and juniors. Our data support the statement by Rampinini et al.,²² who claim that vertical-jump performance is not able to discriminate players of different match performance. Furthermore, Rösch et al.⁹ did not report CMJ differences among French, German, and Czech senior players at different performance levels. In contrast, Arnason et al.⁷ found a significant relationship between average jump height and success among 17 teams in the 2 high-

est divisions in Iceland. Taking all the studies together, there is not enough evidence to claim that CMJ ability is a performance-distinguishing factor among professional soccer players.

Playing Position

Velocity differences across playing positions ranged from small to large in the current investigation. All differences observed were larger than test–retest reliability.¹⁸ The internal ranking by player position is in accordance with the findings by Davis et al.,¹⁰ Boone et al.,¹¹ and Sporis et al.¹² Buchheit et al.¹⁴ and Mendez-Villanueva et al.¹⁵ claim that the impact of physical capacities on game physical performance is position dependent. Taskin¹³ did not find differences in 30-m-sprint times as a function of playing position among 243 Turkish professional soccer players. Physical characteristics may vary across clubs and nations, depending on tactical dispositions and differences in athlete-selection process over time. Sprinting ability must also be seen in relationship to the physical demands of the different positions on the field. Our playing-position categorization is somewhat limited, but forward and defenders are probably the fastest players because they are involved in most decisive duels during match play.⁵ Midfielders cover the longest distance during games,⁶ indicating physical qualities other than sprinting velocity as more important.

Our data showed that midfielders had less vertical-jump capacity than the other positions. This is in contrast to Sporis et al,¹² who reported no CMJ-height differences across positions among 270 Croatian elite soccer players. Goalkeepers performed better in CMJ than sprinting relative to the other position groups in our study, which is in accordance with Boone et al.¹¹ They were also the tallest players (Table 1), supporting the logical expectation that explosive range is an important performance factor for goalkeepers.

Age

No studies have so far examined velocity and power characteristics through different age stages among male soccer players. Overall, the 95% CIs show that sprint velocity peaked in the age range 20 to 28 years, with small but significant decreases in velocity thereafter. Mujika et al¹⁶ reported no significant differences in 15-m-sprint times between juniors and seniors representing a Spanish soccer club. Athletic statistics show that world top-50 sprinters have achieved their best performances at a mean age of 25 ± 3.1 years (<http://www.iaaf.org/statistics/toplists/index.html>). No further improvement in sprint velocity was observed after the age of 20 to 22 years in our study. Thus, peak sprinting performance within the larger skill set of soccer peaks 3 to 4 years earlier than when sprint optimization is the only training goal. This stagnation may be considered in the context of match program and specific training. Extensive soccer training including 1 to 3 hours running with varying intensity 5 to 6 d/wk can possibly inhibit sprinting skills.

No differences in CMJ ability were observed across the age categories. This finding reinforces the notion that vertical-jump performance is less important than sprinting ability in soccer.

Time Epoch

This study demonstrates a small but positive development in sprinting velocity for the professional players over time. No studies have so far monitored a large number of male soccer players' physical characteristics in a long-term perspective. The time-epoch analysis was restricted to professionals, and all of these players were tested as part of routine testing procedures. Therefore, the difference observed cannot be explained by selection bias. Instead, we hypothesize that this provides some evidence for the contention that professional performers have become faster over time. Our data showed no development in CMJ height during the corresponding time epochs. We are not aware of studies reporting development in short sprinting distances without development in CMJ ability. Our results remained consistent even when only players who performed both sprint and CMJ testing were considered. These findings indicate that sprint and vertical jump are specific and independent qualities.

Sprint and CMJ Relationship

Overall, most sprint and CMJ correlation values reported were in the range of moderate to very large. Our findings are in accordance with similar soccer investigations.^{17,23} The coefficients of determination between our sprint and CMJ data were mainly .25 to .5. Variables should be considered specific and independent of each other when the coefficient of determination is less than .50.²⁴ Equally performing players on the sprint test in this study differed by as much as 10 to 15 cm on the CMJ test. Salaj and Markovic²⁵ suggest that vertical and horizontal acceleration characteristics should be tested separately.

Practical Applications

In the current study there were moderate to large velocity differences across performance level, supporting the notion that linear sprinting velocity is an important skill in modern soccer. Small to large performance differences among playing-position groups indicate that individual physical capacity is an important part of tactical dispositions within the team. Sprinting velocity peaks in the age range of 20 to 28 years, with small but significant decreases in velocity thereafter. Based on the smaller between-groups differences in CMJ height in this investigation, it is tempting to claim that speed is more important than vertical-jump ability in soccer, except for goalkeepers. Soccer athletes have many qualities to develop, and coaches should take sprinting velocity into account within the larger skill set of soccer. Selection of players, testing, and physical conditioning of the athletes should reflect the importance of speed. Future research should focus more on the relationship between physical demands of the game, capacity profiles among players, and consequences for long-term planning of individual fitness programs in soccer.

Conclusion

This study provides effect-magnitude estimates for the influence of performance level, player position, and age on sprint and CMJ performance in soccer. There was a small but positive difference in sprinting velocity among professional players over time, whereas CMJ performance has remained stable.

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Speed and Countermovement-Jump Characteristics of Elite Female Soccer Players, 1995–2010

Thomas A. Haugen, Espen Tønnessen, and Stephen Seiler

Purpose: The purpose of this investigation was to compare sprint and countermovement-jump (CMJ) performance among female competitive soccer players as a function of performance level, field position, and age. In addition, the authors wanted to quantify the evolution of these physical characteristics among elite players over a 15-y period. **Methods:** 194 female elite players (22 ± 4.1 y, 63 ± 5.6 kg), including an Olympic winning squad, tested 40-m sprint with electronic timing and CMJ on a force platform at the Norwegian Olympic training center from 1995 to 2010. **Results:** Moderate to large velocity differences across performance levels and positions were observed. National-team players were 2% faster than 1st-division players ($P = .027$, $d = 0.5$) and 5% faster than 2nd-division players ($P < .001$, $d = 1.3$) over 0–20 m. National-team players jumped 8–9% higher than 1st-division players ($P = .001$, $d = 0.6$) and junior elite players ($P = .023$, $d = 0.5$). Forwards were 3–4% faster than midfielders ($P < .001$, $d = 0.8$) and goalkeepers ($P = .003$, $d = 0.9$) over 0–20 m. No differences in velocity or CMJ height were observed among the age categories. Players from 2006–2010 were 2% faster ($P < .05$, $d = 0.6$) than players from 1995–1999 over 20 m, whereas no differences in 20- to 40-m velocity or CMJ performance were observed. **Conclusions:** This study provides effect-magnitude estimates for the influence of performance level, age, and player position on sprint and CMJ performance in female soccer players. While 20- to 40-m velocity and CMJ performance have remained stable over the time, there has been a moderate but positive development in 0- to 20-m velocity among elite performers.

Keywords: 20-m, 40-m, vertical-jump height, sprint performance.

Women's soccer has, during the last 2 decades, become one of the most popular women's sports worldwide. According to FIFA, more than 4 million female players are registered in football associations (www.fifa.com/mm/document/fifafacts/bcoffsurv/emaga_9384_10704.pdf). Despite the high participation rates, there is room for more research on women's soccer. While physical characteristics of male soccer players have been well described,^{1–8} fewer studies are available involving female players.^{9–12} Time-motion analyses show that elite female players perform high-intensity running 120 to 150 times during a game, for 2 to 3 seconds on average.^{13,14} Although sprinting and high-intensity actions in soccer matches represent only 8% to 12% of covered running distance, these capabilities are considered position dependent and important for soccer performance.^{5,6,15–17} Within this decisive portion of movement performed during a match, it is likely that maximal-sprint situations represent particularly critical moments. Both horizontal acceleration (sprinting) and vertical acceleration (jumping power) are involved in

ball possession and repossession, defense play, corner kicks, and attacks on goal.

Sedano et al⁹ and Mujika et al¹⁰ found no differences in sprint or vertical-jump ability among female soccer players as a function of performance level. Vescovi et al¹¹ reported no further development in sprint or countermovement-jump (CMJ) ability after 15 to 16 years of age among youth, high school, and college athletes 12 to 21 years old. Another study by Vescovi et al¹² did not reveal any positional sprinting skill or CMJ differences in 64 female university soccer players. These findings from female players stand in contrast to corresponding data from male soccer players, for whom sprint performance varies according to performance level and playing position.^{2–4} No studies have examined female world-class players over time. Many coaches claim that international soccer players are faster now than 10 years ago, but objective data supporting this claim have not been available.

The Norwegian Olympic training center has served as a standard testing facility for a large number of teams at different performance levels, including the champions of the Sydney 2000 Olympics. A database of sprint and CMJ results collected over 15 years provides the potential to address several different questions related to the role of sprint and vertical-jump performance in women's soccer. Thus, the aim of this study was to use a database of women soccer athletes' sprint and CMJ tests collected

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under the same highly standardized conditions over 15 years to quantify possible differences in sprinting velocity and jump height as a function of athlete performance level, field position, and age. In addition, we evaluated the evolution of sprinting velocity and CMJ height in the Norwegian national squad over a 15-year period.

Materials and Methods

Subjects

Data from 194 female soccer players, 15 to 35 years old (22 ± 4.1 y), body mass 63 ± 5.6 kg, representing a broad range of performance levels, were tested from 1995 to 2010. In total, 355 sprint tests and 250 CMJ tests formed the basis for this investigation (Table 1). For the sprint tests, 108 players tested once, 37 tested twice, 26 tested 3 times, 21 tested 4 times, 1 player 5 times, and 1 player 6 times. For the CMJ tests, 107 players tested once, 31 tested twice, and 27 tested 3 times. The difference in sample size between sprint and CMJ is mostly due to 2 first-division teams (29 players in total) who did not test CMJ. All tests were performed in the afternoon (between 3 and 8 PM) at the Olympic training center in Oslo. These were preexisting data from the semiannual or annual testing that these teams performed for training monitoring purposes, so no informed consent was obtained. The Norwegian Olympic Committee and Norwegian Confederation of Sports approved the use of the data, provided there would be no publishing of confidential individual test results. This study was approved by the ethics committee of the Faculty for Health and Sport, University of Agder, in accordance to the Helsinki Declaration.

Senior national-team athletes were defined as players who represented Norway in Olympic Games, World Cup, Euro Cup, qualifying matches, or training matches. Since 1995, the Norwegian squad has won gold and bronze in the Olympic Games, gold in World Cup, and silver in the

Euro Cup. First-division athletes in this study represented female clubs from the highest division level in the Norwegian soccer-league system, while second-division athletes were playing in the second-highest division. The junior elite athletes in the database represented a high school in Oslo with an elite soccer program. They were playing in the highest junior division for different clubs in Norway.

Sprint-Timing Equipment

All tests were performed on a dedicated indoor 40-m track with an 8-mm Mondotrack FTS surface (Mondo, Conshohocken, USA) and electronic timing equipment. A 60×60 -cm start pad was placed under the track at the start line. The clock was initiated when the front foot stepped off the pad. The athlete's center of gravity is therefore about 50 cm in front of the start line when the timer is initiated. Split times were recorded at 10-m intervals. Infrared photocells with transmitters and reflectors were placed in pairs on each side of the running course with 1.6-m transmitter-reflector spacing. The infrared beam was split to reduce the possibility of arms triggering the cells. Transmitters were placed 140 cm above the ground, and reflectors for the split beam were placed 130 and 150 cm above the floor. Both beams had to be interrupted to trigger each photocell. Electronic times were transferred to computer software (Biorun, made in MatLab by Biomekanikk AS, Norway). The timing system used in all tests has been recently assessed for accuracy and reliability.^{18,19}

Force Platform

CMJ tests were performed on a 122×62 -cm AMTI force platform, model OR6-5-1. Jump height was determined as the center-of-mass displacement calculated from force development and measured body mass. The system setup was in accordance with the guidelines recommended by Street et al.²⁰ Force data were sampled at 1000 Hz

Table 1 Sample Size, Age, and Body Mass for the Subject Categories

Performance level	Position	Age	Time period
National team (n = 85/85): age 23.5 ± 3.6 y, body mass 63.7 ± 5.2 kg	Forward (n = 52/44): age 21.9 ± 3.8 y, body mass 64.1 ± 6.7 kg	<18 y (n = 30/31): body mass 60.2 ± 6.1 kg	1995–1999 (32/28): age 23.8 ± 3.6 y, body mass 64.2 ± 5.3 kg
First division (n = 47/46): age 21.2 ± 3.6 y, body mass 62.4 ± 6.6 kg	Defenders (n = 63/55): age 21.6 ± 4.1 y, body mass 61.9 ± 5.7 kg	18–19 y (n = 36/25): body mass 64.8 ± 4.6 kg**	2000–2005 (29/35): age 23.3 ± 4.3 y, body mass 64.2 ± 3.8 kg
Second division (n = 29/0): age 22.3 ± 4.8 y, body mass not measured	Midfielders (n = 62/50): age 21.6 ± 4.3 y, body mass 61.5 ± 4.6 kg	20–22 y (n = 56/46): body mass 63.1 ± 4.6 kg	2006–2010 (24/23): age 23.3 ± 2.9 y, body mass 63.2 ± 4.8 kg
Junior elite (n = 33/34): age 18.1 ± 2.9 y, body mass 61.7 ± 5.9 kg	Goalkeepers (n = 17/16): age 21.4 ± 4.7 y, body mass 67.3 ± 4.6 kg*	23–25 y (n = 39/35): body mass 62.7 ± 6.3 kg	
		>25 y (n = 33/28): body mass 64.3 ± 6.7 kg	

Note: Sample sizes reported are for sprint and countermovement jump.

*Goalkeepers were significantly heavier than midfielders ($P = .008$) and defenders ($P = .013$). **Players 18–19 y of age were significantly heavier than those <18 y ($P = .030$).

for 5 seconds with a resolution of 0.1 N. The data were amplified (AMTI Model SGA6-3), digitized (DT 2801), and saved to dedicated computer software (Biojump, Norway). The force platform has been recently assessed for accuracy and reliability.¹⁹

Testing Procedures

Athletes completed a standard warm-up program before sprint testing, beginning with a 10- to 15-minute easy jog. They then performed 5 to 6 minutes with sprint-specific drill exercises followed by 2 or 3 strides with increasing speed. Athletes completed 1 or 2 trial starts before testing. During testing, athletes assumed the starting position and started running on their own initiative after being cleared to start by the test leader. New trials were performed every 3 to 5 minutes until evidence of peak performance was observed. In practice, 80% of all athletes achieved their best performance within 2 trials. CMJ tests were performed 10 to 15 minutes after the 40-m tests. Each athlete was weighed on the force platform for system calibration before testing. All subjects underwent 1 or 2 easy trial jumps to ensure testing-procedure familiarization. They then performed 4 to 6 jumps with 45 to 60 seconds recovery between trials until jump height stabilized. All jumps were performed with hands on the hips. The subjects were required to bend their knees to approximately 90° and then rebound in a maximal vertical jump. The best result for each player was retained for analysis. Nearly 50% of the players also performed a VO_{2max} test in addition to sprint and CMJ. The order was always sprint, CMJ, and VO_{2max} . The experimental setting was consistent, and our test results were not affected by other tests. Regarding nutrition, hydration, sleep, and physical activity, the athletes were instructed to prepare themselves as they would for a regular competition, including no high-intensity training in the 2 or 3 days before testing. All subjects underwent identical testing procedures and conditions, including equipment and surfaces, during the 15-year data-collection period.

Statistics

SPSS 18 was used for all analyses. Means and SDs of each 10-m split are presented for all analyzed categories. Reliability calculations were based on mean difference, correlation (R), absolute variation, standard error of measurement, and coefficient of variation (CV) between the first 2 tests for the athletes who tested twice or more. The analyses of sprint velocity as a function of performance level, position, age, and time period were based on best individual 40-m-sprint test results ($n = 194$) with associated 0- to 20-m and 20- to 40-m split times. Several studies show that sprint bouts during games last 2 to 4 seconds on average.^{1,7,21} For these reasons, we chose 0- to 20-m times to represent acceleration capability in the current study. Similarly, we chose to use 20- to 40-m split time as the basis for calculating maximum sprint velocity to maximize the signal-to-noise ratio for this variable. Expressing the data in terms of 20- to 40-m velocity provides a reference for game-activity analysis.

CMJ analyses were based on best individual CMJ test results ($n = 165$). In some cases, best sprint and CMJ test results occurred on different testing days. Data from a single athlete were only included in 1 category for each analysis. That category was the athlete's affiliation on the day of her best result. Player position was identified for athletes by their coaches or by self-report as goalkeeper, defense player, midfielder, or forward. Athlete age was calculated from date of birth and testing date and categorized as under 18, 18 to 19, 20 to 22, 23 to 25, and 25 plus. The time-period analysis was restricted to members of the national team ($n = 85$) at the time of testing. To quantify the development of sprinting velocity and CMJ ability over time, the database was divided into 3 time periods: 1995–1999, 2000–2005, and 2006–2010.

Means and 95% confidence intervals were calculated for each group or category. Pearson R was used to examine the relationship between CMJ and sprint ability. Best individual sprint tests formed the basis for split-time correlations. The best individual CMJ test with corresponding sprint test during the same testing day formed the basis for correlation analyses between sprint and vertical-jump ability. One-way ANOVA followed by Tukey post hoc test where necessary was used to identify differences among groups or categories. Effect size (Cohen d) was calculated to evaluate the meaningfulness of the difference between category means. Effect magnitude was interpreted categorically as small (0.2–0.6), moderate (0.6–1.2), or large (1.2–2.0) using the scale presented by Hopkins et al.²² To assess test–retest reliability for the sprint and CMJ test, data from all athletes who performed sprint ($n = 86$) and CMJ tests ($n = 58$) on 2 or more occasions at varying intervals were analyzed. Results from the first 2 tests were used for the analysis.

Results

Table 2 presents 10-m split times for the analyzed categories. Our data showed that 50% of the players increased their velocity from 30 to 40 m compared with 20- to 30-m times, 9% remained stable, and 41% of the athletes reduced their speed during the same split. However, the difference between the last two 10-m splits was never more than 0.02 seconds for any category.

Table 3 presents test–retest reliability statistics for our sprint and CMJ tests. The CV was ~2% for the 20-m splits, 2.57% to 3.3% for the 10-m splits, and ~3% for CMJ height.

Figure 1 (panel A) shows the average velocity over 0 to 20 m for all performance-level categories. National-team players were 2% faster than first-division players ($P = .027$, $d = 0.5$) and 5% faster than second-division players ($P < .001$, $d = 1.3$). First-division players were 3% faster than second-division players ($P = .006$, $d = 0.8$). Junior elite players were 3% faster than second-division players ($P = .003$, $d = 0.8$). Figure 1 (panel B) presents the 20- to 40-m velocity for the performance-level categories. National-team players were 5% faster than second-division players ($P < .001$, $d = 1.1$). First-division

Table 2 Ten-Meter Split Times and Countermovement-Jump Height (Mean ± SD) for Analyzed Categories

Category	0–10 m (s)	10–20 m (s)	20–30 m (s)	30–40 m (s)	Countermovement-jump height (cm)
Level					
national team	1.67 ± 0.07	1.38 ± 0.06	1.30 ± 0.06	1.29 ± 0.06	30.7 ± 4.1
first division	1.70 ± 0.07	1.41 ± 0.06	1.32 ± 0.07	1.32 ± 0.06	28.1 ± 4.1
second division	1.77 ± 0.06	1.45 ± 0.06	1.36 ± 0.05	1.35 ± 0.07	Not tested
junior elite	1.70 ± 0.09	1.42 ± 0.07	1.32 ± 0.08	1.33 ± 0.11	28.5 ± 4.1
Position					
forward	1.68 ± 0.09	1.37 ± 0.07	1.29 ± 0.08	1.28 ± 0.07	30.5 ± 4.5
defender	1.69 ± 0.07	1.40 ± 0.06	1.31 ± 0.05	1.31 ± 0.06	29.6 ± 4.0
midfielder	1.70 ± 0.07	1.42 ± 0.05	1.32 ± 0.06	1.32 ± 0.05	28.4 ± 3.9
goalkeeper	1.71 ± 0.08	1.43 ± 0.06	1.34 ± 0.07	1.35 ± 0.08	30.0 ± 4.8
Age, y					
<18	1.70 ± 0.08	1.42 ± 0.05	1.33 ± 0.05	1.32 ± 0.06	27.9 ± 3.1
18–19	1.70 ± 0.09	1.41 ± 0.07	1.32 ± 0.08	1.32 ± 0.10	29.7 ± 4.3
20–22	1.70 ± 0.07	1.40 ± 0.05	1.32 ± 0.06	1.30 ± 0.06	30.0 ± 4.4
23–25	1.70 ± 0.07	1.40 ± 0.05	1.31 ± 0.06	1.31 ± 0.06	29.7 ± 4.6
>25	1.70 ± 0.08	1.41 ± 0.07	1.32 ± 0.07	1.32 ± 0.07	30.4 ± 4.2
Time period					
1995–1999	1.70 ± 0.08	1.40 ± 0.06	1.31 ± 0.06	1.31 ± 0.07	31.5 ± 4.2
2000–2005	1.69 ± 0.06	1.38 ± 0.06	1.29 ± 0.06	1.30 ± 0.06	30.9 ± 4.0
2006–2010	1.65 ± 0.07	1.38 ± 0.06	1.30 ± 0.05	1.28 ± 0.06	31.1 ± 3.5

Table 3 Test–Retest Reliability for Analyzed Split Times During 40-m-Sprint Testing

Variable	n	Trial 1	Trial 2	Δ	AV	R	SEM	CV
0–10 m	86	1.69 s	1.69 s	0.00 s	0.03 s	.77	0.03 s	2.91%
10–20 m	86	1.40 s	1.40 s	0.00 s	0.03 s	.82	0.03 s	2.64%
20–30 m	86	1.32 s	1.32 s	0.00 s	0.02 s	.85	0.02 s	2.57%
30–40 m	86	1.32 s	1.31 s	0.01 s	0.03 s	.81	0.03 s	3.30%
0–20 m	86	3.10 s	3.09 s	0.01 s	0.04 s	.90	0.04 s	1.82%
20–40 m	86	2.63 s	2.63 s	0.00 s	0.04 s	.88	0.04 s	2.11%
Countermovement jump	58	29.7 cm	28.4 cm	1.3 cm	1.3 cm	.97	0.67 cm	3.26%

Abbreviations: Δ, mean difference; AV, absolute variation; R, Pearson *r*; SEM, standard error of measurement; CV, coefficient of variation.

players were 3% faster than second-division players ($P = .040$, $d = 0.7$). Overall, 95% CIs for sprinting velocity trended predictably across performance level. Figure 1 (panel C) reports CMJ height for all performance-level groups. National-team players jumped 8% to 9% higher than first-division players ($P = .001$, $d = 0.6$) and junior elite players ($P = .023$, $d = 0.5$).

Figure 2 (panel A) shows 95% CIs for 0- to 20-m velocity by position among all players in the current study. Forwards were 3% to 4% faster than midfielders ($P < .001$, $d = 0.8$) and goalkeepers ($P = .003$, $d = 0.9$). Defenders were 2% faster than midfielders ($P = .019$, $d =$

0.5). Figure 2 (panel B) presents 20- to 40-m velocity by playing position. Forwards were 4% faster than midfielders ($P < .001$, $d = 0.9$) and 6% faster than goalkeepers ($P < .001$, $d = 1.3$). Defenders were 3% faster than goalkeepers ($P = .043$, $d = 0.8$).

Figure 3 (panel C) shows that no differences for CMJ among playing positions were observed. No differences in sprint or CMJ performance were observed across the age groups (Figure 3).

Figure 4 (panel A) shows 95% CIs for 0- to 20-m velocity by time period among national-team players. Players from 2006–2010 were 2% faster for 0 to 20 m

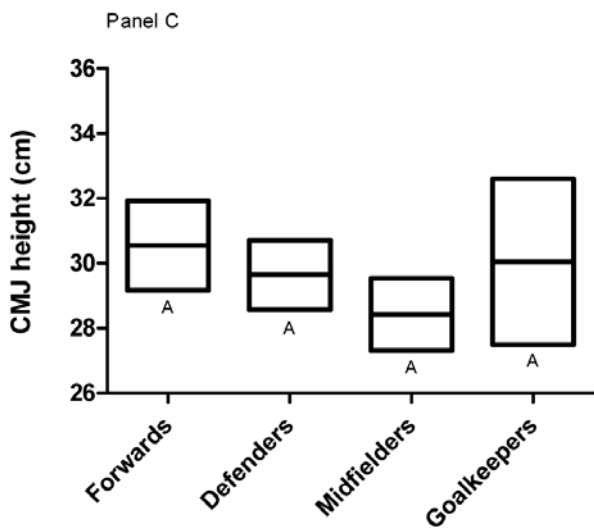
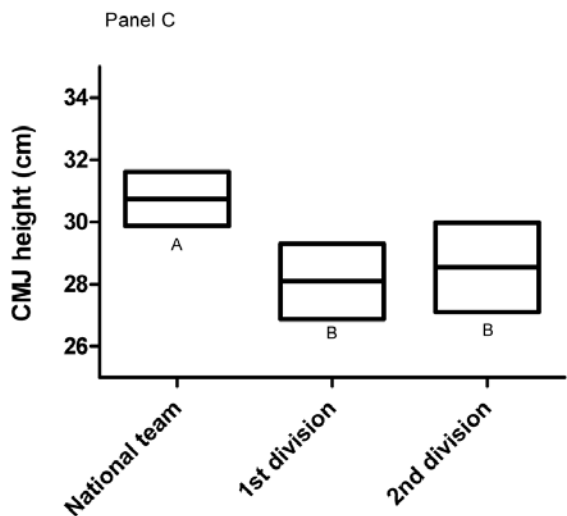
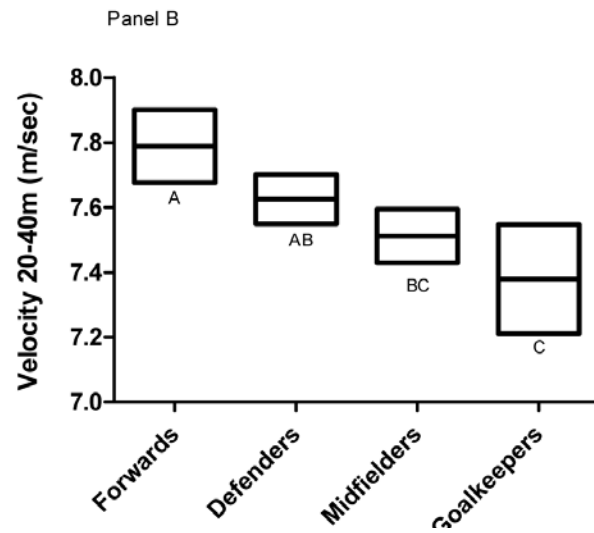
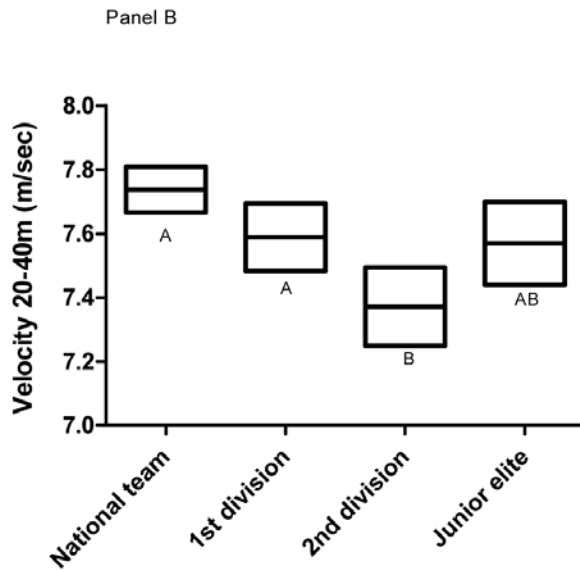
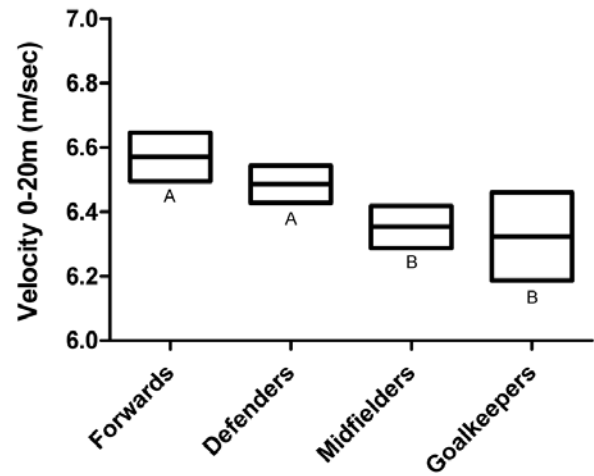
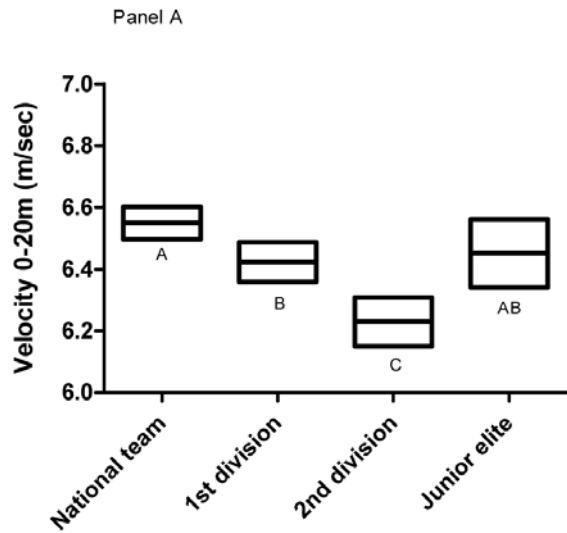


Figure 1 — 95% confidence intervals for 0- to 20-m velocity (panel A), 20- to 40-m velocity (panel B), and countermovement-jump (CMJ) height (panel C) as a function of performance level. Differing letters indicate significant differences among groups.

Figure 2 — 95% confidence intervals for 0- to 20-m velocity (panel A), 20- to 40-m velocity (panel B), and countermovement-jump (CMJ) height (panel C) as a function of playing position. Differing letters indicate significant differences among groups.

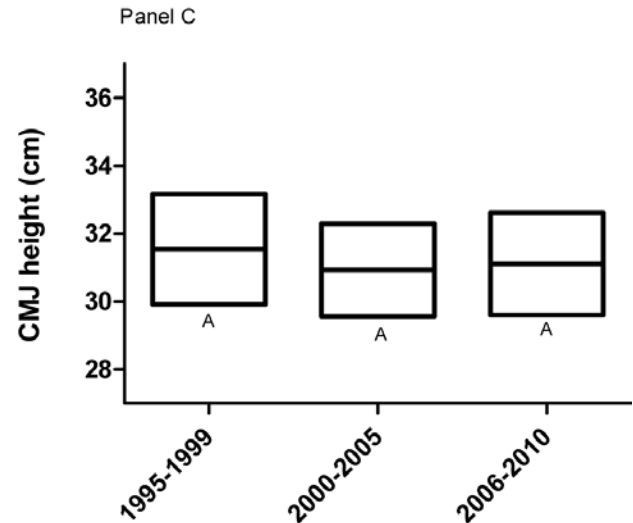
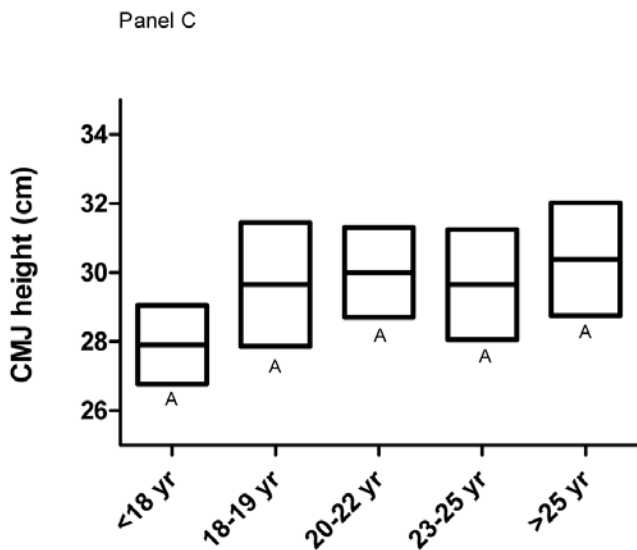
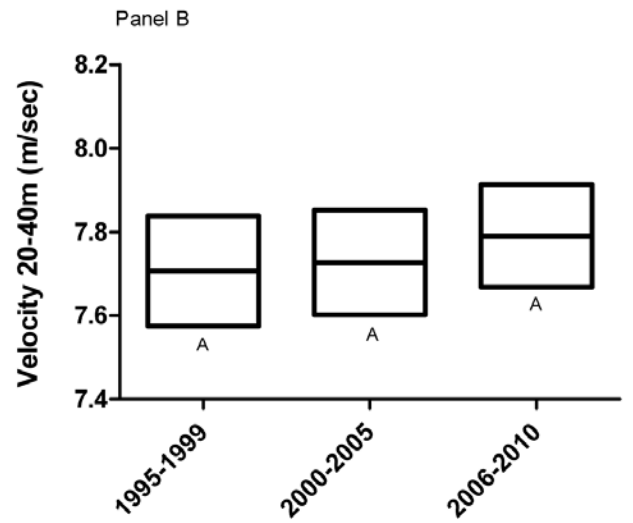
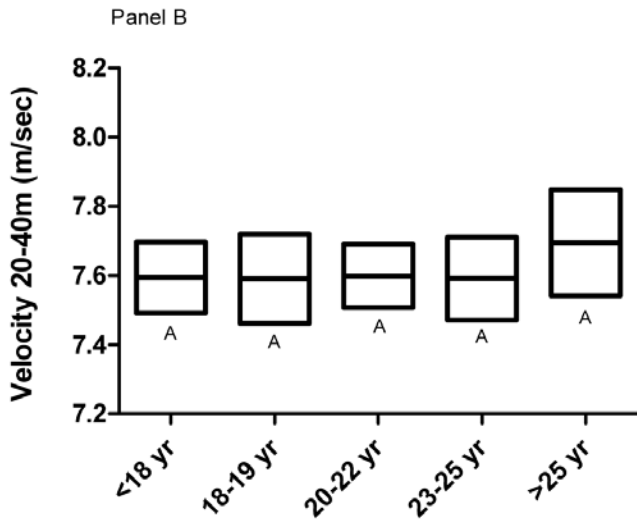
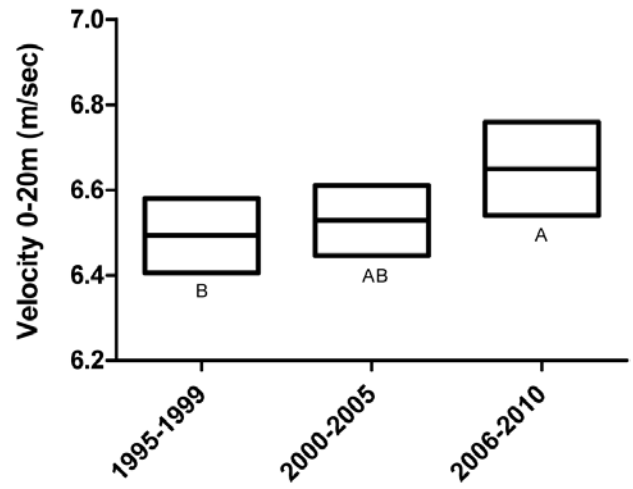
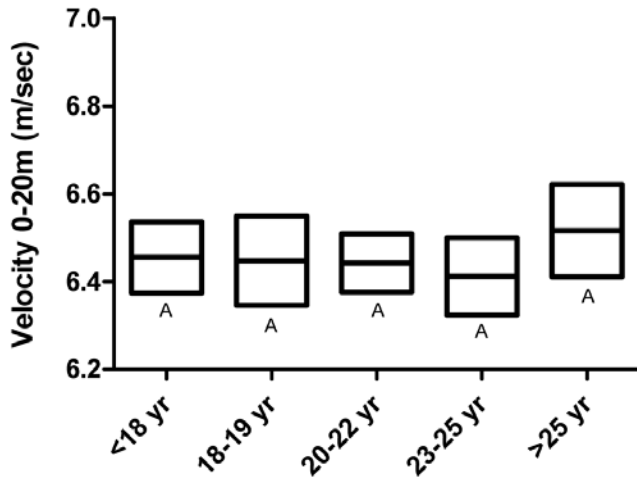


Figure 3 — 95% confidence intervals for 0- to 20-m velocity (panel A), 20- to 40-m velocity (panel B), and countermovement-jump (CMJ) height (panel C) as a function of age. Differing letters indicate significant differences among groups.

Figure 4 — 95% confidence intervals for 0- to 20-m velocity (panel A), 20- to 40-m velocity (panel B), and countermovement-jump (CMJ) height (panel C) as a function of time period. Differing letters indicate significant differences among groups.

than players from 1995–1999 ($P = .046$, $d = 0.6$). Overall, the 95% CIs demonstrate a slight trend toward faster national-team players over time (Figure 4, panels A and B). No differences in CMJ ability were observed across time periods (Figure 4, panel C).

Table 4 shows correlation values between sprint and CMJ performance among analyzed categories in the current study. Overall, there was a strong correlation between CMJ height and 0- to 20-m velocity ($r = .63$, $P < .001$, $n = 165$) and between CMJ height and 20- to 40-m velocity ($r = .64$, $P < .001$, $n = 165$). The correlation between 0- to 20-m and 20- to 40-m velocity was very high ($r = .86$, $P < .001$, $n = 194$).

Discussion

In the current study, data from a large sample of athletes tested under identical conditions demonstrate moderate to large differences in sprinting velocity as a function of soccer performance level and playing position. We also observed a moderate positive development in 0- to 20-m sprinting velocity among elite performers over a 15-year period of testing, but no significant changes in 20- to 40-m velocity or CMJ ability. No differences in sprinting velocity or CMJ height were observed across age categories in these athletes.

Table 1 shows that Norwegian national-team players were on average 2 years older than elite series players and represented 71% of all players in the >25 age category. That is, in this sample, only the very best female soccer players tend to continue their careers beyond age 25.

Table 2 shows the development of 10-m split times through the entire sprint test for all analyzed categories. Even though we have no data beyond 40 m, sprinting velocity appears to peak between 20 and 40 m at 7.4 to 7.8 m/s (10-m splits between 1.28 and 1.35 s) for the elite female soccer players in this study. Comparatively, female world-class sprinters' velocity peaks between 60 and 80 m at ~10.5 m/s.²³

There are several potential ways to quantify sprint performance. Table 3 demonstrates lower CV values and higher correlation values for 20-m splits than for 10-m splits. Most athletes performed 1 or 2 tests each year, and the large time interval may affect the reliability outcomes because of variability in training status. Despite this methodological weakness, we believe that our data are highly representative for these athletes. Haugen et al¹⁸ reported a CV of ~1% for 40-m times among track-and-field athletes using the same timing system. Thus, perhaps half of the test-to-test variation observed here is attributable to variation in form or training status over the longer time gaps between tests.

Table 4 Correlation Values (95% Confidence Intervals of r) for Sprint and CMJ Performance Among Analyzed Categories

Category	Countermovement Jump vs 0- to 20-m Velocity				Countermovement Jump vs 20- to 40-m Velocity			
	Lower bound	r	Upper bound	P	Lower bound	r	Upper bound	P
Level								
national team	.44	.60	.72	.001	.41	.61	.73	.001
first division	.40	.62	.77	.001	.46	.66	.80	.001
junior elite	.27	.56	.76	.001	.37	.63	.80	.001
Position								
forward	.26	.52	.71	.001	.48	.68	.81	.001
defender	.41	.61	.75	.001	.42	.62	.76	.001
midfielder	.47	.66	.79	.001	.54	.71	.83	.001
goalkeeper	.55	.82	.94	.001	.31	.70	.89	.001
Age, y								
<18	.43	.67	.82	.001	.34	.61	.79	.001
18–19	.14	.47	.70	.001	.29	.58	.77	.001
20–22	.40	.66	.82	.001	.43	.68	.77	.001
23–25	.40	.62	.77	.001	.41	.63	.78	.001
>25	.36	.67	.85	.001	.40	.70	.86	.001
Time period								
1995–1999	.48	.72	.86	.001	.46	.71	.86	.001
2000–2005	.46	.69	.83	.001	.28	.56	.75	.001
2006–2010	.05	.45	.73	.05	.12	.51	.76	.05

Performance Level

To our knowledge, this is the first investigation to describe physical-performance characteristics of female soccer players over a performance range from junior elite to national-team players. The current results demonstrate moderate to large velocity differences across performance levels. National-team players were 2% to 5% faster than first- and second-division players over 0 to 20 m, while first-division players were 3% faster than second-division players over the same distance. The differences were similar for 20- to 40-m velocity, but only the 5% velocity difference between national-team and second-division players was significant. Based on average velocity over the distance, the national-team players were at least 1 m ahead of the second-division players over both 0 to 20 m and 20 to 40 m. All the presented group differences were larger than the corresponding CV values (Table 3). Therefore, it appears that the sprinting-velocity differences observed among performance groups are large enough to be decisive in 1-on-1 duels.

The differences in CMJ ability across performance levels were moderate, but larger than CV (Table 3). National-team players jumped 8% to 9% higher than first-division and junior elite players. These findings are in contrast to those of Sedano et al.,⁹ who reported no differences in vertical-jump ability between elite and nonelite Spanish female soccer players. This divergence with respect to the importance of vertical-jump ability in soccer may be explained by varying fitness programs and training philosophies among teams. Another explanation might be the assumption of CMJ height as a less important performance factor in soccer.²⁴

Playing Position

Our data suggest that there are moderate to large velocity differences across playing positions in women's soccer. Forwards were the fastest players ahead of defenders, while midfielders and goalkeepers were slowest. All significant position differences in velocity were larger than the CVs revealed in Table 3. Our findings are in accordance with earlier findings for male elite players.¹⁻³ In contrast, no differences were observed for CMJ height. However, the results show a similar trend as for the sprint data, except for goalkeepers, who performed better in CMJ than sprinting relative to the other position groups. Buchheit et al.⁵ and Mendez-Villanueva et al.⁶ claim that the impact of physical capacities on game physical performance is position dependent. Vescovi et al.¹² did not report any speed or CMJ differences related to playing position among female college players. This might be due to small sample size ($N = 64$) or differences in the athlete-selection process over time.

Age

We observed no age-related differences in sprint or CMJ performance. Previous studies indicate that peak performance in speed and vertical jump is achieved in

the midteens for female soccer players. In a study of 414 female athletes (12–21 y), Vescovi et al.¹¹ reported that sprint and CMJ ability increased up to the age of 15 to 16 years before stabilizing. Another study by Vescovi et al.¹² revealed no differences in sprint and CMJ scores between female high school and college players. Mujika et al.¹⁰ found differences in CMJ height but not 15-m-sprint time between Spanish junior and senior female elite players. Unfortunately, female soccer players struggle to improve their sprinting velocity and vertical-jump ability from junior age to the mid-20s. We have recently observed that male athletes of similar performance level show peak sprinting ability in their mid-20s before evidence of decline is seen after age 30.² In the current data, we did not observe a decline in sprinting velocity over the age range measured. However, in contrast to men, few female players continue performing at a high level after their late 20s, so potential declines in sprint performance with age tend to be preceded by retirement.

Similar findings were observed in statistics from Norwegian athletics as for the girls in this study. Female sprinters and long jumpers improved their performance level from 13 to 17 years of age before plateauing, while corresponding male athletes achieve their peak performance level several years later.²⁵ Speed and CMJ stagnation in the midteens is a challenge not only for women's soccer but for women's sport in general. Players in the age group 18 to 19 years were heavier than the <18-years category ($P = .030$; Table 1) in this study. Increased body weight might contribute to the failure of continued training to result in improved sprint velocity and power performance. According to the Norwegian elite-series team coaches, their very best players mostly keep participating in soccer after 23 to 24 years of age. This selection bias may mask a small decline in sprinting and power performance already occurring in the mid-20s among women.

Time Period

This study demonstrates a moderate but positive development in 0- to 20-m sprinting velocity for the national-team players over time. Players from 2006–2010 ran 2% faster over 0 to 20 m than those from 1995–1999. This difference was equal to the corresponding CV (Table 3). Only small differences were observed for 20- to 40-m velocity. No studies have so far monitored world-class soccer players' physical characteristics in the long term. The time-period analysis was restricted to national-team athletes, and all of these athletes were tested across time periods as a part of routine testing procedures. Therefore, the difference observed cannot be explained by a selection bias. Instead, we hypothesize that this provides some evidence for the contention that international female performers have become faster over time. It is interesting that our data showed no development in CMJ height during the corresponding time periods. We are not aware of studies reporting development in short sprinting distances without development in CMJ ability. Our results remained

consistent even when only athletes who performed both sprint and CMJ testing were considered. These findings indicate that sprint and vertical jump are specific and independent qualities.

Sprint and CMJ Relationship

Table 4 demonstrates the relationship between sprint and CMJ ability within each category in the current study. Overall, most of the correlation values reported were in the range of moderate to very large. Best sprint and CMJ performance occurred on different testing days for ~10% of the athletes. In theory, this might decrease the magnitude of the correlations. Our findings are in accordance with those of similar investigations performed on male soccer players,^{2,26} rugby players,²⁷ and female high school and college athletes.²⁸ The coefficient of determination between our sprint and CMJ data was mainly between .3 and .5. Variables should be considered specific and independent of each other when the coefficient of determination is less than .50.²⁹ Equally performing players on the 40-m-sprint test in this study differed by as much as 10 to 12 cm on the CMJ test. Salaj and Markovic³⁰ suggest that vertical and horizontal acceleration characteristics should be tested separately.

Bissas and Havenetidis³¹ and Kale et al³² reported drop-jump height as an even better predictor for maximal sprint running than other vertical- and horizontal-jump tests. Considering contact time on the ground, CMJ represents only the first 2 or 3 strides of a maximum sprint. A drop-jump test incorporates aspects of muscle elasticity and stiffness, with very short ground-contact times more similar to sprint-running conditions.

Because testing order was always sprinting followed by jumping tests, jumping performance might have been compromised by fatigue. However, athletes only performed 2 or 3 full 40-m sprints and had good recovery time before jump testing, so we do not think this influenced the results appreciably.

Practical Applications

In the current study, there was a strong relationship between sprinting skills and performance level, supporting the notion that linear sprinting velocity is an important performance factor in female soccer. Moderate to large performance differences among playing-position groups indicate that individual physical capacity is an important part of tactical dispositions within the team. Based on the smaller between-groups differences in CMJ height in this investigation, it is tempting to claim that speed is more important than vertical-jump ability in female soccer, except for goalkeepers. Soccer players have many qualities to develop, and coaches should consider sprinting velocity within the larger skill set of soccer. Selection of players, testing, and physical conditioning of the athletes should be reflected by the importance of speed. Future research should focus more on the relationship between physical demands of the game, capacity profiles among

players, and consequences of long-term planning of individual fitness programs in female soccer.

Conclusion

This study provides effect-magnitude estimates for the influence of performance level, player position, and age on sprint and CMJ performance in female elite soccer. There was a moderate but positive development in 0- to 20-m sprinting velocity among elite performers over time, whereas CMJ performance remained stable.

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Note. This article will be published in a forthcoming issue of the *International Journal of Sports Physiology and Performance*. The article appears here in its accepted, peer-reviewed form, as it was provided by the submitting author. It has not been copyedited, proofread, or formatted by the publisher.

Section: Brief Review

Article Title: The Role and Development of Sprinting Speed in Soccer

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Journal: *International Journal of Sports Physiology and Performance*

Acceptance Date: August 15, 2013

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Abstract

The overall objective of this review was to investigate the role and development of sprinting speed in soccer. Time motion analyses show that short sprints occur frequently during soccer games. Straight sprinting is the most frequent action prior to goals, both for the scoring and assisting player. Straight line sprinting velocity (both acceleration and maximal sprinting speed), certain agility skills and repeated sprint ability are shown to distinguish groups from different performance levels. Professional players have become faster over time, indicating that sprinting skills are becoming more and more important in modern soccer. In research literature, the majority of soccer related training interventions have provided positive effects on sprinting capabilities, leading to the assumption that all kinds of training can be performed with success. However, most successful intervention studies are time consuming and challenging to incorporate into the overall soccer training program. Even though the principle of specificity is clearly present, several questions remain regarding the optimal training methods within the larger context of the team sport setting. Considering time-efficiency effects, soccer players may benefit more by performing sprint training regimes similar to the progression model used in strength training and by world leading athletics practitioners, compared to the majority of guidelines that traditionally have been presented in research literature.

Introduction

Performance in soccer depends upon a variety of individual skills and the interaction among different players within the team. Technical and tactical skills are considered to be predominant factors, but physical capabilities must also be well developed in order to become a successful player. During the last decade, the focus in soccer-related research literature has shifted from aerobic to anaerobic demands. Recent studies suggest that elite or professional players have become faster over time, while aerobic capacity has plateaued or decreased slightly.¹⁻³ While the physiology of soccer has been well explored, several aspects regarding the role and development of sprinting speed remain unclear. The aim of this review is three fold: 1) to synthesize the research that has been undertaken so far regarding the role and development of sprinting speed in professional soccer, 2) identify methodological limitations and concerns associated with these investigations, and 3) outline specific training recommendations. Hopefully, this review can contribute to improve best practice regarding sprint conditioning of soccer players.

Literature search

The databases of PubMed and SPORTDiscus were used to search for literature. For scientific studies, only peer-reviewed articles written in English were included. The search was conducted in two levels; type of sport and type of athlete. Regarding the first level, the terms “soccer” and “football” were used. In order to narrow the search, studies including the terms “American football”, “Australian football”, “Australian Rules football”, “Gaelic football”, “rugby” and “futsal” were excluded. Secondly, to ensure that the involved players were of a certain playing standard, the search was restricted to > 16 yr athletes categorized as “elite”, “professional”, “high level”, “top class”, “first division”, “upper division”, “top level”, “high class”, “high standard” or “national team”. Only the studies who investigated

the role or development of sprinting skills in soccer were included. In addition, the reference lists and citations (Google Scholar) of the identified studies were explored in order to detect further relevant papers. To ensure updated sprinting demands, test results reported before the year 2000 were excluded. In order to restrict the total number of references, only the most recent studies were referred when multiple investigations reported identical findings.

Sprinting demands during match play

A large number of soccer players from the best European soccer leagues have been analyzed according to motion during match play. Data are commonly generated by either semiautomatic video analysis systems or global positioning systems (GPS). The analyses show that both male and female outfield soccer players cover 9-12 km during a match.⁴⁻⁹ Of this, 8-12 % is high intensity running or sprinting.^{4,6,8,9} Wide midfielders and external defenders perform more high intensity running and sprinting compared to the other playing positions.^{5,6} Reported peak sprint velocity values among soccer players are 31-32 km·h⁻¹.^{6,7} Number of sprints in the range 17-81 per game for each player has been reported,^{4,5,9} Mean sprint duration is between 2 and 4 s, and the vast majority of sprint displacements are shorter than 20m.^{4,8,9} The varying estimates of sprints reported is likely due to varying intensity classifications, as different running velocities (18-30 km·h⁻¹) have been used to distinguish sprint from high speed running. It is important to note that running speed in the range 20-22 km·h⁻¹ is equivalent to the mean velocity in male elite long distance running, and mediocre sprinters run faster than 35 km·h⁻¹. Therefore, definitions based upon absolute velocity are methodologically problematic in terms of validity and reliability, in addition to limiting comparisons across studies. Furthermore, absolute speed values exclude short accelerations from analysis. Players perform 8 times as many accelerations as reported sprints per match, and the vast majority of these accelerations do not cross the high-intensity running threshold.¹⁰ Thus, high intensity running and sprinting undertaken may be

underestimated.^{10,11} Measuring methods that capture accelerations would markedly strengthen game analyses.

To date, no full game analyses have quantified the movement patterns of intense actions across playing level or positions in terms of sharp turns, rotations, change of direction, etc. with and without the ball. However, Faude et al. have used visual inspection to analyze videos of 360 goals in the first German national league.¹² They reported that the scoring player performed straight sprints prior to 45 % of all analyzed goals, mostly without an opponent and without the ball. Frequencies for jumps and change-in-direction sprints were 16 and 6 %, respectively. Straight sprinting was also the most frequent action for the assisting player, mostly conducted with the ball.

Sprinting characteristics of soccer players

Straight line sprinting skills

In research literature, straight line sprinting is commonly categorized as acceleration, maximal running velocity and deceleration. Since game analyses have shown that more than 90 % of all sprints in matches are shorter than 20 m, acceleration capabilities are obviously important for soccer players in this context.⁹ However, the importance of peak velocity increases when sprints are initiated from a jogging or non-stationary condition. Practically all soccer related studies have used testing distances in the range 5-40 m. Since sprint performance differences that separate the excellent from the average are relatively small on an absolute scale, and the effects of training interventions are even smaller, valid and reliable timing and test procedures are critical. Haugen et al. demonstrated that the starting method and timing system used can combine to generate differences in “sprint time” up to 0.7 s.¹³ Thus, the method of sprint timing used can result in greater differences in sprint time than several years of a conditioning training program. Time differences can be explained by

inclusion or exclusion of reaction time, center of gravity placement at time triggering and horizontal center of gravity velocity at time triggering.¹³ Furthermore, footwear, running surface, wind speed and altitude can generate further time differences over short sprints.¹⁴⁻¹⁶ A review of published studies monitoring speed performance reveals considerable variation and/or insufficient information regarding timing methods, hardware manufacturers, testing procedures and method of reporting (i.e. best sprint vs. mean sprint time of several trials). It is therefore important to describe the methodological sprint test approach as detailed as possible.

Several studies have concluded that mean sprinting velocity (both acceleration and maximum sprint capacity) distinguishes soccer players from different standards of play.^{1,17-19} Sprint time comparisons across studies based on available correction factors for time initiating/starting procedures,¹³ wind,¹⁶ footwear and running surface,¹⁴ indicate that professional players from the best European soccer leagues sprint slightly faster than professional soccer players from lower ranked soccer nations.^{1,19,20} We calculate that the fastest soccer players are ~ 0.6 s slower than the world's fastest sprinters over 40 m.^{1,21} However, individual test results from recent studies have shown that the very fastest male soccer players may achieve 40-m sprint times on par with 60-m sprint finalists from national athletics championships.^{1,13,14}

In practical terms, individual differences in sprinting skills are even more critical than mean differences among groups of players. Database material from the Norwegian Olympic Training Center, including 40-m sprint tests of 628 male and 165 female elite players between 1995 and 2010,^{1,18} shows that the 75th -25th percentile difference is 0.13 and 0.16 s over 20 m sprint for male and female players, respectively (Table 1). Based on average velocity over the distance, the fastest quartile is at least 1 m ahead of the slowest quartile over 20 m. Similarly, the 90th -10th percentile difference over 20 m sprint is equivalent to more

than 2 m. Furthermore, the 10 % fastest players run 1 m further than the 10 % slowest players for each second during peak sprinting. According to Hopkins et al., the smallest worthwhile performance enhancement/change in team sport is 0.2 of the between-subject standard deviation.²² Based on the present database material, this corresponds to ~0.02 s over 20-m sprint, which is quite similar to typical variation associated with sprint testing (CV 1-1.5 %).^{13,14} In practical settings, a 30-50 cm difference (~0.04-0.06 s over 20m) is probably enough in order to be decisive in one-on-one duels by having body/shoulder in front of the opposing player. Thus, the ability to either create such gaps as an attacker or close those gaps as a defender can be fundamental to success in elite level soccer. The chance of dribbling an opponent out of position, or successfully defending an attack, increases with greater acceleration and sprinting ability.

While sprint velocity for males peaks in the age range 20-28 yr, with small but significant decreases in velocity thereafter, female soccer players struggle to improve their sprinting skills after their teens.^{1,18,23} Increased non-lean body mass might contribute to the failure of continued training to result in improved sprint velocity and power performance among female players.

The majority of sprint test results shows that forwards are faster than defenders, midfielders and goalkeepers, respectively.^{1,18,24-26} Similar relationships are observed among youths, suggesting selection processes in early junior talent development as a possible explanation for the rank of speed pattern among playing positions.²⁷ However, sprinting ability can also be seen in relationship to the physical demands of the different positions on the field. Forwards and defenders are perhaps the fastest players because they are involved in most sprint duels during match play.^{5,6} Players in different positions should therefore prioritize different physical conditioning regimes in order to solve positional dependent tasks during play.

Agility

During the last decade, several authors have emphasized the importance of agility skills in soccer. Agility was originally defined by Clarke as “speed in changing body positions or in changing direction”.²⁸ More recently, Sheppard & Young defined agility as “a rapid whole-body movement with change of velocity or direction in response to a stimulus,” based on the conception that agility has relationships with both physical and cognitive components.²⁹ The vast majority of agility tests in soccer are designed to evaluate the physical qualities of the players, without cognitive (i.e. choice reaction) challenges. Zig zag runs, 90-180° turns, shuttle runs, sideways, and backwards running with maximal intensity are commonly used drills. Agility patterns may vary as a function of playing role, and Sporis et al. suggested different tests for different positions.³⁰ Published agility tests do not reflect the nature of deceleration and turning performed during elite soccer matches. In fact, the vast majority of turning movements are initiated from a stationary or jogging condition, while change-in-direction within sprinting movements rarely occur.³¹

Marcovic reported a poor relationship between strength and power qualities and agility performance.³² Little & Williams and Vescovi et al. concluded that straight sprint, agility and vertical jump capabilities are *independent* locomotor skills.^{33,34} This is demonstrated on the YouTube video of Cristiano Ronaldo racing against the Spanish 100 m champion, Angel David Rodriguez (<http://www.youtube.com/watch?v=hZqEj-Qyg6U>). Ronaldo lost by 0.3 s over 25 m straight sprint, but won by 0.5 s when running in a zig zag course over the same distance.

Several studies have reported that professionals or elite players have better agility skills compared to players of lower standard.^{19,35-37} However, Rösch et al. found no differences across a broad range of playing standard.³⁸ The literature is equivocal regarding agility performance across playing positions.^{24,26,30} Interestingly, midfielders perform

relatively better in agility tests compared to linear sprint tests. The literature also suggests that when change-of-direction is preceded by braking from a nearly full sprint, the agility difference across position categories shrinks. In classical mechanics, the kinetic energy of a non-rotating object of mass m travelling at a speed v is $\frac{1}{2}mv^2$. Thus, faster players with more body mass must counteract a larger kinetic energy during sharp turns while sprinting. Since midfielders in general have lower body mass and lower peak sprinting speed,^{1,25} it is reasonable to expect smaller performance differences in certain agility tests compared to linear sprint tests.

Timing of ground reaction forces, body configuration and center of gravity placement are crucial biomechanical elements when changing direction while sprinting. By lowering the center of gravity while changing direction, the involved lower extremity muscles can work under more optimal conditions. By leaning the upper body towards the intended direction during turns, combined with foot placement in the opposite intended running direction away from the vertical center of gravity-line during ground contact, more kinetic energy can be counteracted. Correct technique during change-in-direction movements is also important from an injury prevention perspective.

Repeated sprint ability

Repeated sprint ability (RSA) is the ability to perform repeated sprints with brief recovery intervals.³⁹ In recent years, this topic has received increasing attention as a central factor in most field-based team sports. Numerous field tests have been developed to evaluate RSA. Sprint distances of 15-40 m x 3-15 repetitions have been used in elite or professional soccer, and the vast majority of tests have included 15-30 s recovery periods between sprints (Table 2). Several tests have combined agility and repeated sprints.⁴⁹⁻⁵³

Primarily two measures have been used in order to evaluate RSA: total time and/or deterioration in performance. Total time or mean sprint time have been used as performance

indices, and results from RSA tests have been shown to differentiate professionals from amateur players.^{7,43,49,51} Deterioration in performance, calculated as sprint decrement, has generally been used to quantify the ability to resist fatigue during such exercise.⁵⁸ Fatigue resistance depends upon a wide range of physiological factors, mostly related to aerobic metabolism, and athletes with a higher $\text{VO}_{2\text{ max}}$ have smaller performance decrements during repeated sprint exercise.⁴² This is most likely explained by the linear relationship between PCr resynthesis and mitochondrial capacity within muscle.⁵⁹ A full review of the physiological mechanisms related to RSA is beyond the scope of this review, but this topic is well described elsewhere.⁶⁰

The outcome and usefulness of the repeated sprint tests has been questioned over the years. Insufficient timing information and variations in testing protocols complicate comparisons across studies. Based on the short recovery periods between each sprint, most RSA test protocols simulate the most intensive game periods, leading to a possible overrating of the aerobic demands. Pyne et al. reported that total time in a RSA test was highly correlated with single sprint performance and concluded that RSA was more related to short sprint than endurance capacity.⁶¹ In order to detect the “sprint endurance” component, repeated sprint test protocols with higher total volume is perhaps required. According to Balsom et al., it is more difficult to detect detrimental effects with shorts sprints (15 m) compared to slightly longer sprints (30-40 m).⁶² Medical data derived from American football indicate that extensive sprint testing/training without prior gradual progression increases the risk of hamstring injuries.⁶³ This is perhaps why most repeated sprint test protocols are designed with a relatively small total volume of sprinting.

Training to improve sprint performance

Soccer related intervention studies

In research literature, the majority of interventions involving soccer players have provided positive effects, leading to the assumption that all kinds of training can be performed with success. A plausible explanation is that the majority of studies have been performed on young players (16-18 yr). Less experience with physical conditioning provides more potential for stimulating positive effects. A well-trained professional soccer player can be considered untrained in terms of sprint training. When evaluating research literature, it is important to keep in mind that successful interventions vary in terms of training time investment, and time consuming interventions will probably be rejected by team coaches. A great deal of knowledge can be gathered from non-successful conditioning programs as well, which so far are underrepresented in research journals. With these considerations in mind, we have tried to identify criteria for success in order to improve soccer related sprinting skills. Future research regarding dosing strategies should be designed to validate these recommendations.

Principles of sprint training in soccer

Specificity: A review of published sprint intervention studies on soccer players confirms the principle of specificity. Short sprint training (sprinting distance ≤ 30 m) improves short sprint ability,⁶⁴ while longer sprints (~ 40 m) improves maximal sprint velocity.⁵⁵ Prolonged sprints (≥ 30 s) have limited effects on acceleration or peak velocity.⁶⁵ Linear sprint training does not improve performance in sprints with changes of direction.^{56,66} Agility training improves the specific agility task performed during practice.⁵⁶ Repeated sprinting improves RSA.^{50,55,67} The superiority of resisted or assisted sprint training compared to normal sprinting has so far not been clearly established.^{64,68}

Several “less specific” training forms have also been explored in order to improve sprinting skills of soccer players. Contrast training (combination of strength, power and sport specific drills) has provided positive effects on soccer-specific sprint performance,^{69,70} but twice weekly training sessions do not seem to be more beneficial than one weekly session.⁷¹ Plyometric training interventions have so far provided limited effects on soccer players’ sprint performance.⁷²⁻⁷⁴ Furthermore, strength training with heavy weights does not consistently improve sprinting capabilities.⁷⁵⁻⁷⁷ Sedano et al. stated that improved explosive strength can be transferred to acceleration capacity, but a certain time is required for the players in order to transfer these improvements.⁷³ Kristensen et al. recommend normal sprinting over other training forms in order to obtain short distance sprinting improvement in a short period of time.⁷⁸

Several authors have reported that a combination of high-intensive interval training and heavy strength training have enhanced sprinting performance in soccer players.^{54,79,80} These interventions are extensive and time consuming, as they include at least 4 weekly training sessions. Some authors recommend high-intensive aerobic interval training (80-90 % of $VO_{2\max}$) in addition to repeated sprint in order improve RSA.^{20,60,81} However, Ferrari Bravo et al. demonstrated that repeated sprint training was superior to high-intensity aerobic interval training in terms of aerobic and soccer specific training adaptations.⁵⁰ Tønnessen et al. showed that elite soccer players were able to complete repeated sprints with intensity closer to maximum capacity after repeated sprint training once a week, without additional high-intensive intervals.⁵⁵ Even though the principle of specificity is clearly present, sprinting skills in soccer may be improved in several ways.

Individualization: Unfortunately, most interventions in sport science are limited to answering typical one-dimensional questions, more specifically whether certain types of training are more effective than others. In practice, however, coaches are concerned with

three dimensions; 1) what kind of training should be performed, 2) by which individuals, 3) at what time point in the season. Similar to medical consultations, a broad range of performance factors should be tested and evaluated before necessary treatment is prescribed.

Capacity profiles are essential in order to diagnose each individual and develop training interventions that target the major limiting factors. We were somewhat surprised by the relatively small differences in physical skills across playing positions in Norwegian professional soccer, as goalkeepers and midfielders showed practically identical values for vertical jump performance (~ 2 cm difference) and $\text{VO}_{2\text{ max}}$ (only ~ 5 ml difference).^{1,2}

Logistically, individualized training of physical capacity is demanding to organize in a team sport setting. This is probably a greater problem in high-level female and youth soccer, where team staff is smaller compared to male professional teams. In such cases, most soccer coaches perform similar training for all outfield players within the team, despite large individual differences in capacity profiles. However, it is unlikely that similar training doses lead to similar responses for players belonging to opposing extremes. Surprisingly, there has been little research about how individual capacity profiles can be developed in team sports. The data presented in table 1 can form a basis for capacity profiles for linear sprinting skills, but similar profiles should also be developed for agility, RSA and other soccer related capabilities.

Familiarization, progression and periodization: Sprinting is the most frequent mechanism associated with hamstring injuries, and age/previous injuries are the most important risk factors.⁸² About 17 % of all injuries in soccer are hamstring injuries, and more than 15 % of all hamstring injuries are reported as re-injuries.⁸² Players that have not been fully rehabilitated following sprint-related injury, or who have had such injuries during the previous weeks, should be particularly cautious. Many hamstring injuries occur during the short pre-season period because of the relative deconditioning that occurs in the off-season.⁶³

Thus, during the initial weeks of a sprint training program there should be a gradual familiarization, both in terms of intensity and the number of sprint repetitions. Somewhat surprisingly, we have not identified progression or periodization models regarding sprint training in the research literature. In contrast, a classic linear model of periodization is well established in strength training research. This is characterized by high initial training volume and low intensity. During the training cycle, volume gradually decreases and intensity increases.^{83,84} This periodization model is similar to the sprint training philosophy developed by athletic sprint pioneer coach Carlo Vittori in the mid-1970s.⁸⁵ Pre season conditioning for his athletes was initiated with short sprints at low intensity. As training progressed, the intensity and/or total volume gradually increased in order to improve alactic capacity. To the author's knowledge, Vittori first published the repeated sprint training-method (at that time termed “speed endurance training”). He was national team sprint coach and personal coach to Pietro Mennea, Olympic gold medalist in 1980 and former world record holder for the 200 meter. Recently, we have performed sprint training interventions with a similar progression model.^{55,67} These studies have provided positive and time-efficient effects on soccer-related sprinting skills. Further studies are warranted in order to establish progression and periodization models for sprint development.

Integration of sprint training: According to acknowledged practitioners in soccer, physical conditioning of players must be integrated with the remaining soccer-specific training.⁸⁶ It is important to keep in mind that playing soccer is an important contribution to the overall fitness level of the players. Sporis et al. reported that starters developed sprinting skills to a higher level compared to non-starters.⁸⁷ Successful off-field interventions will not automatically be accepted by the soccer coaches. It is therefore essential that the small amount of time available for physical training is used effectively. Hoff et al. demonstrated

how aerobic endurance training can be integrated into soccer specific training,⁸⁸ and a similar approach should also be used in order to improve sprinting skills.

Physical coaching expertise: Research has highlighted the importance of direct supervision in order to obtain optimal training outcomes.⁸⁹ Coaching centers to a larger degree on continually evaluating and making adjustments to the training process. In research related intervention studies, such opportunities are limited due to issues of standardization and validation. However, sprinting skills are heavily dependent upon technical elements, increasing the needs of feedback during practice. Continuous presence of a physical conditioning expert probably increases the odds for a more successful outcome in soccer.

Essential loading factors

Intensity: To the authors` knowledge, the vast majority of soccer studies make no other recommendations than that sprint velocity should be maximal throughout. However, recent studies of soccer players and track & field athletes have shown that 40 m linear sprint performance is significantly reduced already after 3-4 maximal repetitions.^{13,14} Thus, the intensity (calculated as percentage of maximal sprint velocity) should perhaps be reduced in order to complete a higher number of repetitions during practice. The lowest effective sprinting intensity for stimulating adaptation is so far not established in research literature. Successful sprint coaches have performed sprint training sessions with an intensity as low as 90 % during the initial pre-season conditioning.⁸⁵ Recent successful intervention studies have revealed that most soccer players through gradual progression are capable of completing at least twenty 40-m sprint repetitions with intensity >95 %.^{55,67} Future randomized controlled trial studies should explore the impact of different sprinting intensities. In strength training literature, greater loading/intensity is needed for 1RM improvements as one progresses from untrained to more advanced levels of training.^{90,91}

Recoveries: Recovery duration between repetitions and sets is one of the most important variables in manipulating the training intensity. Shorter recovery time forces lower intensity per sprint repetition. The longer the recoveries, the more repetitions can be completed at a high intensity. Balsom et al. found that when soccer players ran 15x40 m at maximal intensity, separated by 30 s recovery, the performance drop-off was 10 %. However, when the same training was performed with either 60 or 120 s recovery, the performance drop-off was reduced to 3 and 2 %, respectively.⁶² To date, no studies have investigated the effect of recovery duration during sprint training on soccer related sprinting skills. In strength training research, long-term studies have shown greater maximal strength improvements with long (2-3 min) versus short (30-40 s) recovery periods between sets.^{92,93}

Sprint training frequency: Recent sprint training regimes conducted on elite soccer players have shown positive effects following sprint training as little as once a week.^{55,67} The question remains whether even greater effects would have occurred with more frequent training sessions. No studies have so far compared the effects of different sprint training frequencies. If a greater number of sprint training sessions per week results in only marginally better training effects, it is likely that the majority of soccer coaches would choose to implement only one session per week. This is in order to reduce the risk of injury, in addition to allowing more time for soccer-specific training.

Season time considerations: Dupont et al. reported positive training effects after repeated sprint training in-season.²⁰ Other studies suggest that the largest effects are seen when sprint training is conducted in the off-season or early pre-season.^{55,56,67} Soccer specific training contributes to maintaining RSA gained during pre-season training. Sprinting ability depends to a large degree on the athlete being well rested and is therefore difficult to combine with other forms of training. This is particularly relevant in soccer, which is driven primarily by aerobic metabolism. Recently, we had to abort an intervention study performed at the end

of pre-season and season start due to drop-out issues caused by injuries. Future intervention studies should report the number of injuries sustained during the intervention period, alongside any potential training effects, as this is equally important in soccer.

In summary, sprinting ability in soccer is regulated by a complex interaction of multiple factors. Our understanding of this interaction is far from complete, a reality that is likely part of the reason that intuition, experience and tradition carry so much weight in the training and coaching of elite athletes. Conditioning programs should be ideally be focused on closing the gap between the positional demands of play and actual individual capacity. Several questions remain regarding optimization of training methods, and it is reasonable to believe that there is a gap between science and best practice regarding sprint development of soccer players. We believe that future studies regarding this topic should be based upon progression models and program design recommendations from scientific strength training literature, as this research field is much more developed per se.

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Table 1. Percentiles (PCTL) of split times, peak velocity (PV) and countermovement jump (CMJ) for male professionals and female elite soccer players.

PCTL	Males (n=628/411 for sprint/CMJ)						Females (n=165/165 for sprint/CMJ)					
	10m (s)	20m (s)	30m (s)	40m (s)	PV ($m \cdot s^{-1}$)	CMJ (cm)	10m (s)	20m (s)	30m (s)	40m (s)	PV ($m \cdot s^{-1}$)	CMJ (cm)
99	1.40	2.58	3.65	4.69	9.71	52.1	1.55	2.86	4.10	5.30	8.55	41.0
95	1.42	2.61	3.70	4.77	9.43	47.0	1.57	2.90	4.13	5.34	8.33	37.3
90	1.44	2.64	3.75	4.84	9.30	45.2	1.59	2.93	4.15	5.41	8.20	35.4
75	1.48	2.70	3.82	4.92	9.10	42.0	1.64	3.00	4.29	5.54	7.94	32.7
50	1.52	2.76	3.91	5.04	8.81	38.7	1.69	3.08	4.37	5.69	7.65	29.4
25	1.56	2.83	4.00	5.17	8.55	35.7	1.72	3.16	4.53	5.86	7.40	26.8
10	1.60	2.89	4.08	5.26	8.36	33.3	1.79	3.23	4.64	6.02	7.19	24.5

Note: For the sprint tests, a floor pod placed on the start line was used for time initiation.

Table 2: Repeated sprint field test protocols [sets x (repetitions x distance)] used on elite or professional soccer players >16 yrs ranged according to total sprinting distance (TSD) during the test. Recovery is reported as time between each sprint.

Study	Test protocol	TSD (m)	Recovery (s)
Krustrup et al. ⁴⁰	1x(3x30m)	90	25
Gabbett ⁴¹	1x(6x20m)	120	< 15
Aziz et al. ⁴²	1x(6x20m)	120	20
Aziz et al. ⁴³	1x(8x20m)	160	20
Mujika et al. ⁴⁴	1x(6x30m)	180	30
Dellall et al. ⁴⁵	1x(10x20m)	200	25
Dupont et al. ⁴⁶	1x(7x30m)	210	20
Chaouachi et al. ⁴⁷	1x(7x30m)	210	25
Meckel et al. ⁴⁸	1x(6x40m)	240	~ 25
Meckel et al. ⁴⁸	1x(12x20m)	240	~ 17
Impellizzeri et al. ⁴⁹⁻⁵¹	1x(6x20+20m)	240	20
Bangsbo et al. ^{52,53}	1x(7x34.2m)	240	20-25
Wong et al. ⁵⁴	1x(9x30m)	270	25
Tønnessen et al. ^{55,56}	1x(10x40m)	400	60
Dupont et al. ²⁰	1x(15x40m)	600	25
Little & Williams ⁵⁷	1x(15x40m)	600	~ 8-12
Little & Williams ⁵⁷	1x(40x15m)	600	~ 20-30



Not quite so fast: Effect of training at 90% sprint speed on maximal and repeated sprint ability in soccer players

Journal:	<i>International Journal of Sports Physiology and Performance</i>
Manuscript ID:	Draft
Manuscript Type:	Original Investigation
Keywords:	physical fitness, physical performance, training, exercise physiology, exercise training, fitness

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1 **Not quite so fast: Effect of training at 90% sprint**
2 **speed on maximal and repeated sprint ability in**
3 **soccer players**

4

5 *Sprint training in soccer players*

6

7 This is an original investigation with 3 tables and 4 figures. The
8 abstract consists of 186 words and the text 3453 words.

9

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16

17 "This manuscript has been read and approved by all the listed co-
18 authors and meets the requirements of co-authorship as specified in
19 the Human Kinetics Authorship Guidelines. This manuscript is
20 original and not previously published, nor is it being considered
21 elsewhere until a decision is made as to its acceptability by the
22 IJSPP Editorial Review Board."

23

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31

32 **Abstract**

33 **Purpose:** The aim of the present study was to investigate the effect
34 of training at an intensity eliciting 90 % maximal sprinting speed
35 on maximal and repeated sprinting performance in soccer. We
36 hypothesised that sprint training at 90% of maximal velocity would
37 improve soccer related sprinting skills. **Methods:** Twenty-two
38 soccer players (age 17±1 yr, body mass 64±8 kg, body height
39 174±8 cm) completed an intervention study where the training
40 group (TG) replaced one of their weekly soccer training sessions
41 with a repeated sprint training session performed at 90% of
42 maximal sprint speed, while the control group (CG) completed
43 regular soccer training according to their teams` original training
44 plans. Countermovement jump, 12x20 m repeated sprint, $VO_{2\max}$
45 and the Yo-Yo Intermittent Recovery 1 test were performed prior
46 to and after the 9 week intervention period. **Results:** No significant
47 between group differences were observed for any of the
48 performance indices, and effect magnitudes were trivial or small.
49 **Conclusions:** Before rejecting the hypothesis, we recommend that
50 future studies should perform intervention programs with either
51 stronger stimulus or at other times during the season where total
52 training load is reduced.

53

54 **Key words:** repeated sprint ability; sprint conditioning; sub-
55 maximal sprint

56

57 **Introduction**

58 Sprint speed is a crucial performance factor in soccer. A review of
59 published studies reveals that no specific training method has
60 emerged as superior.¹ Typical loading factors in sprint training
61 such as exercise mode, distance, repetitions and recovery periods
62 are well explored, but available research is surprisingly lacking in
63 terms of training intensity. The vast majority of studies involving
64 sprint training interventions for soccer players make no other
65 recommendation than that sprint velocity should be maximal for
66 every repetition.¹ In contrast, available evidence in endurance
67 training and strength training demonstrates that high, but sub-
68 maximal intensity loading effectively stimulates adaptation
69 through the interaction between high intensity and larger
70 accumulated work that can be achieved before onset of fatigue,
71 compared to maximal efforts.^{2,3} This makes it tempting to
72 speculate similar effects on sprinting.

73 Maximal sprinting is the most frequent mechanism associated with
74 hamstring injuries in soccer.⁴ According to Elliott et al.⁵, many
75 hamstring injuries occur during the short pre-season period
76 because of the relative deconditioning that occurs in the off-season.
77 Thus, during the initial weeks of a sprint training program there
78 should be a gradual familiarization, both in terms of intensity and
79 the number of sprint repetitions. Anecdotal evidence in support of
80 this is observed in the sprint training philosophy developed by
81 athletic sprint pioneer coach Carlo Vittori in the mid-1970s.⁶ His
82 successful athletes performed repeated sprint training sessions with
83 an intensity as low as 90% of maximal sprint intensity during the
84 initial pre-season conditioning. The lowest effective sprinting
85 intensity for stimulating adaptation is so far not established in the
86 research literature. The aim of the present study was therefore to
87 investigate the effect of training at an intensity eliciting 90%
88 maximal sprinting speed on maximal and repeated sprinting
89 performance in soccer. We hypothesised that a relatively large
90 repetition load of sprints at 90% of maximal velocity would
91 improve soccer related sprinting skills.

92 **Material and methods**

93 **Experimental approach to the problem**

94 In this randomized controlled trial, the control group (CG)
95 completed regular soccer training according to their teams' original
96 training plans, while the training group (TG) replaced one of their
97 weekly soccer training sessions with a repeated sprint training
98 session performed at 90% of maximal sprint speed. The duration of
99 the intervention period was nine weeks. Results from soccer
100

101 specific physiological test results were compared before and after
102 the intervention period.

103

104 **Subjects**

105 Twenty-five male and female soccer players (17 ± 1 yrs)
106 volunteered to participate. They were students at a local high
107 school/academy which included a soccer specialization
108 programme. Norwegian high school programs are 3 years in
109 duration and equivalent to years 11 to 13 of formal education.
110 Eleven players were in the first year, 10 in the second and 4
111 players in their third year. All athletes were playing in the highest
112 junior division level for different clubs in Norway. They performed
113 four weekly soccer training sessions during school hours, while the
114 remaining sessions and games were performed with each subject's
115 club in the afternoon and/or at weekends. In athletes' regular
116 soccer training, warm up consisted of short passing or coordination
117 exercises with the ball, followed by more intensive exercises such
118 as cuts, moves, turns and feints with or without ball. Main soccer
119 practice was mostly performed as either small-, medium- or large-
120 sided games (3 vs. 3 to 11 vs. 11). Technical elements were
121 focused during small-sided practice, while tactical
122 drills/formations were emphasized during medium- and large-sided
123 practice. During the intervention period, participants were
124 requested to refrain from performing any other off-field physical
125 training regimes in terms of speed, strength and/or endurance.
126 None of the athletes had previous experience with specialized
127 repeated sprint training. The study was approved by the human
128 subjects review committee of the Faculty for Health and Sport,
129 University of Agder. All participants gave their written voluntary
130 informed consent (parental consent also provided for <18 yrs
131 players) before participation according to the declaration of
132 Helsinki.

133 Gender and age information were used to pair match subjects for
134 gender and grade level. Subject pairs were then randomized to
135 either TG or CG by a co-author not directly involved in testing or
136 the training intervention. TG subjects were required to complete at
137 least 7 out of 9 training sessions during the intervention period in
138 addition to all performance tests in order to be included. CG
139 subjects were required to perform at least 80% of planned sessions
140 and complete all pre- and post tests. Two participants from TG and
141 one from CG dropped out due to acute knee or ankle injuries
142 sustained during soccer practice or matches. Final group sizes were
143 13 in TG and 9 in CG. Physical and training characteristics (11
144 male, 11 female) are presented in Table 1. Frequency and volume

145 of games and training sessions were consistent throughout the
146 entire intervention period.

147

148 (Table 1 about here)

149

150 **Procedures**

151 Pre- and post tests were conducted at Norwegian Olympic Training
152 Centre on two separate days, with two days in between. All

153 participants completed the tests in the same order and at the same
154 time of day. Regarding nutrition, hydration, sleep and physical

155 activity, the athletes were instructed to prepare themselves as they
156 would for a regular soccer match, including no high intensity

157 training the last two days before testing. They were instructed to
158 use identical footwear and outfit for each of the tests. Test day one

159 consisted of CMJ test, 12x20m repeated sprint test and VO_{2max} test.
160 On test day two, the athletes completed Yo-Yo IR1 test.

161 Participants were familiarized with CMJ, sprint and Yo-Yo IR1
162 procedures through bi-annual or annual testing that their high

163 school/academy performed for training purposes. Athletes were not
164 specifically familiarized with the VO_{2max} test, but they were all

165 familiar with treadmill running at higher intensities.

166 Participants completed a 25 min standardized warm-up consisting
167 of 10 min jogging at 50–70% of HR_{max} on a treadmill, followed by

168 3 sets of 4 exercise drills (high knees, back kick, sideway and
169 backwards running) and finally 3–4 repetitions of 40m runs with

170 progressive speed increase. Then the athletes performed three trials
171 of CMJ with 45 – 60 s recovery in between. Best result for each

172 player was retained for analysis. Setup and procedures are

173 described in Haugen et al.⁷ A 12x20 m repeated sprint test with
174 start each 60 s was performed after the CMJ test. Distance and

175 recovery were chosen in line with mean frequency and typical
176 distance of all-out sprints reported from match analyses.^{8,9} Dual

177 beamed timing system and procedures are described in Haugen et
178 al.¹⁰ Best 20m time was used to determine maximal sprint capacity,

179 while mean sprint time was used to determine repeated sprint
180 ability (RSA). Heart rate was measured continuously during the

181 test (Polar RS400, Kempele, Finland). Blood lactate concentration
182 (BLa^-) was acquired (LactatePro LT-1710, Arkay KDK, Kyoto,

183 Japan) immediately after the last sprint.

184 All sprint tests were video captured from start to finish with Sony
185 HDR-HC9E video camera. Video recordings were analysed in

186 ProSuite 5.5 (Dartfish, Switzerland) to quantify the number of
187 steps during each 20m sprint. For precision, a digital ruler was

188 used to analyse the last step across the finish line. For example; if
189 13th and 14th ground contact occurred 0.8 m in front of and 1.2 m

190 beyond the finish line, respectively, the recorded number of strides
191 was registered as 13.4. Mean stride length was calculated by
192 dividing number of steps by distance (in this case: $20\text{m} \cdot 13.4^{-1}$
193 $=1.49\text{m}$). Mean stride frequency was calculated from mean
194 velocity and mean stride length. Prior to the study, we validated
195 this measurement method by rolling out thin paper at the finish line
196 area in order to measure the distance between the visible spike
197 shoe marks from athletics sprinters. The absolute difference across
198 twenty sprint comparisons never exceeded 0.1 steps. Thus,
199 maximal margin of error for stride counts over 20m is $\sim 0.7\text{-}0.8\%$
200 for athletes using 13-15 steps.

201 $\text{VO}_{2\text{max}}$ test was performed 80-90 minutes after the sprint test.
202 Apparatus and procedures are described in Tønnessen et al.¹¹ On
203 test day two, the Yo-Yo IR1 test was performed indoors on
204 artificial turf. Prior to the test, participants performed a
205 standardized warm up consisting of 10 min easy jog at 60-75% of
206 $\text{VO}_{2\text{max}}$, followed by the initial 90-120 s of the IR1 test. Setup and
207 procedures were in accordance with the guidelines by Krustup et
208 al.¹²

209 The training intervention took place from mid August to mid
210 October, corresponding to the last part of the Norwegian soccer
211 season. During all training sessions, TG performed repeated 20m
212 sprints at 90% intensity with start every 60 s outdoor on an
213 artificial turf soccer pitch. Their sessions were performed at the
214 same time and day throughout the intervention. Twenty sprints
215 were performed in the first training session, while 25 sprints were
216 performed in the remaining eight training sessions. Warm up
217 procedures before training were similar to those formerly described
218 prior to CMJ/sprint testing. Electronic timing was used to control
219 speed and adjust intensity according to each player's "target time".
220 Target time was based on best sprint time achieved during
221 preliminary testing by multiplying mean velocity over the 20m
222 distance by 0.9. Figure 1 shows intensity distribution for TG
223 during the first two training sessions. While the athletes struggled
224 to hit correct intensity during the initial runs of the first session,
225 about 90% of all sprints were between 89 and 91% intensity in the
226 second session (Figure 1). Similar intensity distributions were
227 observed for the remaining sessions throughout the intervention.

228
229 (Figure 1 about here)

230

231 **Statistical analyses**

232 Statistical analyses were carried out using SPSS 17.0 (SPSS Inc.,
233 Chicago, IL, USA). Level of significance was set to $p < 0.05$. Paired
234 samples t-tests were used to examine within group changes.

235 Analysis of Covariance (ANCOVA) models adjusting for pre-test
236 value and stratification factor (gender) were used to examine
237 between group differences. The differences were evaluated by
238 using estimated marginal means (EMM). The other stratification
239 factor (grade) was not included in this analysis due to sample size
240 and the ability to identify parameter estimates. Unadjusted effect
241 size (Cohen's d) was calculated to evaluate the meaningfulness of
242 the difference between category means. The first 6 sprints from
243 pre-test were used to calculate typical variation for sprint time.
244 Effect size of the within group changes for mean sprint time were
245 based on change in central location (mean) and typical variation.
246 Pearson's R was used to examine the relationship across
247 anthropometric and physical parameters. Effect magnitudes were
248 interpreted categorically according to the scale presented by
249 Hopkins et al.¹³ Results are expressed as mean \pm SD, and 95% CIs
250 was calculated for all measures.

251

252 Results

253

254 (Table 2 about here)

255 (Figure 2 about here)

256

257 Typical variation for 12x20 m sprint time was 0.025 s for both
258 groups (CV 0.8%). TG improved 12x20 m mean sprint time and
259 Yo-Yo IR1 performance by a significant margin. No significant
260 between group differences for performance parameters were
261 observed, and effect magnitudes were trivial or small. In CG, we
262 observed \pm 0.06 s absolute variation in mean sprint time between
263 the pre- and post tests.

264

265 (Table 3 about here)

266

267 Table 3 presents changes in anthropometric, physiological and
268 biomechanical indices between and within groups from pre- to
269 post-test. TG increased body mass significantly (1.5%, $p=0.007$).
270 However, no significant between group differences were observed,
271 and effect magnitudes were small.

272

273 (Figure 3 about here)

274 (Figure 4 about here)

275

276 Figure 3 shows that the correlation between individual changes in
277 mean sprint time and corresponding changes in blood lactate from
278 pre- to post test was 0.5 ($n=22$, $p<0.05$). Figure 4 shows a nearly
279 perfect relationship between changes in mean sprint time and
280 corresponding changes in best sprint times ($r=0.92$, $n=22$,

281 $p<0.001$). Changes in body mass were correlated with changes in
282 mean sprint time ($r=-0.45$), $BLa\bar{v}$ ($r=-0.43$) and Yo-Yo IR1 test
283 performance ($r=0.50$) by small to moderate margins ($p<0.05$,
284 $n=22$).

285

286 Discussion

287 The main finding in the present study was that RSA training at
288 90% of maximal 20m sprint time was not sufficient to improve
289 either maximal sprinting or repeated sprinting performance, when
290 compared to an age and gender matched control group assumed to
291 maintain a constant training pattern. TG improved repeated sprint
292 ability and Yo-Yo IR1 performance significantly. However, effect
293 magnitudes for the between group changes were in the range trivial
294 to small for all analyzed performance parameters.

295 To the authors' knowledge, this is the first study to investigate the
296 effect of training at 90% sprint speed on maximal and repeated
297 sprinting performance in soccer or other speed related sports.
298 Based on the small benefits presented (Table 2, figure 2), it is not
299 recommended that players should perform the present training
300 regime under otherwise identical conditions. However, a great deal
301 of knowledge can be gathered from non-successful conditioning
302 programs for soccer players as well, which so far are
303 underrepresented in research journals.

304 The unexpected result in this study is that both the intervention and
305 control groups demonstrated meaningful improvements in sprint
306 performance over the nine week intervention period, despite no
307 quantifiable between group changes in training load or specific
308 sprint training. Within subject typical variation for 20m sprint time
309 was 0.025 s, demonstrating excellent reliability of the criterion
310 measure. Nine of 13 TG and 5 of 9 CG subjects improved both
311 maximal and mean sprint time by a margin (0.04 to 0.12 s) clearly
312 exceeding typical variation. Theoretically, the large RSA
313 improvements could be due to learning effects. However, this is
314 likely not the case, as the players were well familiarized with sprint
315 testing through their bi-annual or annual testing that their high
316 school/academy performed for training purposes. Previous studies
317 have reported no apparent learning effects associated with sprint
318 testing, and high test-retest reliability can be achieved without
319 prior familiarization.^{14,15} We argue instead that the observed
320 performance improvement in both groups points to a positive
321 impact of a reduced competition load at the very end of the
322 intervention period, which overlapped the end of the competitive
323 season by one week.

324 While 9 of 13 TG athletes improved RSA substantially, we cannot
325 conclude that training at 90% sprint speed is a sufficient sprinting
326 intensity for stimulating adaptation over short sprint distances.
327 Previously, we have observed unaltered 0-20m sprint performance
328 but improved RSA (10x40m) and 20-40m top speed as a result of
329 weekly repeated 40m sprints at maximal or near maximal intensity
330 over ten weeks.¹⁶ This suggests that players are more disposed to
331 adaptations over somewhat longer but less soccer-specific sprint
332 distances. Soccer players perform a high number of accelerations
333 during training and games. Thus, one could argue that most players
334 have likely taken out much of their 0-20m sprint potential during
335 regular soccer conditioning.

336 The concept of training at slightly sub-maximal sprinting intensity
337 is derived from pioneer coaches in track and field athletics. It is
338 possible that sub-maximal sprint training is more appropriate for
339 typical athletic sprinting distances (100-200m) compared to 0-20m
340 accelerations. In strength- and endurance training, reduced training
341 intensity can be compensated for with substantially increased
342 accumulated work to enhance performance.^{2,3} In these training
343 situations, the physiological energy demand is controlled using
344 heart rate/oxygen consumption for endurance training, or external
345 load for strength training, such that percentage work intensity is
346 linearly related to the objectively measured change in workload up
347 to 100% of $\text{VO}_{2\text{max}}$, or 100% of 1RM. However, 20m sprints are
348 comprised of high to maximal acceleration from a resting state and
349 continuing through the timed distance. In this condition, energy
350 demands during the acceleration phase greatly exceed those at
351 peak velocity.¹⁷ These calculations are complex, but a relevant
352 simplification is to compare the change in kinetic energy that must
353 be achieved at maximal and 90% of maximal acceleration. The
354 change in kinetic energy ($0.5\text{Mass}\cdot\text{V}^2$) is proportional to the square
355 of the change in velocity, such that the 90% sprint condition is
356 associated with a nearly 20% reduction in kinetic energy change
357 (and presumably muscular energetic demand) compared to
358 maximal sprinting velocity. Due to this non-linearity, a 5%
359 reduction in short sprint velocity during RSA training over short
360 distances would correspond to 90% workloads in strength training
361 and endurance training, and might give a more optimal balance of
362 stress, injury risk reduction and adaptive signal retention. This
363 possibility remains to be explored.

364 It is possible that a larger total stimulus than the present
365 intervention is required in order to improve 0-20m sprint
366 performance. More sprint repetitions per session or more weekly
367 sprint training sessions could have been performed. Even though
368 the present players perceived each sprint session as easy or

369 moderate, they were skeptical to performing additional repetitions,
370 fearing a negative impact on performance in approaching highly
371 prioritized games/soccer sessions. Hectic timetables during the
372 soccer season limit the magnitude and number of training sessions
373 that can be dedicated to fitness development, and the participating
374 players and their respective coaches were not willing to “sacrifice”
375 further soccer training sessions in the season. Our intervention was
376 shaped by several training-related constraints due to the high
377 volume of overall conditioning. We argue that these constraints are
378 indeed an important aspect of assessing the practical efficacy of
379 training interventions in team sport.

380 We observed a significant and moderate relationship between
381 individual changes in mean sprint time and corresponding changes
382 in BLa⁻ immediately after the repeated sprint tests (Figure 3).
383 Reduced maximal performance accompanied with reduced lactate
384 production has been proposed as typical markers of overreaching
385 or overtraining.^{18,19} Insufficiently recovered athletes are perhaps
386 not able to fully activate the central nervous system or tax the
387 anaerobic system maximally during repeated sprints. Since
388 individual sprint performance depends upon the ability to fully
389 activate fast twitch motor units with maximal firing frequency
390 (23), it is reasonable to speculate that increased BLa⁻ during
391 sprinting reflects enhanced neural activation on an individual level.

392 Ross & Leveritt suggest that the outcome of sprint training is best
393 following a period of rest or reduced training, as this leads to
394 appropriate contractile adaptations.²⁰ If extensive soccer training
395 inhibits sprint performance, prioritization of training goals
396 becomes critical. In a recent review, we summarized relevant
397 sprint-specific training regimes in soccer and suggested that the
398 largest effects were seen when the sprint conditioning was
399 conducted in the off-season or early pre-season.¹ The present study
400 adds further support to this conclusion, as the players performed
401 14-15 hours of soccer training each week during the entire
402 intervention period (Table 1).

403 We observed a trivial increase in body mass (~1 kg) for both
404 groups from pre- to post test (Table 3) accompanied by trivial or
405 small improvements in sprinting capacity and Yo-Yo IR1
406 performance (Table 2). Pre- and post tests were performed at the
407 same time of day for all participants and with standardized
408 footwear and outfit for each test. The participants were requested
409 to refrain from performing strength training regimes during the
410 intervention period. In the absence of body composition data, we
411 ascribe the slight body mass increases mainly to natural growth
412 typical for this age group.

413 Figure 4 reveals a nearly perfect correlation between changes in
414 best sprint time and changes in mean sprint time during 12x20m
415 sprint from pre- to post test. This is in accordance with Pyne et al.,
416 who reported that RSA is more correlated with maximal sprinting
417 velocity than endurance capacity.²¹ Balsom et al. observed that it is
418 more difficult to detect detrimental effects with short sprints
419 compared to slightly longer sprints.²² Our results support this
420 observation, as the absolute time difference between best and mean
421 sprint time was only 2x the typical variation calculated from pre-
422 testing (Table 2).

423 In CG, we observed ± 0.06 s absolute variation in mean sprint time
424 between the pre- and post tests, and several players differed as
425 much as ± 0.1 s in repeated sprint performance between the tests
426 (Figure 2). This “seasonal variation” is considerably higher than
427 the observed typical variability. If improvement of sprinting skills
428 is the primary goal for certain players in-season, future studies
429 should explore whether it is more effective to structure the players’
430 weekly soccer training rather than introducing an additional
431 physical conditioning regime.

432 **Practical applications**

433 In the present study, we hypothesized that sprint training at 90%
434 maximal sprint speed would enhance sprint performance in
435 adolescent soccer players. However, our conditioning program
436 only resulted in trivial or small group effects, and it is therefore not
437 recommended that soccer players perform the present sprint
438 program under otherwise identical conditions. Taking our findings
439 together with previous sprint training interventions in soccer, it
440 becomes increasingly evident that sprinting skills are difficult to
441 develop in combination with extensive soccer training. Before
442 rejecting the hypothesis, we recommend that future studies should
443 perform intervention programs with either stronger stimulus or at
444 other times during the season where total training load is reduced.
445

446 **Conclusions**

447 In the present study, weekly repeated sprint training at 90% of
448 maximal sprint speed over nine weeks was not sufficient to
449 improve either maximal sprinting or repeated sprinting
450 performance in soccer players.
451

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For Peer Review

552 **Tables**

553 **Table 1.** Physical and training characteristics at inclusion.

554

555 **Table 2.** Physical performance between and within groups from
556 pre to post-test.

557

558 **Table 3.** Underlying performance variables between and within
559 groups from pre to post-test.

560

561 **Figure captions**

562 **Figure 1.** Intensity distribution for training group (TG) during the
563 first two training sessions.

564

565 **Figure 2.** Individual changes in 12x20 m mean sprint time from
566 pre- to post test for training group (TG) and control group (CG).

567

568 **Figure 3.** Scatter plot of changes in 12x20 m mean time vs.
569 changes in blood lactate (BLa⁻) from pre- to post test.

570

571 **Figure 4.** Scatter plot of changes in 12x20 m mean time vs.
572 changes in best sprint time from pre- to post test.

573

574 **Table 1.** Physical and training characteristics at inclusion

Group	Age (yr)	BM (kg)	Height (cm)	Training frequency (sessions/wk)	Games/ week	Tot. vol. (h/wk)
TG (<i>n</i> =13)	17 ±1	65 ±8	174 ±8	8.9 ±1.6	1.3 ±0.4	14.7 ±2.3
CG (<i>n</i> =9)	17 ±1	62 ±7	173 ±6	8.3 ±0.9	1.4 ±0.4	13.6 ±0.9

575 Values are mean ± SD. TG= Training group. CG= Control group. BM= Body mass,
 576 Tot. vol.= Total training volume. Training values are based on self-reported weekly averages
 577 during the intervention period. There where no significant differences among the groups for
 578 any of the variables.

579

580

581 **Table 2.** Physical performance between and within groups from pre to post-test.

TG	Best sprint (s)	Mean sprint time (s)	CMJ (cm)	VO₂ max (mL·min⁻¹·kg⁻¹)	Yo-Yo IR1 (m)
Pre-test	3.11±0.17	3.16±0.17	30.0±4.9	58.2±8.3	1583±669
Post-test	3.08±0.14	3.12±0.15	31.1±5.8	57.7±7.9	1858±773
Change	-0.03±0.06	-0.04±0.05*	1.1±3.0	-0.5±2.3	275±240*
95% CI	[-0.07,0.00]	[-0.07,-0.01]	[-0.6,2.9]	[-1.9,0.9]	[113,436]
CG					
Pre-test	3.02±0.17	3.07±0.17	32.0±6.0	63.0±5.2	2030±599
Post-test	2.99±0.13	3.04±0.14	32.1±4.9	62.5±5.5	2153±694
Change	-0.03±0.05	-0.03±0.06	0.1±1.9	-0.5±1.6	123±330
95% CI	[-0.07,0.02]	[-0.08,0.01]	[-1.4,1.4]	[-1.8,0.7]	[-154,399]
Δ groups					
EMM/ <i>p</i> =	-0.02/0.33	-0.02/0.51	0.8/0.45	-0.3/0.76	111/0.45
95% CI	[-0.06,0.02]	[-0.06,0.03]	[-1.4,3.0]	[-2.5,1.9]	[-193,415]
ES	0.2	0.2	0.4	0.0	0.5

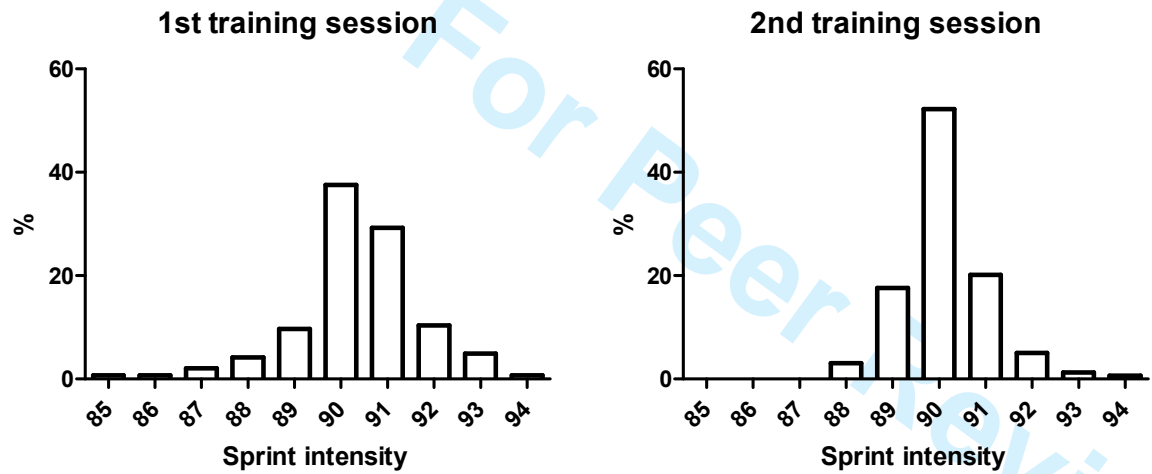
582 TG = Training Group, CG = Control Group, CMJ = countermovement jump, VO_{2max} = maximal
583 oxygen uptake, Yo-Yo IR1 = Yo-Yo intermittent recovery level 1, CI = confidence interval,
584 Δ groups = between group differences, EMM = Estimated Marginal Mean from ANCOVA
585 model, *p* = significance value, ES = unadjusted effect size (Cohen's *d*), **p* < 0.05.
586

587 **Table 3.** Underlying performance variables between and within groups from pre to post-test.

TG	Body mass (kg)	HR_{peak} (% of HR_{max})	Lactate (mmol·L⁻¹)	Stride length (m)	Stride freq. (strides/s)
Pre-test	65.1±7.8	84.8±3.9	3.8±1.3	1.49±0.09	4.25±0.20
Post-test	66.1±7.4	85.6±3.8	4.0±1.3	1.50±0.09	4.29±0.19
Change	1.0±1.1*	0.8±2.0	0.3±1.5	0.01±0.05	0.04±0.12
95% CI	[-0.3,1.6]	[-0.5,2.1]	[-0.6,1.2]	[-0.02,0.04]	[-0.04,0.11]
CG					
Pre-test	61.5±6.8	81.0±6.2	3.5±1.4	1.47±0.11	4.46±0.40
Post-test	62.8±7.2	82.7±4.6	3.2±1.4	1.48±0.10	4.47±0.32
Change	1.3±1.8	1.7±3.1	-0.2±0.7	0.01±0.02	0.00±0.11
95% CI	[0.1,2.7]	[-1.2,4.6]	[-0.8,0.4]	[0.00,0.03]	[-0.08,0.08]
Δ groups					
EMM/ <i>p</i> =	-0.1/0.92	0.2/0.87	0.6/0.29	0.00/0.89	-0.01/0.76
95% CI	[-1.3,1.2]	[-2.2,2.6]	[-0.5,1.7]	[-0.04,0.04]	[-0.11,0.08]
ES	0.2	0.3	0.5	0.3	0.3

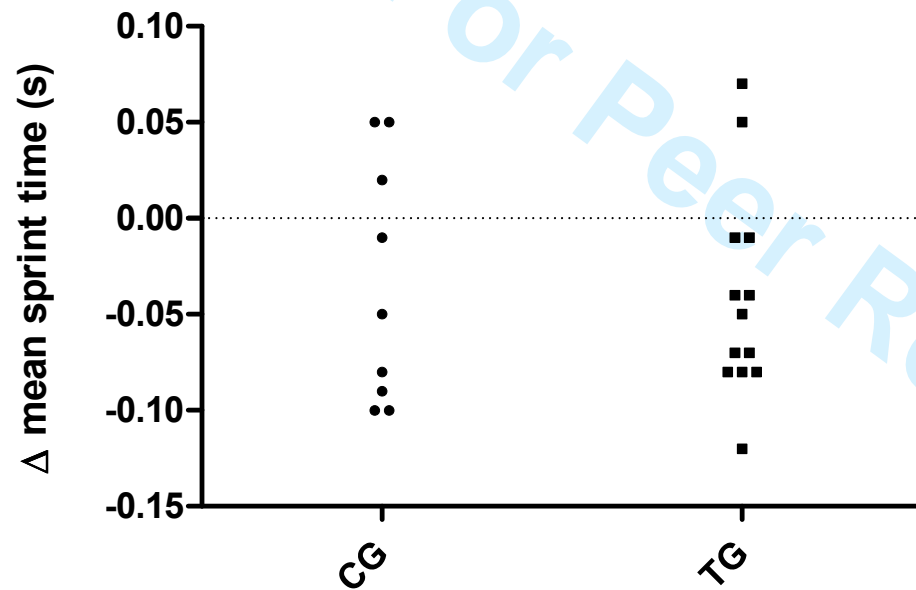
588 TG = Training Group, CG = Control Group, HR = heart rate, freq. = frequency, CI = confidence
589 interval, Δ groups = between group differences, EMM = Estimated Marginal Mean from
590 ANCOVA model, *p*= significance value, ES = unadjusted effect size (Cohen`s d), **p*<0.05.
591

592 **Figure 1.**



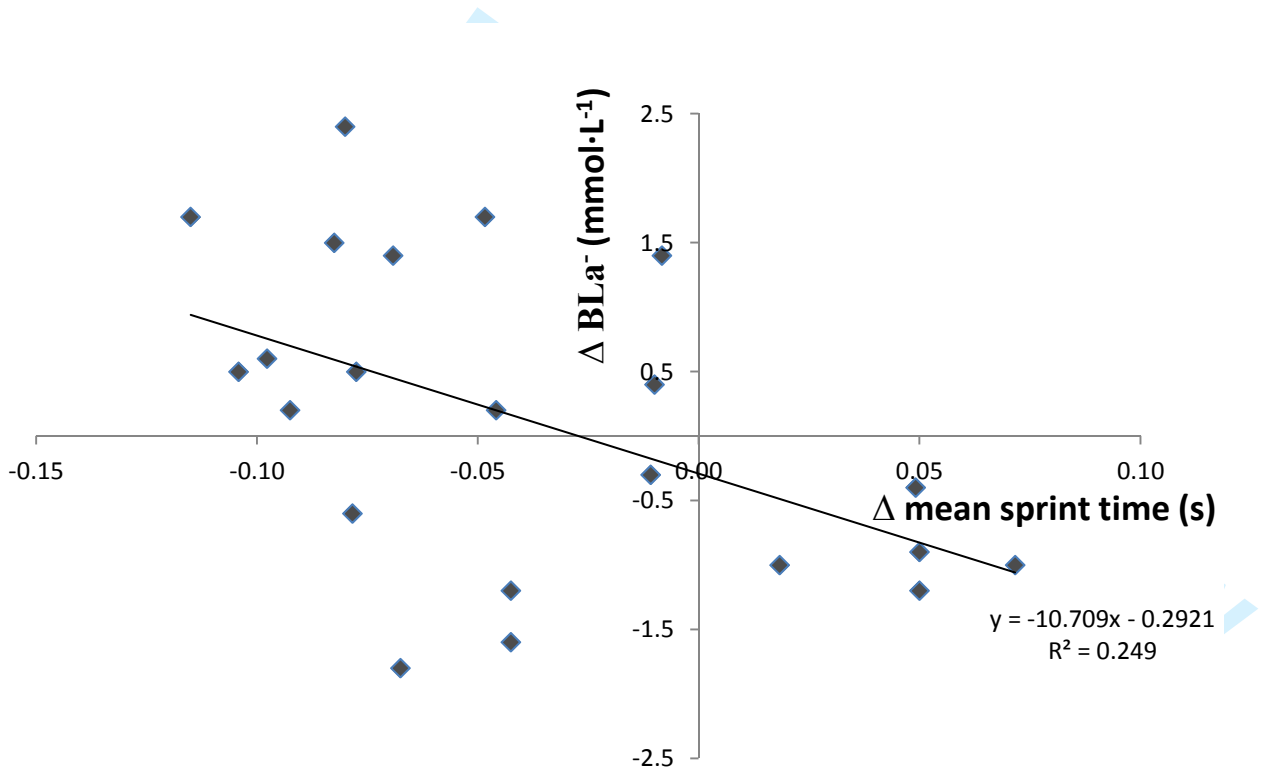
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594 Figure 2.



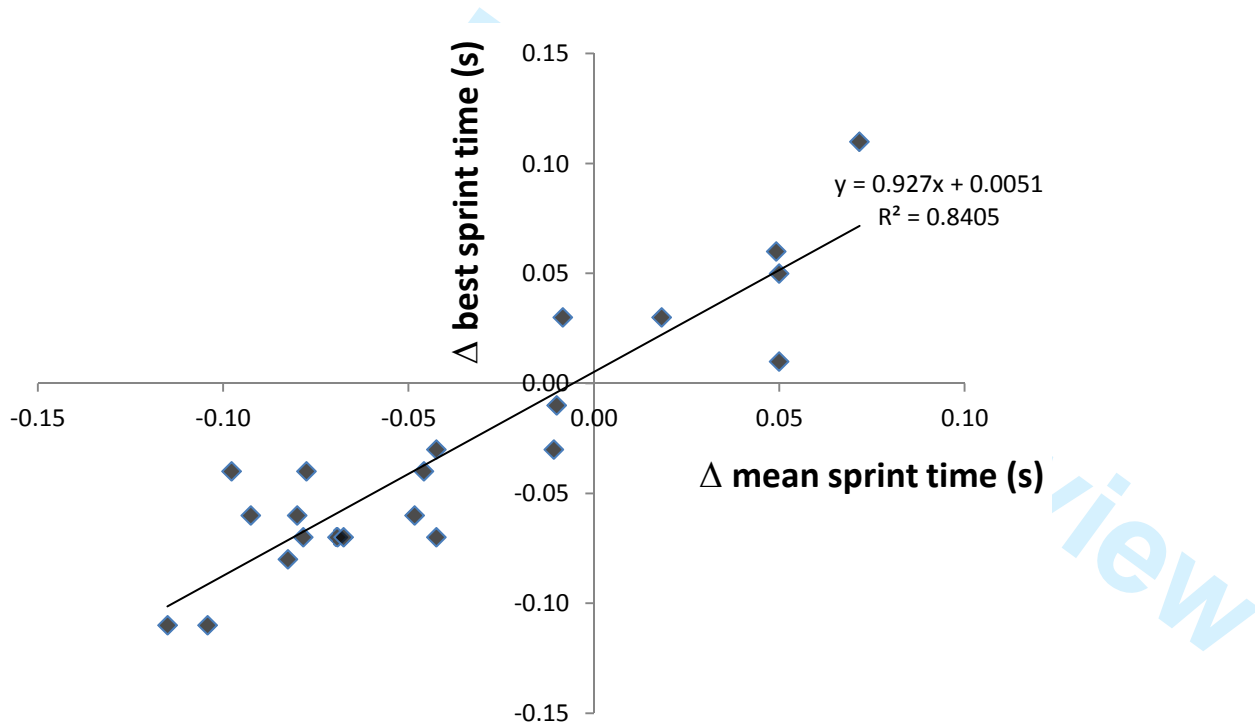
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596 **Figure 3.**



597

598 **Figure 4.**



599

PLOS ONE

Improving sprint performance in soccer: Effects of training intensity and technique supervision --Manuscript Draft--

Manuscript Number:	PONE-D-14-07841
Article Type:	Research Article
Full Title:	Improving sprint performance in soccer: Effects of training intensity and technique supervision
Short Title:	Sprint training in soccer
Corresponding Author:	Thomas Haugen, Ph.D. Norwegian Olympic Sports Program Oslo, NORWAY
Keywords:	physical training; feedback; coaching; sprinting skills
Abstract:	The aim of the present study was 1) to compare the effects of training at 90 and 100% sprint speed, and 2) to compare the effects of directly supervised sprint training versus unsupervised training on maximal sprint performance, repeated sprint ability and gait characteristics in young soccer players. Fifty-two male soccer players (17 ±1 yr, 71 ±10 kg, 180 ±6 cm) were randomly assigned to four different treatment conditions over a 7-week intervention period. A control group completed regular soccer training according to their teams` original training plans. Three training groups replaced one of their weekly soccer training sessions with a repeated sprint training session performed at A) 100% intensity without supervision, B) 90% of maximal sprint speed with direct supervision or C) 90% of maximal sprint speed without direct supervision. No significant differences in performance outcomes were observed across groups. In the absence of evidence supporting the choice of specific training methods at the group level, we suggest that it is essential to diagnose each individual and develop training interventions that target their key physiological and technical weaknesses.
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Opposed Reviewers:	
Additional Information:	
Question	Response
Competing Interest	The authors have declared that no competing interests exist.
For yourself and on behalf of all the authors of this manuscript, please declare below any competing interests as described in the " PLoS Policy on Declaration and Evaluation of Competing	

1 **Abstract**

2 The aim of the present study was 1) to compare the effects of training at 90 and 100% sprint
3 speed, and 2) to compare the effects of directly supervised sprint training versus unsupervised
4 training on maximal sprint performance, repeated sprint ability and gait characteristics in young
5 soccer players. Fifty-two male soccer players (17 ± 1 yr, 71 ± 10 kg, 180 ± 6 cm) were randomly
6 assigned to four different treatment conditions over a 7-week intervention period. A control
7 group completed regular soccer training according to their teams` original training plans. Three
8 training groups replaced one of their weekly soccer training sessions with a repeated sprint
9 training session performed at A) 100% intensity without supervision, B) 90% of maximal sprint
10 speed with direct supervision or C) 90% of maximal sprint speed without direct supervision. No
11 significant differences in performance outcomes were observed across groups. In the absence of
12 evidence supporting the choice of specific training methods at the group level, we suggest that it
13 is essential to diagnose each individual and develop training interventions that target their key
14 physiological and technical weaknesses.

15

16 **Introduction**

17 The importance of sprinting skills in professional soccer is well established [1], and the need for
18 speed is clear. If we look to track and field age-group statistics (unpublished data, Norwegian
19 Athletics Federation), trends over time from large retrospective data collections in soccer players
20 [2,3], and the experience of practitioners [4], it appears that sprint performance is quite resistant
21 to training enhancement. However, numerous intervention studies have been performed over the
22 years in order to enhance sprint performance in soccer players, and the research literature
23 suggests that positive outcomes can be achieved using different training approaches. Sprinting
24 under assisted, resisted, and normal conditions, maximal and explosive strength training,
25 plyometric training, and high intensity running have been investigated in different combinations.
26 The methodological quality of these studies has been variable (absence of control group, learning
27 effects, maturation effect contamination) and no specific training method has emerged as
28 superior [1]. Independent of intervention efficacy, time efficiency is an important constraining
29 aspect of team sport conditioning. Extensive off-field interventions will most likely be rejected
30 by team coaches [1].

31 Sprint velocity is the product of stride length (SL) and stride frequency (SF). SF is considered a
32 main limiting performance factor in elite athletic sprinting, while SL is considered more limiting
33 among athletes of lower sprint standard [5-7]. A wide range of SL and SF combinations are
34 observed in athletes with similar sprint velocities, with several possible mechanisms for a
35 negative interaction [8]. The importance of feedback during practice is well-known in motor skill
36 learning, and performance enhancements may happen immediately in such settings [9]. Mazzetti
37 et al. [10] and Coutts et al. [11] concluded that the presence of a training expert was beneficial

38 for maximal strength development over time. To the authors` knowledge, the effect of direct
39 supervision of sprint training sessions in soccer players has not been investigated.

40 Repetition is the mother of learning [9], so it is reasonable to assume that a high number of
41 repetitions at sub-maximal intensity during technical training is important for stimulating motor
42 adaptations. At the same time, the vast majority of studies involving sprint training interventions
43 for soccer players make no other recommendations than that sprint velocity should be maximal
44 throughout [1]. Available evidence in endurance training and strength training also demonstrates
45 that high, but sub-maximal intensity loading effectively stimulates adaptation through the
46 interaction between high intensity and larger accumulated work that can be achieved before
47 onset of fatigue, compared to maximal efforts [12,13]. This makes it tempting to speculate
48 similar effects on sprinting.

49 Maximal sprinting is the most frequent situation associated with hamstring injuries in soccer
50 [14]. Hamstring injuries are most prevalent during the short pre-season period, and Elliott et al.
51 [15] ascribe this to the deconditioning that occurs in the off-season. Thus, during the initial
52 weeks of a sprint training program there should be a gradual familiarization, both in terms of
53 intensity and the number of sprint repetitions. Anecdotal evidence in support of this is observed
54 in the sprint training philosophy developed by athletic sprint pioneer coach Carlo Vittori in the
55 mid-1970s [16]. His athletes performed repeated sprint training sessions with an intensity as low
56 as 90% of maximal sprint intensity during the initial pre-season conditioning. Importantly, the
57 lowest effective sprinting intensity for stimulating adaptation is so far not established in the
58 research literature.

59 The aim of the present study was therefore two-fold: 1) to compare the effects of training at 90
60 and 100% sprint speed on maximal sprint performance, repeated sprint ability (RSA) and gait
61 characteristics, and 2) to compare the effects of directly supervised sprint training versus
62 unsupervised training on maximal sprint performance, RSA and gait characteristics in young
63 soccer players. We hypothesised that 1) sprinting at 90 and 100% of maximal velocity would
64 improve soccer related sprinting skills to a similar degree, and 2) directly supervised training
65 would enhance sprint performance compared to unsupervised training.

66 **Materials and methods**

67 **Ethics statement**

68 This study was conducted in accordance with the declaration of Helsinki. All participants
69 provided written, voluntary informed consent before participation. Written parental consent was
70 also provided for < 18 yr old subjects. The human subjects review committee of the Faculty for
71 Health and Sport, University of Agder, approved the study.

72

73 **Experimental approach to the problem**

74 In this randomized controlled trial, participants were randomly assigned to four different
75 treatment conditions. A control group (CON) completed regular soccer training according to
76 their teams` original training plans. Three training groups replaced one of their weekly soccer
77 training sessions with a repeated sprint training session performed at A) 100% intensity without
78 supervision (100UNSUP), B) 90% of maximal sprint speed with direct supervision (90SUP) or
79 C) 90% of maximal sprint speed without direct supervision (90UNSUP). The duration of the

80 intervention period was 7 weeks. Results from soccer specific physiological test results were
81 compared before and after the intervention period.

82

83 **Subjects**

84 Fifty-two male soccer players, aged 16-19 years, volunteered to participate. The athletes were
85 playing in the highest junior division level for four different clubs in Norway. Each subject had
86 minimum two years of soccer specific conditioning experience. During the intervention period,
87 the participants were requested to refrain from performing any other off-field physical training
88 regimes in terms of speed, strength and/or endurance. All subjects were free of injuries prior to
89 preliminary testing. None of the athletes had previous experience with specialized repeated sprint
90 training.

91 To eliminate the influence of varying overall soccer conditioning, the participants were initially
92 paired for clubs and then randomly assigned to one of the four intervention conditions by a co-
93 author not directly involved in testing or the training intervention. The subjects in the three
94 training groups were required to complete at least six out of seven training sessions during the
95 intervention period in addition to all performance tests in order to be included in further analyses.
96 CON subjects were required to perform at least 80% of planned sessions and complete all pre-
97 and post tests. One participant each from CON, 100UNSUP, and 90SUP dropped out due to
98 illness during training or testing. Two participants from 90SUP and one from 90UNSUP dropped
99 out due to injuries sustained outside of the sprint training intervention. A final player from
100 90SUP group dropped out due to Achilles tendon strain, possibly associated with the sprint
101 intervention. Thus, 45 of 52 subjects completed the study with the following sample sizes: CON
102 = 9, 100UNSUP = 13, 90UNSUP = 13, and 90SUP = 10. Physical and training characteristics of

103 these subjects are presented group-wise in Table 1. Frequency and volume of games and training
104 sessions were consistent throughout the entire intervention period.

105

106 **** Table 1 about here****

107

108 **Testing procedures**

109 The pre- and post tests were conducted at the Norwegian Olympic Training Centre on two
110 separate days, with two days in between. All participants completed the tests in the same order
111 and at the same time of day. Regarding nutrition, hydration, sleep and physical activity, the
112 athletes were instructed to prepare as they would for a regular soccer match, including no high
113 intensity training the last two days before testing. They were also instructed to use identical
114 footwear and kit for each of the tests. Test day one consisted of a countermovement jump test
115 (CMJ) and a 15x20 m repeated sprint test. On test day two, the athletes completed the Yo-Yo
116 Intermittent Recovery 2 test (Yo-Yo IR2). Prior to testing on test-day 1, participants completed a
117 25 min standardized treadmill warm-up consisting of 10 min general warm-up at 60 – 75% of
118 maximum heart rate (HR_{max}), 3 sets of 4 exercise drills (high knees, back kick, sideway and
119 backwards running) and finally 2–3 repetitions of 40 m runs with a progressive increase in speed.

120 *CMJ test:* Immediately after warm up, each athlete was weighed on a force platform for system
121 calibration before performing three trials of CMJ vertical jump separated by 1min recovery. The
122 best result for each player was retained for analysis. To isolate leg extensor muscles and
123 minimize technical elements, all jumps were performed with hands placed on the hips. The tests
124 were performed on an AMTI force platform (OR6-5-1, Watertown, USA). Calculation of jump
125 height is formerly described in Haugen et al. [2].

126 *Sprint test:* A 15x20 m repeated sprint test with start each 60 s was performed after the CMJ test.
127 Distance and recovery were chosen in line with mean frequency and typical distance of all-out
128 sprints reported from match analyses [17]. The test was performed with the athletes` regular
129 running shoes on a dedicated indoor track with 8 mm Mondo FTS surface (Mondo,
130 Conshohocken, USA). The electronic timing system at the Norwegian Olympic Training Centre
131 was used for all sprint tests. Specific setup details are described in Haugen et al. [18], as the
132 timing system has been recently assessed for accuracy and reliability. Best 20 m time was used
133 in order to determine maximal sprint capacity, while mean time for the 15 sprints was used to
134 determine repeated sprint ability. Heart rate was measured continuously during the test (Polar
135 RS400, Kempele, Finland). A blood sample was acquired via finger stick to quantify the blood
136 lactate concentration (BLa^-) immediately after the last sprint (LactatePro LT-1710, Arkay KDK,
137 Kyoto, Japan).

138 All sprint tests were video captured from start to finish (Sony HDR-HC9E). Video recordings
139 were analysed in ProSuite, version 5.5 (Dartfish, Switzerland) to determine stride count and
140 derive average stride length. For precision, the digital ruler in the analyser window was used to
141 interpolate the last step across the finish line. For example; if the 13th and 14th ground contact
142 occurred 0.8 m in front of and 1.2 m beyond the finish line, respectively, the recorded number of
143 strides was registered as 13.4. Mean SL was calculated by dividing the number of steps by the
144 distance (in this case: $20\text{ m} \cdot 13.4^{-1} = 1.49\text{ m}$). Mean SF was calculated from mean velocity and
145 mean SL. Prior to the present study, we validated this measurement method by rolling out thin
146 paper at the finish line area in order to measure the distance between the visible spike shoe marks
147 from competitive sprinters. The absolute difference across twenty sprint comparisons never

148 exceeded 0.1 steps. Thus, the maximal margin of error for stride counts over 20 m is ~ 0.7-0.8%
149 for athletes using 13-15 steps.

150 *Yo-Yo IR2 test:* On test day two, the Yo-Yo IR2 test was performed indoors on artificial turf.
151 Prior to the test, participants warmed up with 10 min easy jog at 60 – 75% of HR_{max} , followed by
152 the initial 60-90 s of the IR2 test. The test set-up and procedures were in accordance with the
153 guidelines by Krustup et al. [19]. Two test leaders supervised the tests. The athletes were
154 divided in small consecutive groups, such that each supervisor was responsible for $\leq 4-5$ athletes
155 during the test.

156

157 **Intervention program**

158 The training intervention took place from the end of October to mid December, corresponding to
159 off-season in the Norwegian soccer annual cycle. The three training groups performed a weekly
160 sprint training session in addition to their regular soccer training program. Athletes in
161 100UNSUP performed 15x20 m maximal sprints with start each 60 s once a week. Groups
162 90SUP and 90UNSUP performed one weekly training session consisting of a larger dose of
163 30x20 m sprints at 90% of maximal sprint velocity with start each 60 s. In the absence of
164 previously published studies, we estimated a 1:2 repetition ratio between 100% and 90%
165 sprinting based on both anecdotal and experimental evidence from strength training and
166 endurance training studies comparing interventions where similar intensity ranges were utilized.
167 For example, within endurance training, elite athletes accumulate about twice as much duration
168 when performing intervals at 90% of HR_{max} as when performing at $\geq 95\%$ of HR_{max} [13]. In
169 order to compare the two repeated sprint training sessions used in the present study, session rated
170 perceived exertion (RPE) was recorded for all athletes after the repeated sprints performed in pre

171 test and first training session. Written and verbal instructions regarding its use were provided in
172 advance [20]. Heart rate was measured continuously during the first training session for all
173 athletes who ran at 90% sprint intensity, in addition to blood lactate concentration (BLa⁻)
174 immediately after their last sprint. Mean SL and SF for this session were calculated by identical
175 procedures as for the pre- and post tests. Finally, all training group athletes performed 3x20 m
176 maximal sprints with start each 60 s 48 hours after the first training session in order to quantify
177 performance recovery. The mean time for these three sprints was compared with the
178 corresponding sprints from the pre test.

179 Two sprint training experts, with extensive national level coaching experience, supervised the
180 90SUP group during the intervention. Three key sprint-technical elements and corresponding
181 verbal instructions were emphasized during the training sessions:

182

- 183 • Optimal upper body angle relative to the ground during the initial steps in order to create
184 higher horizontal propulsive forces through more effective utilization of hip and knee
185 extensors [21,22]. The athletes were instructed to assume a start position with forward leaned
186 upper body and lowered centre of gravity, and to gradually become more upright throughout
187 the acceleration.
- 188 • Minimize horizontal braking forces [21]: Athletes with apparently too high braking forces
189 were encouraged to assume a more favourable configuration at the point of ground contact
190 with the foot plant closer to the perpendicular line from the centre of mass. This can be
191 achieved by hitting the ground with a bent knee (relevant during acceleration) or with the
192 centre of mass at a large vertical distance above the ground (relevant during maximal
193 sprinting).

194 • Produce a stiff rebound during ground contact in order to minimize degeneration of
195 horizontal propulsive forces [23-25]: Identified “heel runners” were encouraged to pre
196 activate dorsiflexion muscles prior to foot plant and stiffen the ankle joint during ground
197 contact, allowing them to utilize the elasticity in the plantar flexors for greater force
198 development. These instructions were emphasized during the warm up drills.

199

200 After video analysis of the first training session, the two sprint training experts prepared an
201 individual capacity profile for all participants in the 90SUP group. Each athlete was presented
202 one technical task at a time, in accordance with general feedback principles [9]. Players with
203 obvious technical limitations were provided more verbal instructions than technically well-
204 performing athletes.

205 All sprint training sessions were performed indoors (air temperature ~ 20° C) on an 8 mm Mondo
206 FTS surface (Mondo, Conshohocken, USA). The sessions were performed at the same time and
207 day for each training group throughout the intervention period. Electronic timing was
208 continuously used to control running speed and adjust intensity according to each player`s
209 “target time”. Target time for the 90SUP and 90UNSUP subjects were derived from best sprint
210 time achieved during preliminary testing by multiplying mean velocity over the 20 m distance by
211 0.9. No feedback other than sprint time information was provided for 90UNSUP and 100UNSUP
212 group after each run. Figure 1 shows intensity distribution for the two 90% groups during all
213 training sessions. More than 90% of all sprints were completed with intensity between 87 and
214 93% of maximal sprint velocity (Figure 1).

215

216 ***Figure 1 about here***

217

218 Statistical analysis

219 All statistical analyses were carried out using SPSS 17.0 for Windows (SPSS Inc., Chicago, IL,
220 USA). Level of significance was set to $p < 0.05$. The General Linear Model with Repeated
221 Measures followed by Bonferroni adjustment for multiple comparisons was used to examine
222 RSA development (mean sprint time) for 100UNSUP across tests and training sessions. Same
223 model was used for 90SUP and 90UNSUP to compare effort related variables in maximal and
224 sub-maximal sprinting. A paired samples t-test was used to examine within group changes in
225 central location (mean). Analysis of covariance (ANCOVA) adjusting for pre-test value and
226 stratification factor (club) was used to examine between group changes in central location. The
227 differences were judged by using estimated marginal means (EMM). Bonferroni corrections
228 were used to adjust p -values for multiple testing. Unadjusted effect size (Cohen's d) was
229 calculated to evaluate the meaningfulness of the difference between category means. The first 6
230 sprints from pre test were used to calculate typical variation for sprint time, SL and SF. Effect
231 size of the within group changes for mean sprint time were based on change in central location
232 (mean) and typical variation. Pearson's R was used to quantify the relationships among
233 anthropometric and physical parameters. Effect magnitudes were interpreted categorically
234 according to the scale presented by Hopkins et al. [26]. The results are expressed as mean \pm SD,
235 and 95 % confidence interval (95 % CI) was calculated for all measures.

236

237 Results

238 **** Table 2 about here ****

239

240 Table 2 shows effort related variables between the two repeated sprint training sessions used in
241 the present intervention. No differences in RPE were observed between the sessions. The athletes
242 were also equally recovered 48 hours after the respective sprint training sessions. Sprinting at
243 90% velocity was accompanied with reduced HR_{peak} (17%; very large effect; $p < 0.001$), BLa⁻
244 (55%; large effect; $p < 0.001$) and SF (11%; very large effect; $p < 0.001$) compared to maximal
245 sprinting. While heart rate plateaued after ~ 10th repetitions during the 30x20 m 90% sprint
246 training sessions, heart rate increased progressively throughout the 15x20 m 100% sprint
247 sessions.

248

249 **** Table 3 about here ****

250 **** Figure 2 about here ****

251

252 Table 3 shows changes in analyzed performance parameters within groups and compared to
253 controls from pre to post-test, while figure 2 shows individual changes in 15x20 m mean sprint
254 time from pre to post-test. No significant within group differences for the performance
255 parameters were observed, except that the 90SUP group improved Yo-Yo IR2 performance from
256 pre- to post-test ($p < 0.01$). No significant between group differences were observed. The 90SUP
257 group improved Yo-Yo IR2 performance by a moderate margin compared to all other groups.
258 The differences in mean sprint time between CON and the other groups were small. The
259 difference in CMJ between 90SUP and 90UNSUP was small. All other effect magnitudes
260 between or within groups were trivial. Finally, when treatment groups were compared
261 (90UNSUP used as reference in ANCOVA analysis), trivial and non-significant differences were
262 observed for all parameters.

263 Typical variation for sprint time, SL and SF was 0.025 s (CV 1.0%), 0.028 m (CV 1.8%) and
264 0.08 strides·s⁻¹ (CV 1.9%), respectively, for all groups taken together. In CON, we observed
265 ±0.04 s absolute variation in mean sprint time between the pre- and post tests. Corresponding
266 absolute variation for SL and SF was 0.06 m and 0.19 strides·s⁻¹, respectively.

267

268 **** Figure 3 about here ****

269

270 Figure 3 shows the development of repeated sprint performance (mean sprint time) for
271 100UNSUP during the intervention period, including pre- and post test. Weekly changes in
272 group mean values up to 0.05 s were observed.

273

274 **** Table 4 about here ****

275

276 Table 4 shows changes in physiological and gait variables within groups and compared to
277 controls from pre to post-test. In 100UNSUP, significant differences from pre- to post test were
278 observed for BLa⁻ ($p<0.001$), SL ($p=0.020$) and SF ($p=0.019$). A significant difference between
279 100UNSUP and CON was observed for BLa⁻ ($p=0.008$). No other within or between group
280 differences were observed. The change in BLa⁻ within 100UNSUP was moderate while the other
281 effect magnitudes between or within groups were trivial or small.

282

283 **** Table 5 about here ****

284

285 Table 4 shows correlation values across analyzed variables. Overall, changes in $BLa_{\bar{}}$ from pre-
286 to post-test were correlated with changes in heart rate, sprint times and CMJ performance by
287 moderate to large margins. Changes in best sprint time showed a very large correlation with
288 changes in mean sprint time. Changes in sprint times were moderately correlated with changes in
289 CMJ performance.

290

291 **Discussion**

292 In the present study, weekly repeated sprint training sessions at maximal or sub-maximal sprint
293 speed were not sufficient to improve performance outcomes for soccer related sprinting
294 performance, when compared to a matched control group assumed to maintain a constant
295 training pattern. Moreover, no differences in performance outcomes were observed between
296 supervised and unsupervised sprint training groups training at 90% maximal sprinting velocity.

297 To the authors` knowledge, this is the first study to compare the effects of sprint training at 90
298 vs. 100% maximal sprint intensity or supervised vs. unsupervised sprint training in soccer
299 players. The moderate group sample sizes may mask possible significant outcomes. However,
300 based on the effect magnitudes, we cannot recommend that soccer players perform the present
301 training regimes under otherwise identical conditions. Despite the absence of positive outcomes,
302 we believe that a great deal of knowledge can be gathered from this investigation.

303 *Effort matched sprint training:* The current intervention used a 1:2 ratio for sprint repetitions
304 between 100UNSUP (15x20 m) and the two sub-maximal sprint training groups (30x20 m).

305 These two training sessions were equally rated in terms of session RPE (Table 2). Furthermore,
306 no differences in sprint performance were observed between the three initial pre test sprints and
307 the 3x20 m sprints performed 48 hours after the first training session for the maximal and sub-

308 maximal training groups, respectively, indicating similar recovery status 2 days after the sprint
309 training sessions used. Based on these observations, we conclude that the two repeated sprint
310 training sessions were effort matched. However, heart rate values demonstrated a “steady state”
311 condition during repeated 20 m sprints at 90% intensity, and corresponding lactate values were
312 below what has been considered “lactate threshold intensity” (2.5-4.0 mmol·L⁻¹) in endurance
313 training [27]. In contrast, repeated sprinting at maximal intensity induced a progressive increase
314 in heart rate, as well as BLa⁻ at or above the typical lactate threshold range described for
315 endurance athletes. Even though BLa⁻ values obtained from sprint and endurance training are not
316 directly comparable, the data suggest a marked difference in skeletal muscle glycolytic
317 metabolism between 90% and maximal sprinting.

318 *Effect of training at maximal and sub-maximal intensity:* The present results revealed only trivial
319 and non significant changes in soccer related sprinting skills from pre- to post test for
320 100UNSUP (Table 3, Figure 2). Previously, we have observed unaltered 0-20 m sprint
321 performance, but improved 20-40 m speed as a result of weekly repeated 40 m sprints at
322 maximal or near maximal intensity over ten weeks [28]. This suggests that players are more
323 disposed to adaptations over somewhat longer but less soccer-specific sprint distances. Soccer
324 players perform a high number of accelerations during training and games. Thus, one could
325 argue that most players have likely taken out much of their 0-20 m sprint potential during regular
326 soccer conditioning.

327 While sprint performance remained unchanged in 100UNSUP (Table 3), SL and SF changed
328 significantly from pre- to post test (Table 4). This change was higher than the observed typical
329 variation. We suspect that 100UNSUP unconsciously shortened SL and increased SF in the chase
330 of velocity enhancement, as this provides a subjective feeling of running faster. According to

331 Mero & Komi [6] and Mero et al. [7], athletics sprinters should strive to improve performance by
332 increasing SF while maintaining SL. In contrast, SL is considered a more limiting factor among
333 athletes of lower sprint standard [5]. We can only speculate if supervised coaching would have
334 ensured a more optimal combination of SL and SF in 100UNSUP. The correlation values for SL
335 ($r = 0.60$) and SF ($r = 0.63$) across the present tests were surprisingly low when all groups were
336 pooled together (Table 5). This indicates that identical sprint performance can be achieved with
337 varying locomotion efficiency among athletes of lower sprint standard, which is in accordance
338 with observations made by Hunter et al. [8].

339 Based on the current findings, we cannot conclude that training at 90% sprint speed is a
340 sufficient sprinting intensity for stimulating adaptation over short sprint distances (Table 3 and
341 Figure 2). The concept of training at slightly sub-maximal sprinting intensity is derived from
342 coaching practice in track and field athletics, where competitive distances are 60 m and longer
343 [16]. It is possible that sub-maximal sprint training is more appropriate for typical athletic
344 sprinting distances (100-200 m) compared to 0-20 m accelerations. In strength- and endurance
345 training, reduced training intensity can be compensated for with substantially increased
346 accumulated work to enhance performance [12,13]. In these training situations, the physiological
347 energy demand is controlled using heart rate or oxygen consumption for endurance training, or
348 external load for strength training, such that percentage work intensity is linearly related to the
349 objectively measured change in workload up to 100% of VO_2 max, or 100% of 1RM. However,
350 20 m sprints are comprised of high to maximal acceleration from a resting state and continuing
351 through the timed distance. In this condition, energy demands during the acceleration phase
352 greatly exceed those at peak velocity [22]. These calculations are complex, but a relevant
353 simplification is to compare the change in kinetic energy that must be achieved at maximal and

354 90% of maximal acceleration. The change in kinetic energy ($0.5\text{Mass}\cdot V^2$) is proportional to the
355 square of the change in velocity, such that the 90% sprint condition is associated with a nearly
356 20% reduction in kinetic energy change (and presumably, muscular energetic demand) compared
357 to maximal sprinting velocity. Due to this non-linearity, a 5% reduction in short sprint velocity
358 during repeated sprint training over short distances would correspond to 90% workloads in
359 strength training and endurance training, and might give a more optimal balance of stress, injury
360 risk reduction and adaptive signal retention. This possibility remains to be explored.

361 *Effects of supervised training:* The present study revealed no significant training effects when
362 supervised and unsupervised sprint training at 90% sprint speed were compared (Table 3 and
363 Figure 2). However, the 90SUP group improved Yo-Yo IR2 performance by a moderate margin
364 compared to the other groups, indicating that sub-maximal sprint locomotion efficiency had
365 improved. The lack of effects on maximal and repeated sprint ability may have been affected by
366 the possibility that sprint training at 90% sprint speed is below the lowest effective sprinting
367 intensity for stimulating adaptation. Future studies should therefore explore the effect of directly
368 supervised training with a gradual increase in intensity from sub-maximal to maximal sprint
369 velocity.

370 Mazzetti et al. [10] and Coutts et al. [11] showed that the presence of a training expert was
371 beneficial for maximal strength and power development over time. In contrast to the present
372 study, the training experts in these studies were allowed to adjust the total training load during
373 the interventions. Based on these observations, one could argue that the effect of expert
374 supervision during training is optimized when combined with greater flexibility in the day-to-day
375 training prescription.

376 *Training related constraints:* The within-subject typical variation for 20 m sprint time was 0.025
377 s over the first 6 sprints, or < 1%, demonstrating excellent reliability of the criterion measure. In
378 CON, we observed ± 0.04 s absolute individual variation in mean sprint time between the pre-
379 and post tests. More important, weekly changes in group mean values up to 0.05 s (nearly 2%)
380 were observed in 100UNSUP, despite consistent frequency and volume of games and training
381 sessions during the intervention period (Table 1). This weekly or seasonal variation is
382 considerably higher than the observed typical variability. Our findings emphasize the need for
383 more detailed information about overall conditioning load, accepting that intensity and
384 structuring of training are challenging variables to control in a large group of players from
385 different teams. If improvement of sprinting skills is the primary goal for certain players in-
386 season, future studies should explore whether it is more effective to structure the players` weekly
387 soccer training rather than introducing an additional physical conditioning regime. A perfectly
388 designed conditioning program for certain capabilities may limit other important qualities and
389 vice versa. Coaches and conditioning experts have to balance their training methods and
390 exercises in order to optimize different skills in relation to their contribution to overall soccer
391 performance.

392 More sprint training sessions per week or a longer intervention period could increase the
393 potential for developing faster players. According to the session RPE scale [20], the present
394 participants perceived each sprint session as “somewhat hard” (Table 2). Unfortunately, most of
395 their respective team coaches were not willing to “sacrifice” further soccer training sessions,
396 even in the off-season or early pre-season. Our intervention was shaped by several training-
397 related constraints within the overall soccer training program. We argue that these constraints are

398 indeed an important aspect of assessing the practical efficacy of training interventions in team
399 sport.

400 *Correlations across analyzed parameters:* We observed a significant relationship between
401 individual changes in sprint performance and corresponding changes in BLa^- immediately after
402 the repeated sprint tests (Table 4). There was a moderate trend towards lower individual lactate
403 production with reduced repeated sprint performance, and vice versa. Since individual sprint
404 performance depends upon the ability to fully activate fast twitch motor units with maximal
405 firing frequency [29], it is reasonable to speculate that increased BLa^- during sprinting reflects
406 enhanced neural activation on an individual level.

407 Table 4 reveals a nearly perfect correlation between changes in best sprint time and changes in
408 mean sprint time during 12x20 m sprint from pre- to post test. This is in agreement with Pyne et
409 al. [30], who reported that RSA is more strongly correlated with maximal sprinting velocity than
410 endurance capacity. Even when the recovery time between each 20 m sprint is reduced to 25 s,
411 the difference between mean time and best time remain small [31]. Balsom et al. [32] observed
412 that it is more difficult to detect detrimental effects with short sprints compared to slightly longer
413 sprints. Our results support this observation, as the absolute time difference between best and
414 mean sprint time was only 2x the typical variation calculated from pre-testing (Table 3).

415 Changes in sprint performance were only moderately correlated with changes in CMJ
416 performance among the present players (Table 5). Wisløff et al. [33] reported a strong correlation
417 between maximal strength, sprint performance and vertical jump height, while Salaj & Markovic
418 [34] concluded that jumping, sprinting and change of direction speed are specific independent
419 variables that should be treated separately. According to Thomas et al. [35], variables should be

420 considered specific and independent of each other when the coefficient of determination is less
421 than 0.50. We have previously observed that, at the group level, development in short sprinting
422 distances may occur without development in CMJ ability [3].

423

424 **Perspectives**

425 The present study showed that weekly repeated sprint training sessions at maximal or sub-
426 maximal sprint speed were not sufficient to improve performance outcomes for soccer related
427 sprinting performance. Furthermore, no significant differences in performance outcomes were
428 observed between supervised and unsupervised sprint training groups training at 90% maximal
429 sprinting velocity. More frequent training sessions or longer interventions are obviously
430 required, perhaps in combination with other training forms, increasing the risk of training-related
431 constraints to the overall soccer conditioning. Future studies should explore whether it is more
432 effective to structure the players` weekly soccer training rather than introducing an additional
433 physical conditioning regime. In the absence of evidence supporting the choice of specific
434 training methods at the group level, we suggest that it is essential to diagnose each individual and
435 develop training interventions that target their key physiological and technical weaknesses.

436

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516 **Figure legends**

517 **Figure 1. Intensity distribution for 90UNSUP and 90SUP during all training sessions.**

518 **Figure 2. Individual changes in 15x20 m mean sprint time from pre- to post test.**

519 **Figure 3. 95% confidence intervals of mean sprint time for 100UNSUP during the**

520 **intervention.**

521

522 **Table 1.** Physical and training characteristics at inclusion

Group	Age (yr)	BM (kg)	Height (cm)	Weekly training sessions	Games/ week	Tot. vol. (h/wk)
CON	17 ±1	72 ±11	181 ±6	4.4 ±2.3	0.4 ±0.4	6.8 ±3.3
100UNSUP	17 ±1	66 ±9*	178 ±6	4.4 ±2.3	0.3 ±0.7	6.6 ±3.8
90UNSUP	17 ±1	72 ±6	183 ±5	4.5 ±2.4	0.4 ±1.0	7.0 ±3.5
90SUP	17 ±1	72 ±8	178 ±7	4.4 ±1.6	0.4 ±0.9	6.8 ±2.9

523 Values are mean ± SD. BM= Body mass, Tot. vol. = Total training volume. Training values are
524 based on self-reported weekly averages during the intervention period. There were no significant
525 differences among the groups for any of the variables, except for body mass (*100UNSUP >
526 90SUP, $p=0.04$).

527

528 **Table 2:** Effort related variables in maximal (100%) and sub-maximal (90%) sprinting

Sprint session	15x20m (100% intensity)	30x20m (90% intensity)
Δ sprint time 48 h (s)	0.00 \pm 0.02	-0.01 \pm 0.02
Session RPE	3.8 \pm 1.2	4.0 \pm 1.1
HR _{peak} (beats·min ⁻¹)	170 \pm 10	141 \pm 10*
BLa ⁻ (mmol·L ⁻¹)	4.4 \pm 1.8	2.0 \pm 0.7*
SL (m)	1.55 \pm 0.08	1.56 \pm 0.09
SF (strides/s)	4.36 \pm 0.18	3.87 \pm 0.22*

529 Δ sprint time 48 h = pre-test time minus sprint time 48 hours after the first training session (mean
530 of first 3 sprints for each time point), RPE = rated perceived exertion, HR_{peak} = peak heart rate,
531 BLa⁻ = blood lactate concentration, SL = stride length, SF = stride frequency, * = significantly
532 different from 100 % sprinting ($p < 0.001$).

533

534 **Table 3:** Physical performance within groups from pre to post-test.

Group	Best sprint time (s)	Mean sprint time (s)	CMJ (cm)	Yo-Yo IR2 (m)
Pre 100UNSUP	2.94±0.15	2.98±0.15	34.9±4.8	1509±277
Post 100UNSUP	2.93±0.15	2.98±0.16	35.4±4.2	1606±333
Diff/ <i>p</i> =	-0.03/0.24	-0.03/0.57	1.0/0.66	-34/1.0
95% CI	[-0.07,0.00]	[-0.06,0.01]	[-0.6,2,6]	[-272,205]
Pre 90UNSUP	2.94±0.12	2.98±0.12	33.5±4.0	1504±376
Post 90UNSUP	2.93±0.11	2.98±0.11	33.3±4.2	1644±401
Diff/ <i>p</i> =	-0.03/0.30	-0.02/0.78	0.4/1.0	-1/1.0
95% CI	[-0.07,0.01]	[-0.06,0.02]	[-1.3,2,1]	[-220,117]
Pre 90SUP	2.92±0.11	2.97±0.10	35.9±3.5	1493±480
Post 90SUP	2.91±0.09	2.97±0.08	37.0±3.6	1751±412*
Diff/ <i>p</i> =	-0.02/0.66	-0.03/0.54	1.8/0.15	131/0.81
95% CI	[-0.06,0.02]	[-0.07,0.01]	[0.0,3,6]	[-108,369]
Pre CON	2.93±0.13	2.97±0.14	37.3±3.5	1547±376
Post CON	2.95±0.14	3.00±0.14	36.6±3.6	1693±356
Change	0.02±0.03	0.02±0.03	0.7±1.4	147±237
95% CI	[0.00,0.05]	[0.00,0.05]	[-0.7,1.9]	[-101,395]

535 Pre = pre-test, Post = post-test, CMJ = countermovement jump, Yo-Yo IR2= Yo-Yo intermittent
536 recovery level 2, CI = confidence interval, Diff = Difference vs. control group assessed by
537 estimated marginal mean. *p*= Significance values (Bonferroni adjusted), * = significantly
538 different from pre-test (*p*<0.001).

539 **Table 4:** Underlying performance variables within groups from pre to post-test.

Group	Body mass	HR_{peak}	BLa⁻	SL	SF
	(kg)	(beats·min⁻¹)	(mmol·L⁻¹)	(m)	(strides/s)
Pre 100UNSUP	66.0±8.7	166±10	4.2±1.5	1.56±0.09	4.33±0.33
Post 100UNSUP	66.8±8.4	167±12	5.7±2.1*	1.52±0.11*	4.46±0.35*
Diff/ <i>p</i> =	0.3/1.0	5/0.33	1.9/0.01**	0.00/1.0	0.06/1.0
95% CI	[-0.8,1.5]	[-1,12]	[0.7,3,2]	[-0.07,0.06]	[-0.13,0.25]
Pre 90UNSUP	72.2±5.6	174±9	4.3±1.7	1.55±0.09	4.34±0.22
Post 90UNSUP	72.5±5.1	170±14	4.8±2.0	1.56±0.07	4.32±0.24
Diff/ <i>p</i> =	-0.3/1.0	2/1.0	1.1/0.24	0.04/0.54	-0.09/1.0
95% CI	[-1.4,0.8]	[-5,8]	[-0.1,2.3]	[-0.02,0.10]	[-0.28,0.10]
Pre 90SUP	71.9±8.1	166±10	4.5±2.1	1.54±0.06	4.38±0.12
Post 90SUP	72.2±8.4	164±10	5.3±2.2	1.54±0.09	4.39±0.19
Diff/ <i>p</i> =	-0.3/1.0	4/0.87	1.5/0.09	0.03/0.96	-0.04/1.0
95% CI	[-1.5,0.9]	[-3,11]	[0.2,2.9]	[-0.03,0.10]	[-0.24,0.17]
Pre CON	71.6±11.2	172±6.2	5.2±1.4	1.53±0.08	4.42±0.31
Post CON	72.0±11.4	167±4.6	4.8±1.4	1.50±0.05	4.46±0.22
Change	0.4±1.2	-5±3.1	-0.5±0.7	-0.03±0.08	0.04±0.24
95% CI	[-0.5,1.3]	[-10,1]	[-1.4,0.5]	[-0.09,0.03]	[-0.15,0.23]

540 Pre = pre-test, Post = post-test, HR = heart rate, BLa⁻ = blood lactate concentration, SL = stride
541 length, SF = stride frequency, Diff = Difference against control group assessed by estimated
542 marginal mean. *p* = Significance values (Bonferroni adjusted), * = significantly different from
543 pre-test (*p*<0.01), ** *p*<0.01.

544 **Table 5:** Correlations across analyzed variables

Variables	Upper <i>r</i>	<i>r</i>	Lower <i>r</i>
ΔBLa^- ($\text{mmol}\cdot\text{l}^{-1}$) vs. ΔCMJ (cm)	0.86	0.52	0.27
Δ best sprint time (s) vs. ΔCMJ (cm)	-0.64	-0.42	-0.15
Δ mean sprint (s) vs. ΔCMJ (cm)	-0.64	-0.43	-0.16
Δ heart rate ($\text{beats}\cdot\text{min}^{-1}$) vs. ΔBLa^- ($\text{mmol}\cdot\text{l}^{-1}$)	0.65	0.44	0.17
Δ best sprint time (s) vs. ΔBLa^- ($\text{mmol}\cdot\text{l}^{-1}$)	-0.64	-0.43	-0.16
Δ mean sprint time (s) vs. ΔBLa^- ($\text{mmol}\cdot\text{l}^{-1}$)	-0.61	-0.39	-0.11
ΔSL (m) vs. ΔSF ($\text{strides}\cdot\text{s}^{-1}$)	-0.98	-0.96	-0.93
Δ best sprint time (s) vs. Δ mean sprint time (s)	0.90	0.83	0.71
SL pre vs. SL post	0.76	0.60	0.41
SF pre vs. SF post	0.78	0.63	0.42

545 $n = 45$ for all observations. BLa^- = blood lactate concentration, CMJ = countermovement jump,

546 SL = stride length, SF = stride frequency. Only significant correlations ($p < 0.05$) are reported.

547

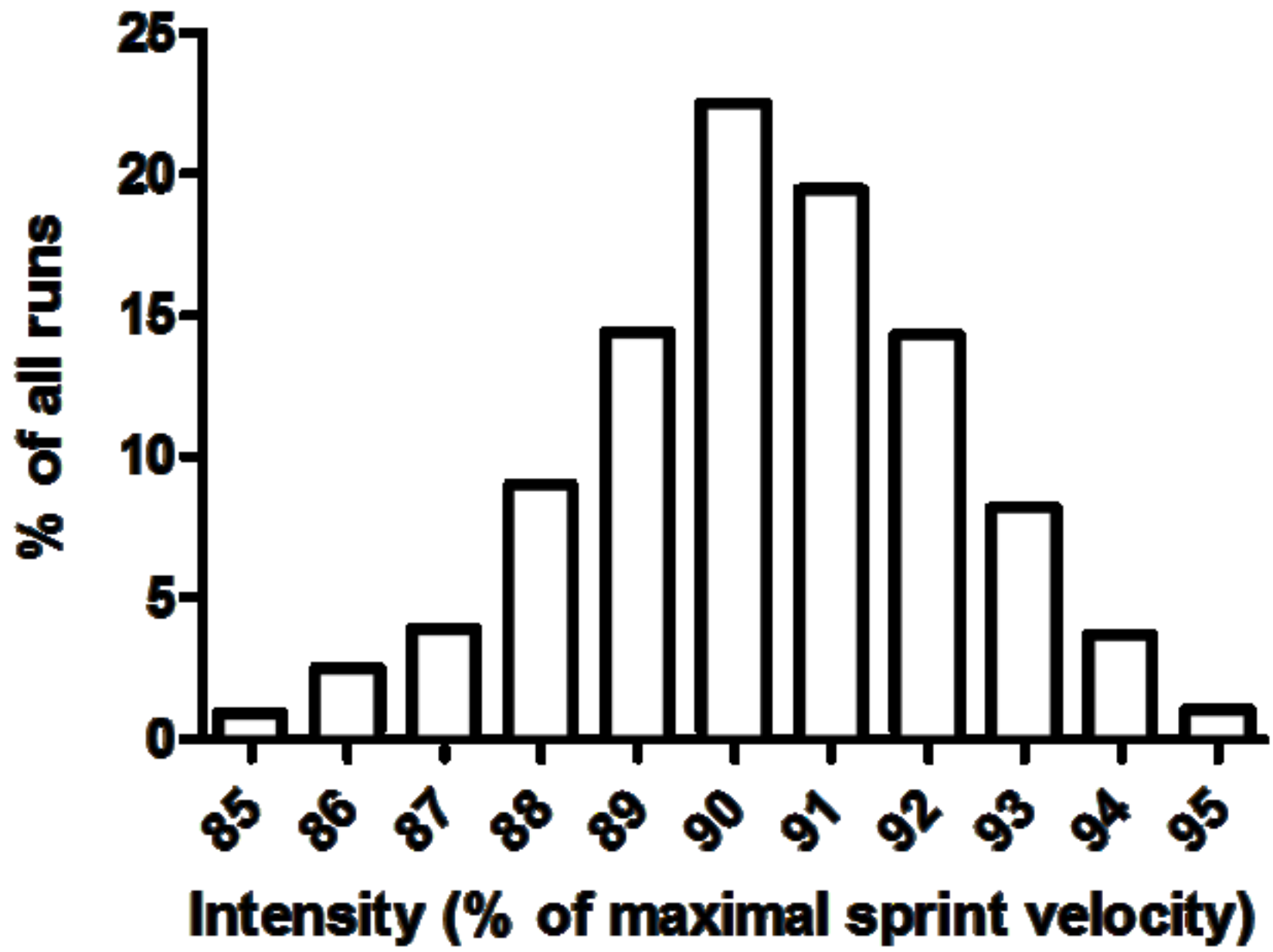


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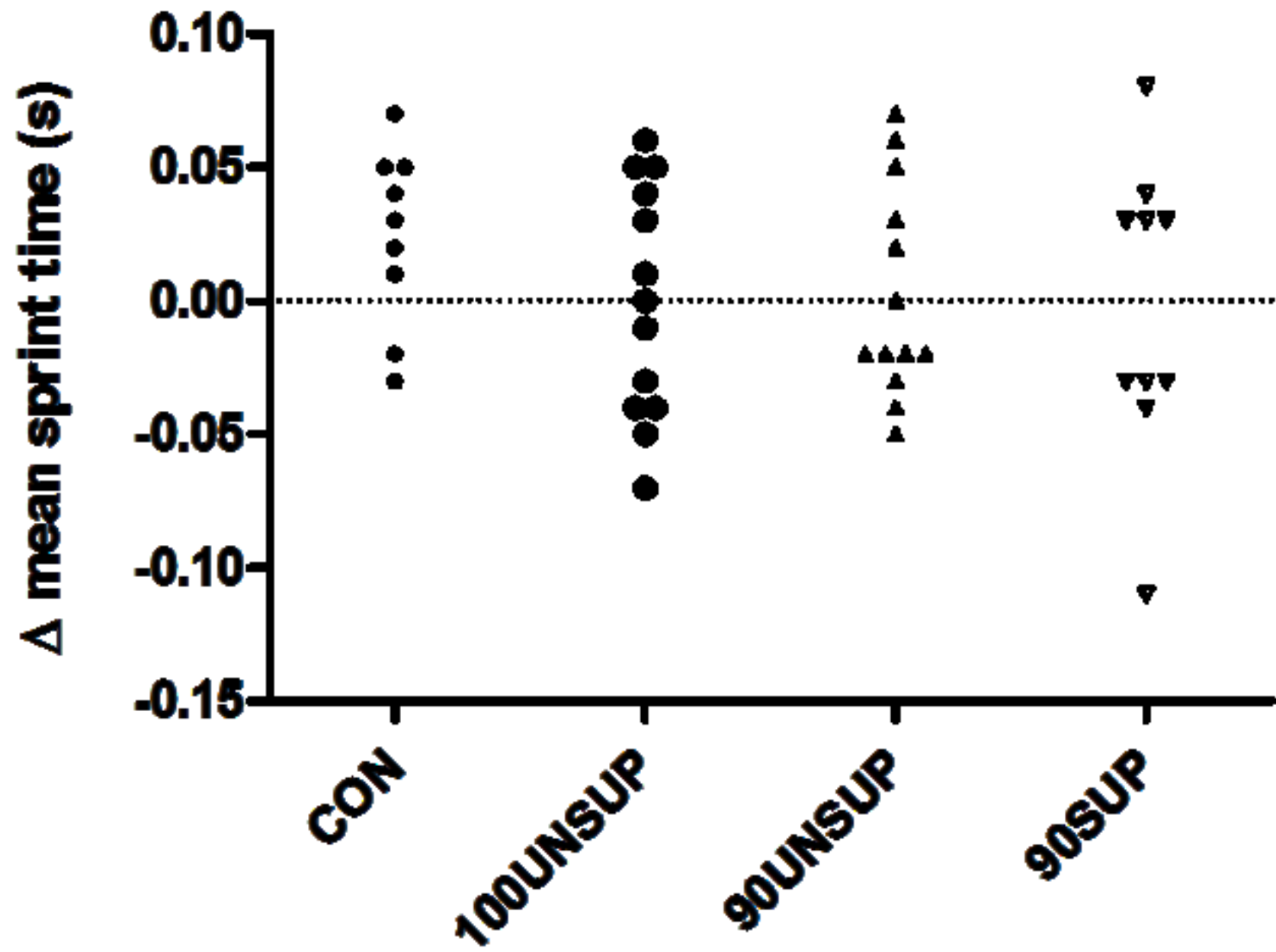


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