Speed Testing:

Methodological Aspects and Applications to Soccer

Zur Erlangung des akademischen Grades eines
DOKTORS DER PHILOSOPHIE
(Dr. phil.)

von der KIT-Fakultät für Geistes- und Sozialwissenschaften des
Karlsruher Instituts für Technologie (KIT)
angenommene

DISSERTATION

von
Stefan Altmann

KIT-Dekan: Prof. Dr. Michael Schefczyk

1. Gutachter: Prof. Dr. Alexander Woll
2. Gutachter: Prof. Dr. Thorsten Stein

Tag der mündlichen Prüfung: 17. Dezember 2019

Acknowledgements

Die vorliegende Dissertation entstand im Rahmen meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Institut für Sport und Sportwissenschaft des Karlsruher Instituts für Technologie (KIT).

Die wissenschaftliche Betrachtung der Bereiche Schnelligkeitsdiagnostik sowie Fußball begleitet und begeistert mich zugleich bereits seit Beginn meines Studiums der Sportwissenschaft. Aus diesem Grund gilt mein herzlicher Dank meinem Doktorvater Prof. Dr. Alexander Woll, der es mir ermöglicht hat, diese beiden Bereiche miteinander zu verknüpfen und meine Dissertation zu meinem Wunschthema – Schnelligkeitsdiagnostik im Fußball – zu verfassen. Neben der intensiven fachlichen Betreuung dieser Arbeit möchte ich insbesondere für die Unterstützung und das Vertrauen im Rahmen vielfältiger Projekte am Institut für Sport und Sportwissenschaft danken, in denen ich meinen fachlichen und persönlichen Horizont deutlich erweitern konnte. Gleichermaßen bedanken möchte ich mich bei meinem Zweitgutachter Prof. Dr. Thorsten Stein für die vertrauensvolle Zusammenarbeit sowohl im Rahmen dieser Dissertation als auch bei gemeinsamen Projekten des BioMotion Centers und der Leistungsdiagnostik sowie für die außerordentliche Unterstützung speziell in der Endphase der Dissertation.

Ebenfalls gilt mein Dank den Kolleginnen und Kollegen am Institut für Sport und Sportwissenschaft, insbesondere den aktuellen und ehemaligen Mitgliedern der Arbeitsgruppe Woll sowie der Leistungsdiagnostik, die maßgeblich dazu beitragen, dass ich auf die bisherige Zeit am KIT mit Dankbarkeit und Freude zurückblicke. Speziell Dr. Sascha Härtel, Dr. Rainer Neumann, Dr. Lars Schlenker, Dr. Steffen Ringhof und Dr. Florian Engel danke ich für den intensiven fachlichen und persönlichen Austausch in den vergangenen Jahren.

Besonders bedanken möchte ich mich bei meiner Familie für die bedingungslose Unterstützung und das Vertrauen in allen Lebenslagen. Zuletzt gilt mein größter Dank meiner Ehefrau Melanie – dein Rückhalt und deine Geduld in den häufigen Phasen der Entbehrungen während der Erstellung meiner Dissertation waren eine unbeschreibliche Hilfe, die ich sehr zu schätzen weiß.

Für Oma

Summary

Within the context of this thesis, speed is considered to be highly task-specific and to incorporate several relatively independent speed skills. In team sports such as soccer, besides other physical, technical, and tactical aspects, speed is widely accepted to play an important role. As a consequence, speed testing has become an essential part of performance assessments in this sport. Currently, there exist a plethora of tests that aim to investigate physical as well as perceptual-cognitive aspects of speed and that are frequently used in soccer research and practice. These existing tests can be categorized into linear sprint, repeated sprint, change-of-direction-sprint, and agility tests as well as combinations of these tests.

From a scientific perspective, in order to be used with confidence and to be able to draw practical conclusions from test results, tests should possess appropriate levels of psychometric properties such as validity and reliability. Therefore, the first aim of this thesis is to comprehensively review the scientific literature on speed tests used in soccer, focusing on the tests' validity and reliability. The findings of this systematic review could aid both scientists and practitioners in deciding which test to choose depending on the specific aspects of speed being of interest.

When looking at elite athletes such as professional soccer players, speed performance of these athletes is usually homogeneous and improvements in speed performance due to training interventions are rather small. Hence, not only the test selection itself should be done with caution but also the specific procedures and equipment applied must permit precise and repeatable measurements. There are a number of methodological aspects that can potentially influence the results of speed tests as well as their validity and reliability. Regarding the timing technology used, timing lights are the most common. Consequently, a second aim of this thesis is to investigate several frequently used methodological approaches, focusing on timing lights, with respect to the test results itself and their validity and reliability. In particular, the four original investigations in this thesis aim to examine the effects of the starting distance to the first timing light (0.3 m–1.0 m) as well as timing light height (0.64 m and 1.00 m) and type (conventional single-beam systems and those using error correction processing) during linear-sprint tests over various distances (5 m–30 m and flying sprints). Again, the findings of these investigations could help those who wish to measure speed performance to select the most promising procedures and equipment.

The results of the systematic review highlight that speed testing in soccer should be based on specific tests in order to address the specific speed skills mentioned above. In terms of linear sprinting (e.g., 5-m, 10-m, 20-m, 30-m, 40-m sprint), repeated sprinting (e.g., 6 x 20-m sprints with 20–25 s of active recovery, 7 x 30-m sprints with 20–30 s of active or passive recovery), change-of-direction sprinting (e.g., T Test, (modified) zig-zag test), and combinations (e.g., (modified) Bangsbo sprint test, repeated shuttle sprint test), there exist a number of valid and reliable tests. However, as no gold-standard test for each skill seems to exist, researchers and practitioners are advised to use the broad database provided in the systematic review for their test selection.

After a specific speed test has been selected, caution should be given to methodological aspects, such as the exact procedures and timing technology applied. In this context, the four original research papers included in this thesis emphasize the influence of methodological aspects on speed test results itself as well as their validity and reliability based on linear sprints over various distances. In case of using conventional single-beam timing lights as a timing technology, results gained by different starting distances from the first timing light are not comparable. The same applies to the comparison of different timing light heights. Because of the high reliability, a starting distance of 0.3 m is advised. Irrespective of timing light height, single-beam systems do not provide valid results over short distances (e.g., 5 m and 10 m), which can be attributed to high measurement errors due to swinging extremities. Conversely, results become more valid with increasing distance (e.g., 30 m). In line with this, flying sprints (e.g., 20-m sprints with a 10-m acceleration phase) can be measured with high validity and reliability using single-beam systems. Bearing the implications of leaning forwards in mind, single-beam timing lights employing error correction processing have been shown to considerably reduce measurement errors, thereby accounting for a high validity of measurement even over short distances (e.g., 5 m and 10 m). Consequently, single-beam timing lights employing error correction processing should be used when possible, especially over short distances.

To summarize, this thesis emphasizes that the selection of both the test itself as well as the exact procedures and timing technology should be done with caution when conducting speed testing (in soccer). Furthermore, this thesis provides practical recommendations for researchers and practitioners who wish to monitor their players‘ speed performance or the effectiveness of a training intervention. In doing so, this thesis contributes to a better understanding of how to test speed with the example of soccer and associated methodological aspects, with speed being one important piece of the puzzle including several other physical, technical, and tactical aspects that contribute to overall soccer performance.

Zusammenfassung

Im Rahmen dieser Thesis wird Schnelligkeit als hochgradig aufgabenspezifisch angesehen. Ebenfalls wird davon ausgegangen, dass Schnelligkeit verschiedene, voneinander relativ unabhängige Fertigkeiten umfasst. In Mannschaftssportarten wie Fußball ist weitgehend anerkannt, dass Schnelligkeit – neben anderen physischen, technischen und taktischen Aspekten – eine entscheidende Rolle zukommt. Als Folge nimmt die Schnelligkeitsdiagnostik eine essentielle Bedeutung während Leistungsdiagnostiken in diesem Sport ein. Derzeit existiert eine Vielzahl an Tests, die darauf abzielen physische sowie perzeptiv-kognitive Aspekte der Schnelligkeit zu erfassen. Ebenfalls finden diese Tests regelmäßig Anwendung in der Wissenschaft und Praxis des Fußballs. Die existierenden Tests können dabei in Linearsprint-, Sprintwiederholungs-, Richtungswechselsprint- und Agility-Tests sowie in Kombinationen dieser Tests eingeteilt werden.

Aus einer wissenschaftlichen Perspektive sollten die wissenschaftlichen Gütekriterien wie Validität und Reliabiliät eines Tests auf einem angemessenen Niveau liegen, um den Test mit Gewissheit verwenden zu können und um in der Lage sein, praktische Schlussfolgerungen aus den Testergebnissen ziehen zu können. Vor diesem Hintergrund ist das erste Ziel dieser Thesis, die wissenschaftliche Literatur zum Thema Schnelligkeitdiagnostik im Fußball mit einem Fokus auf Validität und Reliabilität der Testverfahren umfassend aufzuarbeiten. In Abhängigkeit von den spezifischen infrage kommenden Aspekten von Schnelligkeit könnten die Ergebnisse dieses systematischen Reviews sowohl Wissenschaftlern als auch Praktikern bei der Auswahl des jeweiligen Tests helfen.

Schnelligkeitsleistungen von Elite-Sportlern wie professionellen Fußballspielern sind in der Regel homogen und Verbesserungen in Schnelligkeitsleistungen durch Trainingsinterventionen fallen eher klein aus. Aus diesem Grund muss nicht nur die Testauswahl selbst mit Bedacht erfolgen, sondern auch die spezifische Vorgehensweise und das verwendete Equipment müssen präzise und wiederholbare Messungen ermöglichen. Hierbei gibt es eine Vielzahl an methodischen Aspekten, die die Ergebnisse sowie die Validität und Reliabilität von Schnelligkeitstests beeinflussen können. In Bezug auf die angewandte Messtechnik werden Lichtschranken am häufigsten verwendet. Daher ist das zweite Ziel dieser Thesis, verschiedene häufig verwendete methodische Herangehensweisen mit dem Fokus auf Lichtschranken hinsichtlich der Testergebnisse selbst sowie deren Validität und Reliabilität zu untersuchen. Im Speziellen verfolgen die vier Originalstudien dieser Thesis das Ziel, die Effekte des Startabstands zur ersten Lichtschranke (0,3 m–1,0 m) sowie der Lichtschrankenhöhe (0,64 m und 1,00 m) und -art (herkömmliche Einfachlichtschranken und solche mit Signalverarbeitung) während Linearsprints über verschiedene Distanzen (5 m–30 m und fliegende Sprints) zu untersuchen. Die Ergebnisse dieser Untersuchungen könnten wiederum diejenigen bei der Auswahl der

vielversprechendsten Vorgehensweisen und Equipment unterstützen, die Schnelligkeitsleistungen messen möchten.

Die Ergebnisse des systematischen Reviews zeigen auf, dass Schnelligkeitsdiagnostik im Fußball im auf spezifischen Tests basieren sollte, die die oben erwähnten Schnelligkeitsfertigkeiten untersuchen. In Bezug auf Linearsprinttests (z. B. 5-m-, 10-m-, 20-m-, 30-m-, 40-m-Sprint), Sprintwiederholungstests (z. B. 6 x 20-m-Sprints mit 20–25 s aktiver Erholung, 7 x 30-m-Sprints mit 20–30 s aktiver oder passiver Erholung), Richtungswechselsprinttests (z. B. T Test, (modifizierter Zig-Zag Test) und Kombinationen (z. B. (modifizierter) Bangsbo Sprinttest, wiederholter Shuttle-Sprinttest) liegen eine Vielzahl von validen und reliablen Tests vor. Da es scheint, dass keine Goldstandardtests für die einzelnen Fertigkeiten existieren, wird Wissenschaftlern und Praktikern empfohlen, die umfassende Datenbasis des systematischen Reviews als Grundlage für die Testauswahl zu verwenden.

Nachdem ein spezifischer Test ausgewählt wurde, sollte methodischen Aspekten wie der exakten Vorgehensweise und der verwendeten Messtechnik Aufmerksamkeit geschenkt werden. In diesem Kontext heben die vier Originalstudien dieser Thesis den Einfluss von methodischen Apekten auf die Ergebnisse von Schnelligkeitstests sowie deren Validität und Reliabilität auf Basis von Linearsprints über verschiedene Distanzen hervor. In Bezug auf herkömmliche Einfachlichtschranken sind Ergebnisse, die unter Verwendung unterschiedlicher Startabstände gewonnen werden, nicht vergleichbar. Dasselbe trifft auf die Verwendung unterschiedlicher Lichtschrankenhöhen zu. Auf Basis der hohen Reliabilität wird ein Startabstand von 0,3 m empfohlen. Unabhängig von der Lichtschrankenhöhe können mithilfe von Einfachlichtschranken keine validen Ergebnisse über kurze Distanzen (z. B. 5 m und 10 m) gewonnen werden. Dieses Ergebnis kann einem hohen Messfehler bedingt durch vorschwingende Extremitäten zugeschrieben werden. Im Gegensatz dazu werden die Ergebnisse mit zunehmender Distanz (z. B. 30 m) valider. Damit einhergehend können fliegende Sprints (z. B. 20-m-Sprints mit einer 10-m-Beschleunigungsphase) mit einer hohen Validität und Reliabilität mithilfe von Einfachlichtschranken erfasst werden. Einfachlichtschranken mit Signalverarbeitung reduzieren – unter Berücksichtigung des Effekts einer Vorlage des Oberkörpers – Messfehler beträchtlich und liefern hierdurch auch über kurze Distanzen (z. B. 5 m und 10 m) eine hohe Validität. Aus diesem Grund sollten Einfachlichtschranken mit Signalverarbeitung, vor allem über kurze Distanzen, wenn möglich genutzt werden.

Zusammenfassend hebt diese Thesis hervor, dass sowohl die Auswahl des eigentlichen Tests als auch der exakten Vorgehensweise und der Messtechnik im Rahmen einer Schnelligkeitsdiagnostik (im Fußball) mit Bedacht erfolgen sollte. Darüber hinaus stellt diese Thesis praktische Empfehlungen für Wissenschaftler und Praktiker bereit, die die Schnelligkeitsleistungen ihrer Spieler oder die Effektivität einer Trainingsintervention überprüfen möchten. Damit tägt diese Thesis zu einem besseren

Verständnis, wie Schnelligkeit am Beispiel Fußball getestet werden soll und von damit zusammenhängenden methodischen Aspekten bei. Im Hinterkopf behalten werden muss hierbei, dass Schnelligkeit nur ein wichtiges Teil des Puzzles neben verschiedenen anderen physischen, technischen und taktischen Aspekten darstellt, das die Gesamtleistung im Fußball ausmacht.

Table of Contents

List of Figures

List of Tables

1 General Introduction

1.1 Preface

As the world’s most popular sport (FIFA, 2015), soccer fascinates millions of people around the world every week. Soccer is a complex team sport, requiring the players to master several technical skills such as dribbling, passing, and shooting. These skills must continuously be adopted in a framework consisting of tactical interactions among teammates and opponents. Furthermore, the game is characterized by its intermittent nature, comprising longer low-intensity phases interspersed with short high-intensity periods, placing changing physical demands on the players (Stølen, Chamari, Castagna, & Wisløff, 2005). Its attraction results not least from the fact that the game structure has dramatically changed over the last decades towards a more and more dynamic and faster playing style. While games from years past give the impression to be recorded in slow-motion, modern soccer stands out due to short ball contact times, high passing rates, high player density, and fast transitions (Wallace & Norton, 2014). The changes in game structure also place modified demands on the players. As a consequence, not only technical and tactical aspects but particularly the players‘ speed requirements have changed. They have to perform several accelerations and sprints at maximal speed throughout a match (Haugen, Tønnessen, Hisdal, & Seiler, 2014a). Besides these physical aspects of speed, players need to process information rapidly and to make fast and accurate decisions in order to be successful (Wallace & Norton, 2014), thereby indicating that speed in soccer involves both physical and perceptual-cognitive components (Paul, Gabbett, & Nassis, 2016).

In order to monitor the players’ performances or to evaluate the effectiveness of training interventions, performance assessments are frequently applied in soccer. Based on the widely accepted importance of speed in soccer (Faude, Koch, & Meyer, 2012; Jeffreys, Huggins, & Davies, 2018), speed testing has become a standard component during such performance assessments (Haugen et al., 2014a; Turner et al., 2011). To this end, a variety of tests has been developed aiming to examine physical and perceptual-cognitive aspects of speed (Paul, Bradley, & Nassis, 2015). However, to be used with confidence in both practice and research, and to draw practical conclusions from test results, tests should possess adequate levels of psychometric properties, including validity and reliability (Currell & Jeukendrup, 2008). Therefore, the first aim of the current thesis is to comprehensively review the available literature on speed tests used in soccer with a focus on the tests‘ validity and reliability. Depending on the specific aspects of speed being of interest, both scientists and practitioners might make use of the results of this systematic review in order to decide which test to choose.

At an elite level, the performance differences between the athletes are usually small. In addition, elite athletes such as professional soccer players may spend years of training to improve their speed performance by only a few percent (Haugen, 2017; Haugen, Tønnessen, & Seiler, 2015a). Hence, not only the selection of a test should be done with caution but also the procedures and equipment applied must allow for precise and repeatable measurements. This is mandatory when the speed performance of different athletes should be compared and when small performance changes should be detected (Haugen & Buchheit, 2016). Against this background, there are a number of methodological aspects that can potentially influence the results of speed tests as well as their validity and reliability. Regarding the timing technology used, timing lights are the most common. Consequently, a second aim is to investigate several frequently used methodological approaches during speed testing, focusing on timing lights, with respect to their validity and reliability. In particular, the effects of the starting distance to the first timing light as well as timing light height and type were examined. Again, the findings could help those who wish to measure speed performance to select the most promising procedures and equipment.

As a whole, the results gathered by this thesis can provide a deeper understanding of how to measure speed performance both from a soccer-specific and a methodological view. Thereby, it can provide a solid basis for research involving speed testing, e.g., in the context of monitoring player performance or the effectiveness of training interventions.

1.2 Outline

The present thesis encompasses nine chapters structured according to the hourglass method which is illustrated in Figure 1.1.

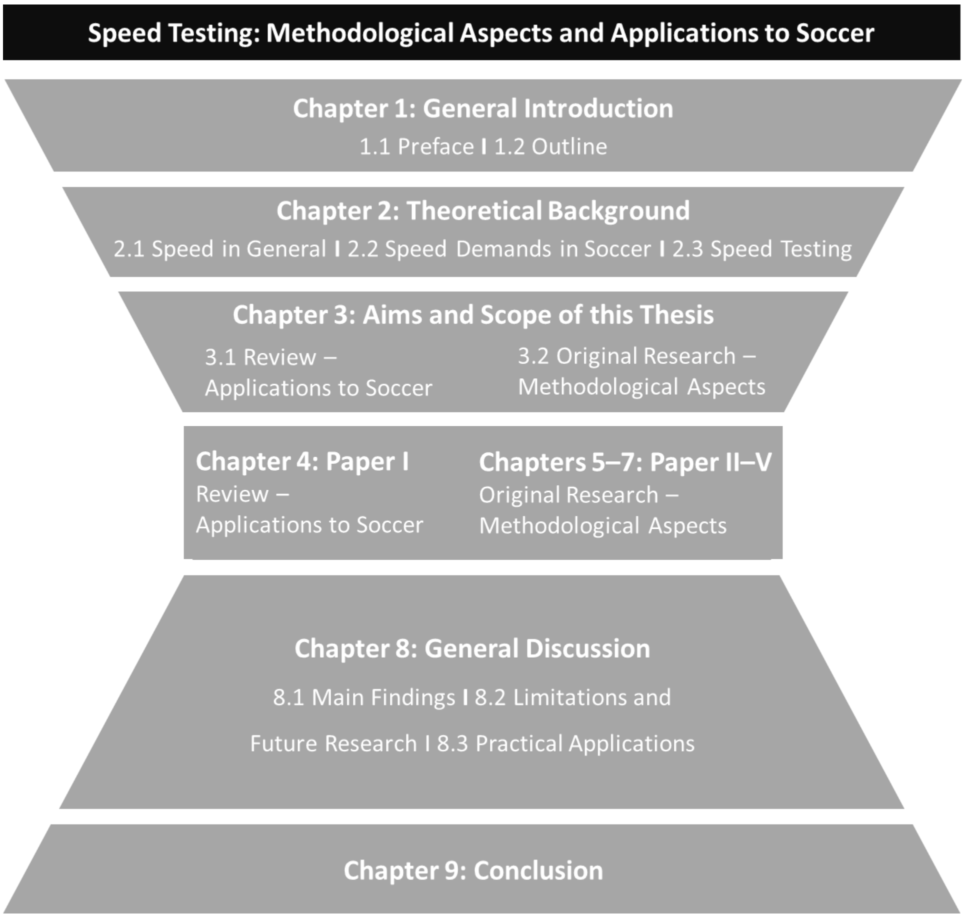


Figure 1.1 Structure of this thesis.

Against the background of the issues regarding speed testing raised in *Chapter 1*, the following *Chapter 2* aims to introduce speed in general. Another focus of the second chapter is to identify speed demands during soccer matches. Based on this, the topic of speed testing is briefly reviewed with both methodological aspects and applications to soccer being covered. Several research questions on this topic remain unsolved, which are addressed in the following chapters. Consequently, *Chapter 3* describes the aims and scope of this thesis.

Chapters 4 to *7* consist of 5 scientific papers (Paper I – Applications to Soccer; Paper II to V – Methodological Aspects) that have been published in international peer-reviewed journals. These papers specifically address the previously deduced research questions, either as a systematic review (Paper I) or as original research (Paper II to V):

Applications to Soccer

- Chapter 4: Speed Testing in Soccer (Paper I)
  Altmann, S., Ringhof, S., Neumann, R., Woll, A., & Rumpf, M. (2019). Validity and reliability of speed tests used in soccer: A systematic review. *PLoS ONE, 14*(8): e0220982. DOI: 10.1371/journal.pone.0220982.

Methodological Aspects

- Chapter 5: Starting Distances (Paper II)
  Altmann, S., Hoffmann, M., Kurz, G., Neumann, R., Woll, A., & Haertel, S. (2015). Different starting distances affect 5-m sprint times. *Journal of Strength and Conditioning Research, 29*(8), 2361–2366. DOI: 10.1519/JSC.0000000000000865.

- Chapter 6: Timing Light Heights (Paper III & IV)
  Altmann, S., Spielmann, M., Engel, F. A., Neumann, R., Ringhof, S., Oriwol, D., & Haertel, S. (2017). Validity of single-beam timing lights at different heights. *Journal of Strength and Conditioning Research, 31*(7), 1994–1999. DOI: 10.1519/JSC.0000000000001889.

  Altmann, S., Spielmann, M., Engel, F. A., Ringhof, S., Oriwol, D., Haertel, S., & Neumann, R. (2018). Accuracy of single beam timing lights for determining velocities in a flying 20-m sprint: does timing light height matter? *Journal of Human Sport and Exercise, 13*(3), 601–610. DOI: 10.14198/jhse.2018.133.10.

- Chapter 7: Type of Timing Lights (Paper V)
  Altmann, S., Ringhof, S., Becker, B., Woll, A., & Neumann, R. (2018). Error Correction Processing in Timing Lights for Measuring Sprint Performance: Does It Work? *International Journal of Sports Physiology and Performance, 13*(10), 1400–1402. DOI: 10.1123/ijspp.2017-0596.

Chapter 8 summarizes the main findings of the above-noted studies and critically discusses these findings in the context of the current literature. Furthermore, recommendations for both researchers and practitioners dealing with speed testing are provided. The thesis closes with a general conclusion in *Chapter 9*.

2 Theoretical Background

This chapter addresses speed in general, thereby discussing definitions and classifications of the term speed as well as describing determining factors of speed. Subsequently, speed demands during soccer matches are described. The last subchapter briefly reviews the topic of speed testing, covering both methodological aspects and applications to soccer.

2.1 Speed in General

Speed can be seen from a variety of scientific perspectives, leading to different definitions and classifications in the context of movement skills and motor abilities. Moreover, there exists a multitude of determinants in relation to speed. Therefore, this subchapter aims to give a brief overview of several existing definitions and classifications as well as determining factors of speed.

2.1.1 Definitions and Classifications

According to physics, speed has been defined as the ratio between distance and time. The same applies to velocity, however, the latter represents a vector and, thus, includes the movement direction (Winter et al., 2016). Relating to sports, speed refers to moving the body (or parts of it) as fast as possible over a given distance (Barlett, 2007). While this view deals with a physical component of speed, other approaches also take a perceptual-cognitive component into account, e.g., the reaction to a stimulus (McLeod, 1987; Nuri, Shadmehr, Ghotbi, & Attarbashi Moghadam, 2013; Williams, Ford, Eccles, & Ward, 2011).

To allow for a definition and a classification of the term speed that can serve as a foundation for this thesis, it is vital to clarify some central concepts of human movement and performance. Looking at the scientific literature, multiple concepts related to human movement can be found. Moreover, terms like movement skills and motor abilities are used inconsistently (Burton & Rodgerson, 2001). Movement skills in the current thesis are defined as a movement class of similar form and function. In contrast, Burton and Miller (1998) defined motor abilities as “general traits or capacities of an individual that underlie the performance of a variety of movement skills”.

As described before, speed can be seen from several perspectives even against the background of sports (Damerow, 2006). Accordingly, a psychologist might focus on perceptual-cognitive aspects, a motor-control specialist on the coordination of sensory and musculoskeletal processes, and a biomechanist on mechanical characteristics that are essential in order to realize a movement. From the view-point of training science, speed has traditionally been considered a unique motor ability, comparable to strength and endurance (Bös, 1987). Accordingly, speed is suggested to be both energetic and information related.

There exist several approaches, which classify speed into different subforms (Schnabel & Witt, 2017). A well-known approach emerging from the research literature divides three subforms, namely reaction speed, cyclic movement speed, and acyclic movement speed (Zaciorskij, 1968). This approach has also made its way into established textbooks (Hohmann, Lames, & Letzelter, 2007). In this context, reaction speed refers to reacting as fast as possible to different types of stimuli, e.g., tactile, acoustic or visual. Cyclic movements, on the one hand, comprise continuous regular movements such as tapping or linear sprinting. Acyclic movements, on the other hand, refer to separate movements where no repetitions of single phases can be observed, e.g., a punch of a boxer, a shot of a soccer player, or changes of direction during racket sports. Indeed, in sports practice, these subforms rarely appear alone but mostly as complex movements. In addition, these subforms can even be further divided (Verkhoshansky, 1996). However, a detailed description goes beyond the scope of this thesis.

In contrast to the abovementioned classification by Bös (1987), recent research suggests that there is no general or basic speed ability that underlies all speed-related requirements during sports. This view is underpinned by the limited relationships between different speed characteristics. An athlete who performs well in basic forms such as tapping does not necessarily achieve comparable results during linear sprinting or change-of-direction tasks (Damerow, 2006; Matlák, Tihanyi, & Rácz, 2016; Verkhoshansky, 1996). In addition, studies have shown that there are relatively low correlations between linear sprinting, change-of-direction sprinting and fast movements in response to generic and sport-specific stimuli (Buttifant, Graham, & Cross, 2001; Little & Williams, 2005; Los Arcos, Mendiguchia, & Yanci, 2017; Paul et al., 2016; Sassi et al., 2009; Šimonek, Horička, & Hianik, 2017; Vescovi & McGuigan, 2008; Young, Dawson, & Henry, 2015). Moreover, there is a limited transfer of linear-sprint training to change-of-direction tasks and vice versa (Young, McDowell, & Scarlett, 2001). In line with this finding, repeated change-of-direction training has been shown to induce specific change-of-direction improvements, while repeated linear-sprint training predominantly enhances repeated linear-sprint performance (Shalfawi, Young, Tønnessen, Haugen, & Enoksen, 2013a). Lastly, an intervention comprising cognitive demanding small-sided games in Australian Rules Football improved performance in a test where the participants had to react to sport-specific stimuli by changing direction. However, these improvements were associated with enhanced perceptual-cognitive aspects of speed rather than change-of-direction performance (Young & Rogers, 2014). Taken together, these results suggest that speed is highly task-specific and that there exist several relatively independent speed skills.

Furthermore, the relationships and transferability between different tasks are assumed to depend on their similarity (Brearley & Bishop, 2019; Issurin, 2013). In that context, Young et al. (2001) showed that there is a transfer from linear-sprint training to a simple change-of-direction task (few directional changes with wide angles) but very limited transfer to more complex tasks (many directional changes with sharp angles). In conclusion, it can be assumed that high speed performance in sports is the sum of specifically-acquired skills. Accordingly, speed is not considered a motor ability anymore in a modified version of the classification by Bös (1987) (Lämmle, Tittlbach, Oberger, Worth, & Bös, 2010).

While the definition and classification of the term speed is still a matter of debate and a definite appraisal is therefore not possible, the following consideration will serve as a foundation for the current thesis:

There is no general or basic speed ability that underlies all speed-related requirements during sports. Speed is defined as specific movement skills referring to moving (parts of) the body as fast as possible, either preplanned or as a reaction to a stimulus.

This shift away from an ability-focused view towards a skill-focused view is also illustrated in Figure 2.1. The present thesis emphasizes speed skills that are running based. Important running-based speed skills in sports include linear sprinting, change-of-direction sprinting, repeated sprinting, and agility (Girard, Mendez-Villanueva, & Bishop, 2011; Haugen & Buchheit, 2016; Paul et al., 2016).

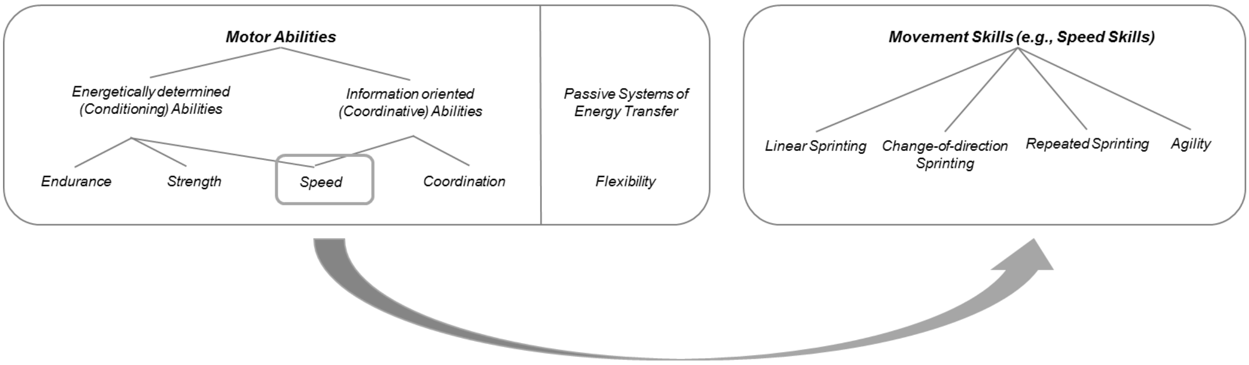


Figure 2.1 Speed in the context of motor abilities (modified illustration; Bös, 1987) on the left side, and in the context of motor skills on the right side. Note that illustrated speed skills are only a selection relating to the current thesis.

In this context, linear sprinting relates to straight-line sprinting over various distances, including acceleration and maximum speed phases (Rumpf, Lockie, Cronin, & Jalilvand, 2016). Moreover, change-of-direction sprinting comprises preplanned whole-body change of direction as well as rapid movement and direction change of limbs (Sheppard & Young, 2006; Young et al., 2015). Repeated sprinting refers to short-duration sprints (< 10 s) interspersed with brief phases of recovery (< 60 s) (Girard et al., 2011). Finally, agility is considered an open skill and has been defined as a „rapid whole-body movement with change of velocity or direction in response to a stimulus“ (Sheppard & Young, 2006). While linear sprinting, change-of-direction sprinting, and repeated sprinting mainly represent physically-driven speed skills, agility refers to both physical and perceptual-cognitive aspects (Girard et al., 2011; Paul et al., 2016).

Now that an understanding of the term speed has been created, the next subchapter will describe underlying determinants of speed skills.

2.1.2 Determinants

As many characteristics of speed and speed skills are evident, so are the determinants that account for their realization. Some of the main, partly overlapping, determinants of the respective speed skills include:

- Psychological Aspects
- Aspects of Motor Control
- Neuromuscular Aspects
- Physiological Aspects
- Biomechanical Aspects
- Genetic Aspects and Trainability

Depending on the specific situation and the speed skill(s) required, the importance and influence of these determinants vary, leading to complex interactions. As a detailed discussion is beyond the scope of this thesis, the following section offers a brief overview of these determinants in relation to several speed skills. Thereby, the focus will be on the abovementioned skills (linear sprinting, change-of-direction sprinting, repeated sprinting, and agility), that incorporate either physical or perceptual-cognitive aspects of speed or both.

2.1.2.1 Psychological Aspects

Psychology of fast and successful skill execution can be understood in several different ways. In the following, aspects emerging from the perspective of cognitive psychology will be addressed. Against this background, a large amount of research is available on perceptual-cognitive aspects in sports (e.g., (Mann, Williams, Ward, & Janelle, 2007; Williams et al., 2011; Williams & Ford, 2008).

While perceptual-cognitive aspects may play a minor role in mainly physically-driven preplanned speed tasks (e.g., linear sprinting, change-of-direction sprinting, repeated sprinting) they become an area of interest relating to unplanned tasks (e.g., changes of direction in response to a stimulus). When exposed to a visual stimulus, e.g., an opponent passing a ball, athletes anticipate the outcome of the action before it is completed. High anticipation skills enable athletes to make fast and accurate decisions, giving them an advantage over opponents with lower anticipation skills. Various studies have shown that knowledge of situations, movement pattern recognition, and visual scanning contribute to identifying relevant cues that, in turn, lead to enhanced anticipation (Mann et al., 2007; Williams et al., 2011; Williams & Ford, 2008). The aforementioned studies were mainly laboratory-based and participants usually were asked to respond verbally to the presented tasks or using pen-and-paper, therefore somewhat lacking stimulus-response compatibility (Kornblum, Hasbroucq, & Osman, 1990) and perception-action coupling (Travassos et al., 2013), respectively.

In contrast, there is a growing body of research using more ecologically valid environments, where participants react in a sport-specific manner (Paul et al., 2016). In this context, an area of special interest is agility. As described above, agility refers to a rapid whole-body movement with change of velocity or direction in response to a stimulus (Sheppard & Young, 2006). As a complex skill comprising both physical and perceptual-cognitive components, agility is thought to play a crucial role in team sports (Young et al., 2015). Recent reviews support this assumption, summarizing that athletes of higher playing standards demonstrate superior performances during agility tasks compared to their counterparts of lower playing standards (Inglis & Bird, 2016; Paul et al., 2016; Sheppard, Dawes, Jeffreys, Spiteri, & Nimphius, 2014). Interestingly, it has been shown that this advantage is mainly attributed to the perceptual-cognitive component of agility (e.g., decision-making). In this context, it is worth noting that the type of stimulus affects the decision-making process. In particular, generic stimuli like flashing lights or arrows do not allow athletes to use their anticipation skills. In contrast, the opposite is true when using sport-specific stimuli such as opponents passing a ball. That is, higher-skilled athletes demonstrate superior performance during tasks that use sport-specific stimuli, while this effect is limited during generic scenarios (Young & Farrow, 2013).

2.1.2.2 Aspects of Motor Control

In the context of speed, **motor control** refers to how to regulate or direct the mechanisms essential for fast movements (Shumway-Cook & Woollacott, 2007), based on the interaction of both the central and the peripheral nervous system (McMorris, 2014). It is widely accepted that motor control is based on a feedforward and a feedback system (Schmidt, 1975; Schmidt & Lee, 2011) which might be utilized to different extents when performing speed skills. On the one hand, feedback (closed-loop) control uses sensory input from interoceptors, exteroceptors as well as proprioceptors, thereby comparing a movement goal to the actual movement. Based on the feedback, differences between a movement goal and the actual movement („error“) can be identified. Subsequently, the motor control system programs instructions to reduce the „error“ (Schmidt & Lee, 2011). The necessary time for initiating corrections ranges between 100 ms and 200 ms, depending on the type of feedback (e.g., proprioceptive, visual) (Desmurget & Grafton, 2000; Schmidt, 1975). Therefore, the feedback strategy can only be utilized with respect to movements that last longer than the respective necessary time. On the other hand, in the case of feedforward (open-loop) control, instructions for a movement are structured prior to their execution. As the feedforward strategy is not sensitive to feedback, the instructions are carried out without the possibility of modification (Schmidt, 1975; Schmidt & Lee, 2011).

Relating to speed demands during sports, most movements comprise both feedforward and feedback control (Wolpert & Ghahramani, 2000; Wolpert & Kawato, 1998; Yeo, Franklin, & Wolpert, 2016). The longer the duration of a movement, the more the outcome is dependent on feedback control. Linear sprinting might be predominantly feedforward-determined at first sight, as even during the initial steps of the acceleration phase the ground contact times are below 200 ms (Harland & Steele, 1997). Consequently, feedback mechanisms to adjust for characteristics like foot placement will occur only at the end of the movement or the ground contact, respectively. It is important to mention that during cyclic movements such as linear sprinting, feedback control is not limited to the current step but can also influence the movement pattern of the following steps. A possible scenario could be that a sprinter twists his ankle and consequently alters his movement pattern by limping.

Feedforward processing also occurs while preparing changes of direction. Based on sensory input from previous experiences, muscles are preactivated to allow for the subsequent deceleration phase (Besier, Lloyd, Cochrane, & Ackerland, 2001b; Chimera, Swanik, Swanik, & Straub, 2004). In contrast to linear sprinting, movement duration and ground contact times are markedly higher during a directional change itself (between 200 ms and 500 ms; Dos'Santos, Thomas, Comfort, & Jones, 2018), allowing for feedback processing to be utilized (Fuerst, Gollhofer, & Gehring, 2017; Taube, Leukel, &

Gollhofer, 2012). In that case, muscle activity is altered in a reactive way by the use of reflexive pathways (Chimera et al., 2004).

However, during unplanned directional changes, poor/inadequate motor control seems to be present, indicated by a mismatch between preprogrammed motor commands (e.g., muscle activation patterns) and joint loading (Weinhandl et al., 2013; Wolpert & Ghahramani, 2000). This observation becomes even more evident when the stimulus that triggers the directional change is presented very late during the running approach. That is, there is not enough time for an adequate motor command based on feedforward processing (Fuerst et al., 2017). In recent studies by Lee et al. (2013; 2017), differences with regard to change-of-direction technique in response to sport-specific stimuli between higher and lower-standard athletes were observed in favor of the higher-standard athletes. This suggests that higher-standard players were able to use a more appropriate feedforward internal model to solve the task. Interestingly, this phenomenon appears to be also represented on a neural level. Research suggests that the cerebellum is a principal brain structure for forward models (Bastian, 2006; Kawato, 1999; Shadmehr, 2017; Wolpert & Kawato, 1998). This assumption is supported by findings that higher-standard players show a stronger activation of the cerebellum when sport-specific stimuli are presented (Balser et al., 2014; Bishop, Wright, Jackson, & Abernethy, 2013). However, as research in this area commonly uses laboratory-based approaches where participants are not required to execute whole-body motor actions, generalizations based on such findings should be treated with caution (Mann, Dicks, Cañal-Bruland, & van der Kamp, 2013; Smith, 2016). In line with this, while it is widely accepted that there exists a dynamical interaction between decision-making and motor control, this interaction has only been studied in a narrow range of less complex tasks rather than in sport-specific settings (Gallivan, Chapman, Wolpert, & Flanagan, 2018).

Coming back to motor control mechanisms during speed tasks, feedback control is also thought to play an important role during repeated sprinting. Specifically, feedback from muscles which fatigue over the course of the task could regulate central motor drive and force output (Girard, Brocherie, Morin, & Millet, 2015b).

2.1.2.3 Neuromuscular Aspects

Neuromuscular aspects of speed relate to the nervous system (central and peripheral), the muscular system, and the interaction of both (Collins, Pearcey, Buckle, Power, & Button, 2018). Temporal sequencing of muscle activation (intermuscular coordination) is considered an important determinant during linear sprinting (Ross, Leveritt, & Riek, 2001). Throughout the running cycle, agonists and antagonists must be activated at the appropriate times and intensities (Howard, Conway, & Harrison, 2018; Majumdar & Robergs, 2011). The intensity of muscle activation is determined by the motor unit activation pattern (recruitment and frequency/firing rate) and increases with increasing sprinting speed (Ross et al., 2001). Considering the frequency, it is suggested that a high nerve conduction speed allows for a high neural firing rate. In addition, a high motoneuron excitability and reflex function is thought to influence muscle contraction or force production, respectively, and therefore performance (Ross et al., 2001).

A well-established determinant of sprinting speed refers to the type of muscle fibers (Majumdar & Robergs, 2011). Research has shown that sprinters benefit from a high proportion of type II muscle fibers, also known as fast-twitch fibers, in relation to type I (slow-twitch) muscle fibers (Bergh et al., 1978; Costill et al., 1976; Mero, 1981; Mero, Komi, & Gregor, 1992). Furthermore, being able to selectively recruit these type II muscle fibers enhances sprinting performance (Ross et al., 2001).

During repeated-sprinting, the typically depressed force development is attributed to a decreased activation (decrease in motor unit recruitment and frequency) of the contracting musculature (Girard et al., 2011). However, the underlying processes causing fatigue in such tasks are not fully understood. Among the possible reasons rank local fatigue (e.g., limited muscle excitability) as well as feedback from the central nervous system (Collins et al., 2018). This feedback is based on intramuscular fatigue yielding a regulation of the neural drive (Girard et al., 2011; Girard et al., 2015b). A shift in the muscle fiber recruitment pattern has also been suggested as a potential reason. As the type II muscle fibers fatigue during repeated sprinting the relative contribution of type I fibers seem to increase as a function of time (Casey, Constantin-Teodosiu, Howell, Hultman, & Greenhaff, 1996). Another potential determinant relates to changes in intermuscular coordination, indicated by modified activation onsets of agonists and antagonists, respectively (Girard et al., 2011).

As with repeated sprints, neuromuscular aspects are altered with regards to change-of-direction sprints compared to linear sprinting. Particularly, the sequencing and intensity of muscle activity vary as a function of change-of-direction angle and approach velocity (Dos'Santos et al., 2018).

As high levels of muscle activation are advantageous during speed tasks, it is plausible to assume relationships between strength and power characteristics on the one side and speed skills on the other side (Cronin & Hansen, 2005). A plethora of research has been conducted on that topic, indicating that different aspects of strength and power contribute on both a neural and muscular level to a high performance in several speed skills. In general, this applies particularly to strength characteristics that are similar in movement pattern and execution speed to the respective speed skill (Cronin & Hansen, 2005; Paul & Nassis, 2015b). However, as these interactions heavily depend on the specific strength and power characteristic as well as the respective speed skills, a detailed discussion is beyond the scope of this thesis (for reviews see Brughelli, Cronin, Levin, & Chaouachi, 2008; Delecluse, 1997; Harries, Lubans, & Callister, 2012; Paul et al., 2016; Paul & Nassis, 2015b; Sheppard & Young, 2006).

2.1.2.4 Physiological Aspects

Physiological aspects refer to the energy supply during speed tasks. A high anaerobic capacity (degradation of creatine phosphate, anaerobic glycolytic metabolism) is an important determinant during single linear and change-of-direction sprint-tasks, while a limited level of aerobic provision to the total adenosine triphosphate (ATP)-turnover is evident. In general, the shorter the task, the higher the anaerobic contribution in relation to the total ATP-production (Majumdar & Robergs, 2011).

In contrast, the contributions of different energy systems change dramatically when the length of the sprint task increases or when sprints have to be completed in a repeated manner with only a short recovery time, e.g., repeated sprinting (Spencer, Bishop, Dawson, & Goodman, 2005). In the latter case, anaerobic glycolytic demands decrease compared to single sprints. As opposed to this, the importance of resynthesizing creatine phosphate increases during repeated-sprint tasks. Concomitantly, an increase in aerobic metabolism has been shown (Girard et al., 2011). Moreover, aerobic metabolism contributes to performance in an additional way as it supports the resynthesis of creatine phosphate between repeated sprints. These findings clearly indicate that, although counterintuitive at first sight, aerobic endurance can influence performance in particular speed tasks (Bishop, Girard, & Mendez-Villanueva, 2011). Indeed, the relative energy system contribution relies on the characteristics of the specific tasks (e.g., sprint duration, number of repetitions, duration and type of recovery). Lastly, whether the accumulation of muscle and blood hydrogen ion contributes to performance decrements during repeated-sprint tasks, is a matter of debate (Girard et al., 2011).

2.1.2.5 Biomechanical Aspects

Another determinant of speed that should be considered is of **biomechanical** nature. Linear sprinting speed is the product of stride length and stride frequency. Therefore, when accelerating, athletes increase both parameters in a linear way. Conversely, when sprinting at higher speeds or when approaching maximum speed, the relative increase in stride frequency is higher than the increase in stride length (Mero et al., 1992). Consequently, high stride frequencies rank among the main contributors to high 100-m sprint performances (Morin et al., 2012). In line with this finding, reduced stride frequencies are considered to accompany fatigue development during repeated-sprint tasks (Girard et al., 2011). Ground contact time has been shown to decrease with increasing sprinting speed as a result of decreased time for both braking and propulsion phases (Morin et al., 2012). Moreover, the vertical peak-to-peak displacement of the body’s center of gravity during the stride decreases in a similar manner while the opposite (increase with increasing speed) has been reported for both horizontal and vertical force production (Mero et al., 1992).

Sayers (2000) suggested that during change-of-direction tasks, the center of mass is lower, accompanied by an increased forward lean compared to linear sprinting, in order to enhance stability and allow for more rapid changes of direction. Furthermore, short ground contact times and great braking and propulsive forces contribute to a high performance during directional changes itself (Dos'Santos et al., 2018). However, biomechanical characteristics vary depending on the specific change-of-direction task. Specifically, parameters such as knee joint loading, whole body kinetics and kinematics, ground reaction force, velocity of center of mass, deceleration and propulsive requirements, and technique, have been shown to be highly influenced by the angle of the directional change(s) and approach velocity (Dos'Santos et al., 2018; Nimphius, Callaghan, Bezodis, & Lockie, 2018). In addition to the angle and approach velocity, the inclusion of generic visual stimuli such as flashing lights or arrows (unplanned change of direction; agility) seems to affect change-of-direction characteristics. In that context, Besier et al. (2001a; 2001b) and Weinhandl et al. (2013) found increased external loads placed on the knee joint and anterior cruciate ligament, respectively, in comparison to preplanned changes of direction. Building on this, Wheeler & Sayers (2010) demonstrated that the change-of-direction technique is modified when reacting to a sport-specific stimulus compared to preplanned conditions. Furthermore, comprehensive studies by Lee et al. (2013; 2017) showed that biomechanical characteristics are not only affected by the presence of a stimulus but also by its type and level of visuospatial and temporal constraints (e.g., generic vs. simple sport-specific vs. complex sport-specific stimuli). Interestingly, the biomechanical characteristics differed between higher and lower-standard athletes particularly in scenarios utilizing high levels of visuospatial and temporal constraints.

2.1.2.6 Genetic Aspects and Trainability

A very popular and frequently discussed topic regarding speed refers to **genetics** and to what extent speed is **trainable** (Hristovski, 2007; Majumdar & Robergs, 2011; Pitsiladis, Davis, & Johnson, 2011). Genetics is defined as the science of heredity and variation in living organisms (Lippi, Longo, & Maffulli, 2010). It has been suggested that athletes might be inherently predisposed towards specialist performance in specific areas, e.g., sprinting (Bouchard, Dionne, Simoneau, & Boulay, 1992). Anecdotally, sprinting speed is thought to be highly dependent on genetics – in the range of 50% – and therefore quite resistant to training (Majumdar & Robergs, 2011). From a scientific perspective, sprinting speed is considered a polygenic trait and a number of polymorphisms have been associated with high performances in this context (Eynon et al., 2013). Among the possible determining polymorphisms, ACTN3 shows the strongest evidence with regards to sprinting performance. The ACTN3 protein is an integral component of fast-twitch muscle fibers and therefore contributes to the determination of muscle fiber type composition. The respective allele has been found to be higher in sprinters compared to controls and endurance athletes (Broos et al., 2016; Eynon et al., 2013; Ma et al., 2013). Further, however, less strong evidence exists relating to the ACE gene. Specifically, the ACE D allele seems to determine sprint performance through enhanced muscle strength gains (Lippi et al., 2010; Wang et al., 2013).

Aside from the abovementioned research derived from a physical perspective, studies have also been conducted focusing on mental and perceptual-cognitive processes (Sheppard & Vernon, 2008). Investigated characteristics include speed of information-processing (e.g., reaction time, inspection time) and executive functions (e.g., inhibition, working memory). These characteristics have been shown to correlate with genetics, resulting in heritability estimates of above 50% (Kuntsi et al., 2006; Wright et al., 2001). In addition, it seems that more complex mental speed measures may be more heritable (Sheppard & Vernon, 2008). However, the studies mentioned above have predominantly been conducted in settings other than sports. Therefore, a special interest relates to whether basic and higher-order cognitive domains like information-processing speed and executive functions (e.g., inhibition and working memory), respectively, transfer to decision-making and anticipation and, therefore, enhance performance during sport-specific situations (Pesce, 2012; Taatgen, 2013). The available „transfer studies“ mainly did not examine speed skills in particular but rather performance in general. However, the research on this topic suggests that the transfer to sports performance generally exists, while team-sport and racket-sports players may benefit the most from improved information-processing speed and executive functions (Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012; Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017; Voss, Kramer, Basak, Prakash, & Roberts, 2010).

Although one can conclude from the above that both physical and cognitive aspects of speed skills are dependent on genetic factors, heredity does only explain a certain degree of the variance in (speed) performance. Consequently, performance is the result of both genetic and environmental factors, such as training (Tucker & Collins, 2012). Training aims to improve certain of the above-described determining factors, and therefore speed performance. In this context, the concept of „deliberate practice“ as proposed by Ericsson, Nandagopal & Roring (2009) suggests that any individual can achieve elite performance through deliberate practice or training, respectively. While this concept has been criticized in some degree and certain questions remain regarding its applicability to sport settings (Hristovski, 2007; Tucker & Collins, 2012), it is important to understand that deliberate practice moderates performance, independent of the extent of performance enhancement.

Again, the individual response to training is also genetically driven to some extent (Bouchard, 2012). Conversely, appropriate training programs lead to performance improvements among different performance levels in various speed skills like linear sprinting (for reviews, see Bolger, Lyons, Harrison, & Kenny, 2015; Petrakos, Morin, & Egan, 2016; Rumpf et al., 2016), repeated sprinting (Bishop et al., 2011; Buchheit, Mendez-Villanueva, Delhomel, Brughelli, & Ahmaidi, 2010; Taylor, Macpherson, Spears, & Weston, 2015), change-of-direction sprinting (Asadi, Arazi, Young, & Sáez de Villarreal, 2016; Brughelli et al., 2008; Miller, Herniman, Ricard, Cheatham, & Michael, 2006), and agility (Paul et al., 2016; Serpell, Young, & Ford, 2011; Young et al., 2015; Young & Farrow, 2013). These improvements are generally higher among athletes at lower performance levels (Haugen, 2017; Petrakos et al., 2016). Conversely, elite athletes that already perform at high levels can improve their performance to only small extends (Tønnessen, Svendsen, Olsen, Guttormsen, & Haugen, 2015). Actually, it is thought that world-class sprinters are already very close to the „citius end“ in terms of the 100-m sprint (Haugen et al., 2015a).

Specific programs and drills for physically-oriented speed skills (e.g., linear sprinting) have been standard components of training in many sports for decades. In contrast, speed skills that are of a perceptual-cognitive nature received less attention in sports practice for a long time. Anecdotally, it is therefore thought that there might be higher performance reserves regarding perceptual-cognitive speed skills. High perceptual-cognitive skills are moderated by training experience and can be achieved through a high amount of hours practicing appropriate tasks (Williams et al., 2011). In addition, specific training interventions have also shown to improve perceptual-cognitive skills, such as anticipation and decision-making among various performance levels (Broadbent, Causer, Williams, & Ford, 2015; Spiteri, McIntyre, Specos, & Myszka, 2018; Williams et al., 2011; Zentgraf, Heppe, & Fleddermann, 2017).

To summarize, there is evidence that genetics influence the predisposition to obtain elite performance. Nevertheless, training helps to improve the likelihood to achieve the individual genetically controlled maximum performance (Tucker & Collins, 2012). Therefore, (elite) speed performance results from both genetic and environmental factors, such as training, as well as their interaction (Lippi et al., 2010).

This subchapter provided a brief overview of several main determinants of speed performance, including psychological, motor control, neuromuscular, physiological, biomechanical, and genetic aspects as well as trainability. The importance of each determinant differs between kind of sports and the specific speed skill in question. In addition, it is important to understand that these determinants do not act independently but interact with each other during planning, executing, and evaluating movements. These interactions between different determinants of speed become obvious during complex tasks in team sports in which psychological aspects, e.g., high anticipation skills might influence the quality of the motor control processes. Moreover, the motor commands affect the neuromuscular activity, which, in turn, alters the physiological demands and biomechanical characteristics of a certain movement. Individual differences in the abovementioned determinants and consequently speed performance are moderated by both genetics and training.

Now that the term speed has been introduced in general, in the next subchapter, a reference to soccer will be established by discussing speed demands during soccer matches.

2.2 Speed Demands in Soccer

In order to determine which speed skills are relevant to soccer, it is essential to analyze the speed demands during match play. In the past, match analysis was carried out through effortful video and notational analysis (Barris & Button, 2008; O'Donoghue, 2004). Nowadays, a variety of progressive technologies such as semi-automatic multiple-camera systems, accelerometry as well as global and local positioning systems (GPS, LPS) are commonly used to track players‘ activity profiles (Buchheit & Simpson, 2017; Carling, Bloomfield, Nelsen, & Reilly, 2008b; Malone, Lovell, Varley, & Coutts, 2017; Palucci Vieira, Carling, Barbieri, Aquino, & Santiago, 2019; Sarmento et al., 2014; Whitehead, Till, Weaving, & Jones, 2018).

A plethora of studies has been conducted aiming to analyze both the general match demands and specific speed demands during soccer matches (Brito, Nassis, Seabra, & Figueiredo, 2018; Carling, 2013; Castellano, Alvarez-Pastor, & Bradley, 2014; Sarmento et al., 2014; Trewin, Meylan, Varley, & Cronin, 2017). Two main issues arise when interpreting results from those studies: Firstly, the abovementioned technologies vary regarding their underlying measurement principle. This leads to different measurement properties in terms of validity and reliability in capturing players‘ movements (Buchheit et al., 2014; Linke, Link, & Lames, 2018; Scott, Scott, & Kelly, 2016). Therefore, direct comparisons between results gained from different technologies should be treated with caution (Buchheit, 2017; Randers et al., 2010). Secondly, there exist different definitions and conflicting classifications of activity categories such as jogging, high-intensity running, and sprinting (Mackenzie & Cushion, 2013; Palucci Vieira et al., 2019; Sarmento et al., 2014; Sweeting, Cormack, Morgan, & Aughey, 2017). For example, a sprint can be defined as activities above 18.0 km/h (Castagna, Manzi, Impellizzeri, Weston, & Barbero Alvarez, 2010), while other studies set the minimum speed at 25.2 km/h (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007b) or even 30.0 km/h (Mohr, Krustrup, & Bangsbo, 2003). In addition, the minimum duration of a respective activity to be coded as a sprint varies between 0.5 s (Gregson, Drust, Atkinson, & Salvo, 2010), 1.0 s (Carling, Le Gall, & Dupont, 2012), and 2.0 s (Altmann, Kuberczyk, Ringhof, Neumann, & Woll, 2018a). Conversely, other researchers do not state the minimum duration (Dellal et al., 2011; Di Salvo et al., 2010).

Despite these limitations, the current body of research provides valuable information on soccer players‘ speed demands during matches. Specifically, the following topics of interest in relation to this thesis will be discussed:

- Evolution of Speed Demands
- Sprinting and Accelerating
- Changes of Direction During Sprinting
- Repeated-Sprint Sequences
- Soccer-Specific Aspects of Sprinting
- Perceptual-Cognitive Aspects and Agility
- Influencing Factors and Variability of Speed Demands

As the demands placed upon goalkeepers markedly differ from those of outfield players, only the latter will be addressed in the following (for review of goalkeepers‘ match demands, see White et al., 2018).

2.2.1 Evolution of Speed Demands

Soccer constantly evolves, and so do the match demands that relate to speed actions. This is highlighted by a study on world-cup finals from 1966 to 2010 (Wallace & Norton, 2014). During this 44-year period, ball speed as an indicator of game speed increased by 15%. Concomitantly, authors reported an elevated player density, defined as the congestion of players around the ball, as well as an increase in passing rate by 35%. Although not investigated in that study, authors suggested that this evolution would affect the speed of player movement and decision-making demands. Consequently, speed should be prioritized as a critical element in elite-level soccer and future game demands would presumably require faster decision-making athletes (Wallace & Norton, 2014).

While the evolution of the latter (perceptual-cognitive) aspect, e.g., anticipation and decision-making, has not been investigated in particular, some studies examined the evolution of physical aspects of speed, such as sprinting. In this context, Barnes et al. (2014) showed that the sprinting distance in the English Premier League increased by 35% between the seasons 2006/2007 and 2012/2013 with a concomitant increase in the number of sprints. In contrast, the mean distance per sprint slightly decreased during that time period. The same research group investigated the evolution of sprinting relating to playing position (Bush, Barnes, Archer, Hogg, & Bradley, 2015a). Accordingly, all positions increased total sprinting distance and number of sprints in the abovementioned time period with wide positions demonstrating the most pronounced increases. In the English Premier League, a closing gap between the top 4 teams and those finishing in the following 4 places across the number of sprints has been observed, indicating that sprinting requirements are becoming more challenging among the best teams (Bradley et al., 2016).

In conclusion, it can be assumed that speed demands during matches have increased both in the long-term (1966–2010) and short-term (2006–2013), with clear evidence being reported for physical aspects of speed (e.g., sprinting).

2.2.2 Sprinting and Accelerating

Professional outfield soccer players usually cover between 10 and 13 km over the course of a game (Barnes et al., 2014; Mohr et al., 2003; Stølen et al., 2005). While high-intensity runs and sprints, usually defined as running between 19.8–25.1 km/h and above 25.1 km/h, respectively, only account for 7–12% and 1–4% of the total distance covered (Bradley et al., 2009; Carling et al., 2008b; Di Salvo et al., 2010), these actions can be decisive. This statement is supported by research of Faude et al. (2012), who investigated goal situations in the German Bundesliga. They found that 83% of all goals were preceded by high-intensity actions of the scoring or assisting player, with linear sprinting being the most frequent action.

The sprinting profile of soccer players has been well investigated. Depending on the tracking technology and definition used, players sprint between 20 and 40 times per game, thereby covering a distance of 250 m to 400 m. The average distance per sprint is around 10–15 m (Andrzejewski, Chmura, Pluta, Strzelczyk, & Kasprzak, 2013; Barros et al., 2007; Dellal et al., 2011; Di Salvo et al., 2007; Di Salvo et al., 2010; Gregson et al., 2010). Short distances (< 10 m) account for 60–70% of the total sprinting distance and middle distances (10–30 m) for 20–30%, while longer sprints (> 30 m) occur very rarely (4–7%) (Di Salvo et al., 2010; Rehhagel, 2011; Stølen et al., 2005). Positional differences regarding sprinting behavior have been examined by several researchers. Accordingly, full backs and wingers have been shown to cover the highest number of sprints as well as the greatest absolute sprinting distance, with similar values obtained for forwards. Central midfielders perform fewer sprints and demonstrate shorter absolute distances while sprinting, followed by central defenders (Di Salvo et al., 2007; Di Salvo et al., 2010; Gregson et al., 2010; Mohr et al., 2003; Sarmento et al., 2014). In line with this, Ingebrigtsen et al. (2015) and Vigh-Larsen et al. (2018) found that wide players exhibit greater sprinting distances than central players. Differences between positions become less evident when regarding the distance of a single sprint. However, Di Salvo et al. (2010) suggest that central midfielders perform more sprints of shorter distances (e.g., 5 m) compared to other positions.

During soccer matches, a large amount of high-intensity actions are of short durations and commence from low velocities, hence often do not exceed the speed threshold necessary to be coded as a sprint (Sweeting et al., 2017). Therefore, accelerations has been introduced as an additional measure in terms of speed demands (Dwyer & Gabbett, 2012; Harper, Carling, & Kiely, 2019). Accordingly, based on an acceleration definition of minimum 2.78 m/s^2, Varley & Aughey (2013) found accelerations to occur eight times more frequently than sprinting. Similar results have been obtained in other studies (Ingebrigtsen et al., 2015). As with sprinting, wide players seem to perform more accelerations than central players (Baptista, Johansen, Seabra, & Pettersen, 2018; Ingebrigtsen et al., 2015; Vigh-Larsen et al., 2018). However, various definitions of accelerations have been used in recent literature, which should be kept in mind when comparing the results of different studies (Abbott, Brickley, & Smeeton, 2018; Sonderegger, Tschopp, & Taube, 2016; Sweeting et al., 2017).

Total sprinting distance has been shown to differentiate international top-class players from lower-level professional players (Mohr et al., 2003) and teams with a high ranking in professional leagues compared to lower ranked teams (Ingebrigtsen et al., 2012) in favor of the top-class players and high-ranked teams, respectively. Conversely, research also exists that show no differences between playing levels (Bradley, Di Mascio, Peart, Olsen, & Sheldon, 2010) or even opposing results (i.e., teams from lower divisions cover more distance while sprinting than teams from higher divisions) (Bradley & Noakes, 2013; Di Salvo, Pigozzi, González-Haro, Laughlin, & Witt, 2013). Currently, there is no data available, if the number of accelerations can differentiate performance levels. Future research could benefit from using consistent definitions of the respective parameters as well as studies that enable a more thorough understanding of accelerations.

2.2.3 Changes of Direction During Sprinting

It is assumed that sprints during soccer matches are not always in a straight line but also include changes of direction. Hence, training of directional changes while sprinting has become a standard component of conditioning programs (Nimphius et al., 2018; Turner & Stewart, 2014). As opposed to this, there is surprisingly little research that objectively examines this assumption (Haugen et al., 2014a; Taylor, Wright, Dischiavi, Townsend, & Marmon, 2017). The only study that particularly investigated changes of directions during sprinting revealed that approximately 50% of all sprints during professional matches incorporate at least one directional change (Rehhagel, 2011). Thereby, most of these sprints are performed with one change of direction, while two occur rather seldom within a sprint. The angles of directional changes have been stated as 39% for <45°, 33% for <90°, 12% for <135°, and 16% for <180° (Rehhagel, 2011). The domination of relatively wide angles of directional changes is supported by findings of Bloomfield et al. (2007) who reported that 609 out of 726 turns during the match are of an angle between 0° and 90°. Albeit, this high number of turns results from all actions and not only sprints during the game being analyzed. In line with this, Robinson et al. (2011) demonstrated that while running, 65% of directional changes are of angles between 45° and 135°, while angles >135° represent only 35%, and Nedelec et al. (2014) only captured 11.9 „hard changes of direction“ during matches. Moreover, in another study where only turn angles ≥90° were analyzed, angles between 90° and 180° were performed more often, while sharp turns (271°–360°) were the least common (Baptista et al., 2018). A detailed evaluation of movement patterns associated with high-intensity runs was performed by Ade et al. (2016). Authors analyzed turns (0°–90°, 91°–180°), swerves (directional change at speed without rotating the body), and arc runs (moving in a semi-circular direction). In addition, results were presented as percentages in and out of ball possession as well as before, during, and after the high-intensity runs. In possession, the actions performed before high-intensity runs were 10.9% arc runs, 36.1% 0°–90° turns, and 11.7% 90°–180° turns. During high-intensity runs, 19.4% arc runs and 38.2% swerves were observed. After the high-intensity efforts, arc runs, 0°–90° turns, and 90°–180° turns occurred in 12.0%, 31.9%, and 18.5% of the scenarios, respectively. Out of ball possession, the following movement patterns were observed. Before: 10.4% arc runs, 29.4% 0°–90° turns, 20.6% 90°–180° turns; during: 15.7% arc runs, and 38.6% swerves; after: 18.2% arc runs, 30.7% 0°–90° turns, 19.5% 90°–180° turns. In sum, this study emphasizes that non-linear movement patterns such as turns, arc runs and swerves occur in approximately 50–70% of all high-intensity runs and wider angles occur more often than sharper angels. As the related speed during high-intensity runs was 23.1 km/h on average, the results of this study to some extent can be transferred to sprinting as this speed is above the sprinting threshold being used in several other investigations (Barros et al., 2007; Di Salvo et al., 2007). As such, the study of Ade et al. (2016) produced comparable results in relation to those of Rehhagel (2011). Regarding positional differences in terms of directional changes, conflicting results have been reported (Ade et al., 2016; Baptista et al., 2018; Bloomfield et al., 2007; Robinson et al., 2011). Therefore, it is not clear from the available literature, which playing position carries out the most changes of direction and if angles vary between positions. In the context of directional changes, decelerations (reduction of speed) is an important aspect (Sweeting et al., 2017). Decelerations have been shown to occur 62–99 times during matches (Baptista et al., 2018; Vigh-Larsen et al., 2018), thereby accounting for up to 18% of total distance (Akenhead, Hayes, Thompson, & French, 2013). Taken together, the research available on this topic suggests, that changes of direction occur frequently during soccer matches and approximately half of all sprinting actions incorporate at least one directional change, usually at a wide angle. However, as the number of studies particularly referring to sprinting is limited, more research is necessary to confirm these findings and to gain more detailed insights on this topic.

2.2.4 Repeated-Sprint Sequences

Given the intermittent nature of soccer (Stølen et al., 2005), it is thought that players have to perform sprints in a repeated manner, interspersed with only brief recovery bouts (Bishop et al., 2011). However, in the past years only a limited amount of studies investigating the occurrence of repeated-sprint sequences during matches of male adult teams have been conducted (Carling et al., 2012; Schimpchen, Skorski, St. Nopp, & Meyer, 2016; Varley, Gabbett, & Aughey, 2014). Therefore, in the following, research dealing with adult female players are also taken into consideration (Datson, Drust, Weston, & Gregson, 2018; Gabbett & Mulvey, 2008; Gabbett, Wiig, & Spencer, 2013; Nakamura et al., 2017). As with single sprints, the definitions of repeated-sprint sequences vary between studies including bouts of ≥3 sprints (≤30 s recovery), ≥3 sprints (≤21 s recovery), and ≥2 sprints (≤20 s recovery). In professional women's matches, such sequences have been reported to occur 5.1 ± 5.1 (Gabbett et al., 2013), 4.8 ± 2.8 (Gabbett & Mulvey, 2008), 2.3 ± 2.4 (Nakamura et al., 2017), and 1.1 ± 1.1 (Datson et al., 2018) times per player. Lower frequencies seem to be evident for professional men, with 1.8 ± 1.7 (Schimpchen et al., 2016), 1.1 ± 1.1 (Carling et al., 2012), and even 0 sequences (Varley et al., 2014) per player being observed. On average, a repeated-sprint sequence comprises 3 to 4 sprints (Carling et al., 2012; Gabbett & Mulvey, 2008; Schimpchen et al., 2016). Carling et al. (2012) investigated positional differences and found central defenders to perform the lowest and full backs the highest amount of such sequences. Interestingly, the recovery intensity between sprints of a sequence also differed with respect to the positional role in that study. While the recovery was active in nature for all positions, central midfielders performed substantially more movements at higher intensities compared to other positions.

Overall, the occurrence of repeated-sprint sequences in professional soccer is infrequent, thereby questioning the importance of repeated sprints in its classical definition (Taylor, Macpherson, Spears, & Weston, 2016). Moreover, Schimpchen et al. (2016) observed no decrement in maximum speed throughout the repeated-sprint sequences, even relating to the most demanding bouts consisting of 5 consecutive sprints. Therefore, several authors refer to the importance of other „maximal actions“ (Dalen, Øverås, van den Tillaar, Welde, & Heimburg, 2018) such as jumps, tackles, changes of direction, accelerations, and decelerations that occur more frequently during match play (Dalen et al., 2018; Schimpchen et al., 2016; Taylor et al., 2016). These actions can cause high physical stress on the players, thereby leading to fatiguing effects similar to sprinting, even though the maximum velocities are low. In particular, the frequent occurrence of accelerations (Varley & Aughey, 2013) has led to the introduction of repeated-acceleration bouts as a new concept (Barberó-Álvarez, Boullosa, Nakamura, Andrín, & Weston, 2013; Taylor et al., 2016). The frequency of repeated-acceleration bouts has not been investigated in adult soccer so far. Nevertheless, research from sub-elite and elite youth soccer indicates the occurrence of 7.3 ± 4.7 (Barron, Atkins, Edmundson, & Fewtrell, 2016) and 5.1 ± 3.5 to

8.0 ± 4.6 (Serpiello et al., 2018) repeated-acceleration bouts per player (three consecutive accelerations interspersed with a maximum of 45 s). Certainly, while investigations with elite male players are needed, these results provide first insights into the importance of repeated accelerations during soccer matches. To sum up, while sequences of repeated sprints appear to be rather less important (at least in men's soccer), a deeper understanding of repeated-acceleration sequences through future studies seems promising.

2.2.5 Soccer-Specific Aspects of Sprinting

Most research evaluating speed demands in soccer matches considered the respective speed action (e.g., acceleration, sprint) in isolation. Conversely, markedly less information is available that integrates the associated movement patterns or technical and tactical data besides physical demands (Bradley & Ade, 2018; Mackenzie & Cushion, 2013). Along with the above-described directional changes related to sprints, there are a number of other aspects of interest, such as movement patterns, technical skills, and tactical actions prior to, during, and after such actions.

Accelerations and sprints are usually not initiated from a standing position but rather when moving at different intensities. Thereby, low running speeds are most common (Rehhagel, 2011; Varley & Aughey, 2013). According to Rehhagel (2011), the proceeding actions comprise pass (37%), dribbling (29%), tackle (18%), and header (16%). 12% of sprints are performed while dribbling with the ball, 36% while the own team is in ball possession, and 52% out of possession. Sprints are often performed with direct contact with one or more opponents (68%). This contact rarely takes place during the whole sprint but more frequently at the end. After a sprint, tackles and actions performed without the ball are most common (Rehhagel, 2011). Ade et al. (2016) conducted a detailed position-dependent analysis of technical skills and tactical actions associated with high-intensity runs. While running with the ball, such efforts were greatest in wide midfielders compared to other positions. Wide midfielders also executed the most tricks and together with full backs the most crosses after the effort. When out of ball possession, central forwards more often run directly towards an opponent on the ball in order to close down the opposition. Conversely, central forwards tracked opposition runners less frequently compared to other positions (Ade et al., 2016). From the limited information currently available, it seems obvious that more research is needed focusing on soccer-specific aspects of sprinting. This information could aid the design of more game-realistic drills and test procedures.

2.2.6 Perceptual-Cognitive Aspects and Agility

It is assumed that the perceptual-cognitive capacities of soccer players are taxed throughout the match (Gabbett, Carius, & Mulvey, 2008a; Lamas, Drezner, Otranto, & Barrera, 2018; Vestberg et al., 2012; Vestberg et al., 2017; Young et al., 2015). In this context, of special interest are game situations where agility is vital. Such situations require the players to perform rapid movements with change of velocity or direction in response to a stimulus (Paul et al., 2016). As such, players need to anticipate in order to make fast and accurate decisions. Examples are intercepting or reaching a pass, evading an opponent, and creating or closing space between oneself and an opponent (Ade et al., 2016). Wallace & Norton (2014) postulate that anticipatory and decision-making skills have become even more important due to higher passing rates, player density, and game speed in modern soccer.

Accordingly, methods for analyzing decision-making during training and competition have been developed (Lorains, Ball, & MacMahon, 2013) and applied to soccer (Gabbett et al., 2008a; González-Víllora, Serra-Olivares, Pastor-Vicedo, & Da Costa, 2015; Romeas, Guldner, & Faubert, 2016). However, there is scarce research available examining stimuli that proceed fast movements or changes of direction during matches. In doing so, the most relevant stimuli according to playing position could be identified.

Although not particularly designed for that purpose, research by Ade et al. (2016) allows for initial context and position-specific insights into this topic. Relevant stimuli for central defenders might be opponents playing a long pass over the defense through the center of the pitch or a ball passed down the side of the pitch. A teammate ahead who dribbles with the ball could be the signal for a full back to perform an overlapping run. Both central defenders and full backs intercept passes from opponents more often than other positions as a result of anticipating the passing direction. In addition, central defenders, full backs, and central midfielders frequently run to cover space or a player on the pitch whilst remaining goal side. However, the actions triggering this behavior can be manifold. The authors also indicate that, except for central forwards, running alongside an opponent with or without the ball is frequent in its occurrence. Therefore, opponents that need to be tracked seem to represent a frequent stimulus for most positions. To put pressure on the opponent‘s defense, wide midfielders and central forwards often run directly towards opposition players on the ball. Another important stimulus for central forwards seems to be passes from teammates. Anticipating the correct moment, forwards try to receive the through pass by sprinting into open space behind the defenders (Ade et al., 2016). Clearly, this study represents only a first approach. Further studies are therefore warranted to better understand relevant context and position-specific stimuli relating to situations that require agility during soccer matches.

2.2.7 Influencing Factors and Variability of Speed Demands

While little information is available regarding accelerations and other soccer-specific aspects of speed (Vigh-Larsen et al., 2018), influencing factors of sprinting behavior have been addressed in a number of studies. Accordingly, sprinting behavior during matches is affected by several contextual and tactical factors (Paul et al., 2015; Trewin et al., 2017). Opposition ranking has been shown to alter total sprinting distance, with greater sprinting distances being observed when playing against higher ranked teams (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009). Referring to the scoreline, sprinting distance decreases during matches when winning (Castellano, Blanco-Villaseñor, & Alvarez, 2011a; Lago, Casais, Dominguez, & Sampaio, 2010). Additional factors that have been identified to influence sprinting behavior include seasonal variation, ball possession (Di Salvo et al., 2009), playing formation, fatigue, and pacing (Bradley & Noakes, 2013).

Different studies examined the variability of match-related sprinting. Similar results have been obtained among these studies, indicating a high within and between match variability of sprinting distance and number of sprints. The variability, expressed as a coefficient of variation in percent, ranges between 31% and 37% (Bush, Archer, Hogg, & Bradley, 2015b; Carling, Bradley, McCall, & Dupont, 2016; Gregson et al., 2010). The studies also demonstrate the position-dependency of sprinting variability. However, position-specific variability differed between studies. Therefore, Carling et al. (2016) suggest that variability estimates for different positions cannot be transferred to other leagues or teams. Moreover, even within a single team, the variability differed between players of the same position (e.g., full backs). Hence, there is a need to quantify individual variability when monitoring players.

Notably, in a study of Bush et al. (2015b) the variability of sprinting distance was altered to only a small extent by match context (match location, match result, and opposition standard). Authors concluded that the influence of match contexts on sprinting performance reported in other studies is possibly driven by different tactics and playing strategies rather than the inherent variability between matches.

In conclusion, these abovementioned findings question the appropriateness of sprinting variables as stable indicators of match performance in soccer (Carling et al., 2016). However, reliable measures are essential for monitoring training interventions or the contribution of underlying capabilities (Mackenzie & Cushion, 2013). While results from match analysis can aid in designing specific training drills, this issue clearly highlights the necessity of performance tests in order to evaluate the effectiveness of intervention programs or to monitor players' actual speed performance. Nevertheless, to account for ecological validity, performance tests should aim to reflect the demands of match play (Beavan, 2019; Ericsson & Smith, 1991). Hence, the results from match analysis relating to speed should be used as a basis when developing soccer-specific speed tests.

This subchapter described the speed demands placed upon soccer players during matches. The main findings are summarized in the following (see Figure 2.2).

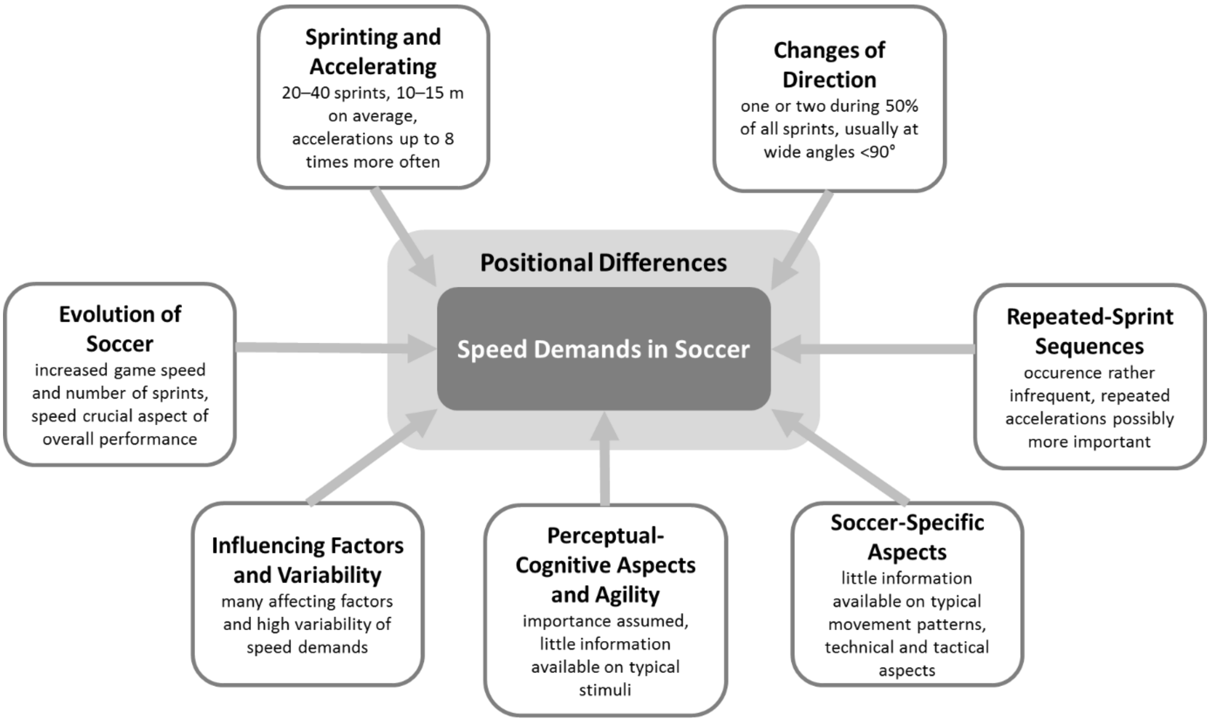


Figure 2.2 Speed demands in soccer based on match analysis.

Given the evolution of soccer, high speed performance is considered a crucial aspect of a high overall performance in modern match play (Wallace & Norton, 2014), while speed demands differ between playing positions (Ade et al., 2016; Bush et al., 2015a; Carling et al., 2016). In general, players sprint between 20 and 40 times per game, with an average sprinting distance of around 10–15 m (Andrzejewski et al., 2013; Dellal et al., 2011; Di Salvo et al., 2010). Accelerations occur up to eight times more frequently than sprinting (Varley & Aughey, 2013). Moreover, 50% of all sprints incorporate one or two directional changes, usually at a wide angle (<90°) (Rehhagel, 2011). Repeated-sprint sequences occur rather infrequent, thereby questioning the importance of repeated sprints in its classical definition (Taylor et al., 2016). Therefore, other maximal actions such as repeated accelerations are becoming a focus of attention (Dalen et al., 2018; Taylor et al., 2016). Relating to speed demands, little information is available that integrates the associated movement patterns or technical and tactical data (Bradley & Ade, 2018; Harper et al., 2019; Mackenzie & Cushion, 2013). In line with this, there is a lack of research investigating perceptual-cognitive demands during matches, e.g., typical stimuli that precede fast movements or changes of direction (Ade et al., 2016). In addition, the occurrence of speed actions such as sprinting is highly variable within and between matches (Brink & Lemmink, 2018; Bush et al., 2015b; Carling et al., 2016). As a consequence, standardized performance tests are necessary in order to monitor players' speed performance (Mackenzie & Cushion, 2013). Nevertheless, the results from match analysis can serve as a guideline when developing soccer-specific speed tests (Bradley et al., 2018; Jeffreys et al., 2018).

Based on the speed demands in soccer discussed in this subchapter, the topic speed testing will be addressed in the following, both from a methodological and a soccer-specific perspective.

2.3 Speed Testing

Along with other performance tests, speed testing has become an integral part of fitness testing in team sports such as soccer (Slimani & Nikolaidis, 2017; Svensson & Drust, 2005). This subchapter aims to review methodological aspects – focusing on timing technology – that are associated with speed testing as well as the application of different speed tests to soccer. Thereby, several unsolved questions on the topic speed testing will be raised. These questions will be taken up and specified in *Chapter 3* and will be subjects of the papers in the subsequent *Chapters 4–7*.

2.3.1 Methodological Aspects

During speed testing, several parameters can be investigated. Thereby, a growing number of studies addresses mechanical properties such as vertical and horizontal force production (Cross, Brughelli, Samozino, & Morin, 2017; Haugen, Breitschädel, & Samozino, 2018; Haugen, McGhie, & Ettema, 2019; Morin & Samozino, 2016; Samozino et al., 2016; Simperingham, Cronin, & Ross, 2016). However, basic kinematic characteristics such as the time needed to complete or the velocity obtained during a speed task are parameters that are reported in practically every study on this topic (Haugen & Buchheit, 2016; Nikolaidis, Knechtle, Clemente, & Torres-Luque, 2016; Rumpf, Cronin, Oliver, & Hughes, 2011; Simperingham et al., 2016). Therefore, for the purpose of this thesis, only the latter (i.e., times to complete and velocities obtained during a speed test) will be addressed.

There exists a multitude of methodological aspects that influence the results of a given speed test (for review, see Haugen & Buchheit, 2016) (see Figure 2.3). While being mainly reported for linear-sprint tests, these aspects include footwear (Stefanyshyn & Fusco, 2004), surface (Brechue, Mayhew, & Piper, 2005; Rehhagel, 2011), clothing (Brechue et al., 2005), environment (Girard et al., 2011; Girard, Brocherie, & Bishop, 2015a; Mureika, 2006; Ward-Smith, 1999), starting procedures (Brown, Kenwell, Maraj, & Collins, 2008; Cronin, Green, Levin, Brughelli, & Frost, 2007; Haugen & Seiler, 2015; Johnson et al., 2010), timing technology (Bond, Willaert, & Noonan, 2017a; Haugen, Tønnessen, & Seiler, 2012a), and data analysis (Al Haddad, Simpson, & Buchheit, 2015).

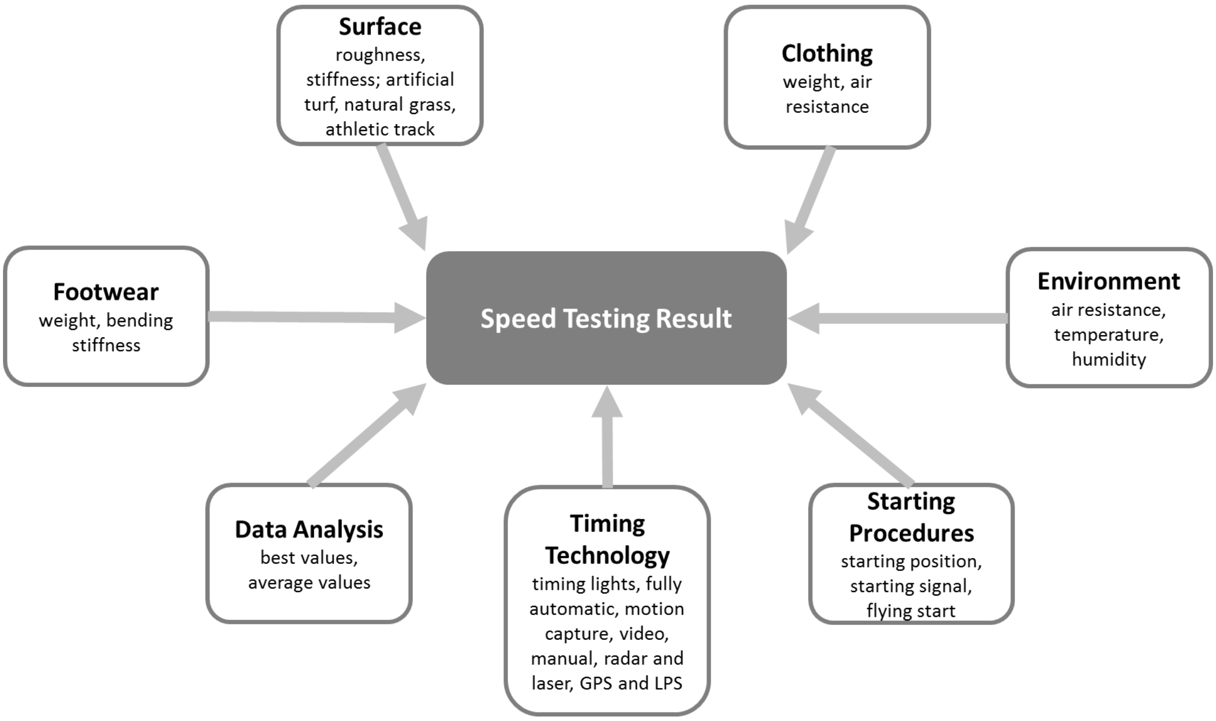


Figure 2.3 Influencing factors and associated examples of speed testing results.

The combination of the abovementioned methodological aspects can generate very large time differences of up to 50–60% over short distances such as 5–10 m (Haugen & Buchheit, 2016). As elite athletes may spend years of training to improve their speed performance by only a few percent (Haugen, 2017; Haugen & Seiler, 2015), the influence of methodological aspects is many times greater. Therefore, tracking player performance should always be based on the same methodology and procedures in order to confidentially associate changes in test results to an altered performance of the athlete. To assist researchers and practitioners, some calibration equations have been developed that enable comparisons between varying circumstances during speed testing at least to some extent (Duthie, Pyne, Ross, Livingstone, & Hooper, 2006; Haugen et al., 2012a; Haugen et al., 2015a). However, using these equations should be avoided in settings other than those described in the respective study (Haugen & Buchheit, 2016). Taken together, these circumstances reinforce the claim of Duthie et al. (2006) that the methodology and procedures during speed testing should be reported as precisely as possible to enable correct interpretation of the data provided. Among the methodological aspects described above, the present thesis focuses on the timing technology applied.

2.3.1.1 Timing Technologies in General

Currently, a variety of timing technologies is available comprising timing lights, fully-automatic timing systems, motion capture, high-speed video recording, manual timing, radar and laser systems as well as global and local positioning systems (Bond, Willaert, Rudningen, & Noonan, 2017b; Haugen & Buchheit, 2016). These technologies vary considerably in their costs, ease of operation as well as validity and reliability (Comfort, Jones, & McMahon, 2018; Haugen & Buchheit, 2016), which will be specified in the following.

Timing lights

The most common timing technology employed by scientists and sports coaches are **timing lights** (Comfort et al., 2018; Haugen & Buchheit, 2016; Rumpf et al., 2011). As there is a focus on timing lights in the present thesis, such systems will be described in detail in the next subchapter.

Fully-automatic timing systems

Fully-automatic timing systems are considered the gold standard for speed testing and, therefore, are mandatory during international athletic events, such as the 100-m dash. These systems consist of a silent gun and pressure-sensitive blocks at the start as well as high-speed cameras at the finish line („foto finish“), and excellent precision and high reliability have been reported (Haugen et al., 2012a). However, due to their high costs and impracticability, fully-automatic timing systems are not widely spread in both research and sports practice (Haugen & Buchheit, 2016).

Motion capture

3-dimensional motion capture systems are based on one or more reflective markers that are placed on the athlete. At least two cameras track these markers, thereby allowing to capture the displacement of landmarks on the athlete’s body (e.g., sacrum, hip) or an approximation of the center of mass (Whitting, de Melker Worms, Maurer, Nigg, & Nigg, 2013). Motion capture has been shown to possess high levels of precision and reliability (Richards, 1999; Whitting et al., 2013). Therefore, such systems have been used as a reference method in several studies aiming to validate other timing technologies (Bond et al., 2017a; Clark et al., 2019; Whitting et al., 2013; Yeadon, Kato, & Kerwin, 1999). As motion capture systems are expensive and time-consuming (e.g., calibration, data filtering, and data analysis), their use for speed testing purposes is limited even in a scientific setting (Bond et al., 2017a; Dolenec & Čoh, 2009).

High-speed video recording

A further alternative for capturing times and velocities during speed testing is **high-speed video recording**. Using a standardized starting criterion (e.g., gun smoke, foot lift-off, movement of the sacrum or hip) and the passing of the finish line, the time needed to travel a given distance can be determined with high accuracy and reliability (Bond et al., 2017a; Haugen et al., 2012a; Haugen & Buchheit, 2016). Specifically, during short (3.05 m) and longer (40 m) sprints, video recording has been reported to possess a low typical error of <0.01 s in comparison to 3-dimensional motion capture (Bond et al., 2017a) and precision limits of ± 0.01 s compared to a fully-automatic timing system (Haugen et al., 2012a). Furthermore, an intraclass correlation coefficient (ICC) > 0.98 (Harrison et al., 2005) and ICC > 0.97 (Haugen et al., 2012a) gathered with video cameras sampling at 50 Hz and 100 Hz, respectively, over various distances indicate excellent reliability. When only one video camera is used, this camera has to be placed perpendicular to the running lane at a distance ensuring that the starting and finish line is in the field of view. In addition, timing markers (e.g., banners) behind the running lane are required to correct for parallax errors (Bond et al., 2017b). This becomes an issue when space for speed testing is restricted (Clark et al., 2019). The major limitation of high-speed video recording is that it does not provide feedback instantaneously, as the recordings first have to be analyzed using specific software. This limits its use when testing teams or large groups of athletes (Haugen & Buchheit, 2016). However, recent technological developments enable faster data analysis, e.g., specifically-designed applications on smartphones (Balsalobre-Fernández et al., 2019; Romero-Franco et al., 2017; Stanton et al., 2016).

Manual timing

Manual, hand-held timing through stopwatches is a simple and inexpensive timing method used during speed testing. Nonetheless, there are several limitations regarding validity and reliability with manual timing. Regarding inter-rater reliability, Mayhew et al. (2010) reported a difference among hand timers of up to 0.19 ± 0.14 s during a 36.6-m sprint. A comparable result was obtained in a study by Vicente-Rodríguez et al. (2011), where untrained hand timers recorded substantially higher shuttle and linear-sprint times than trained hand timers. In terms of validity, manual timing yields 4–6% faster sprint times compared to timing lights (Ebben, Petushek, & Clewein, 2009; Houser et al., 2010; Mann, Ivey, Brechue, & Mayhew, 2015; Mayhew et al., 2010). Despite high correlations between sprint results via stopwatches and timing lights (Hetzler, Stickley, Lundquist, & Kimura, 2008; Mayhew et al., 2010), the large absolute errors of manual timing make them unsuitable above a certain level of performance (Haugen & Buchheit, 2016). In addition, the rather unsystematic distribution of errors does not allow for a reliable correction factor to convert results from manual timing to timing lights (Hetzler et al., 2008). Hence, manual timing is predominantly prevalent at an amateur level or in school settings.

Radar and laser systems

Due to their similarity, **radar and laser systems** will be addressed mutually. Radar systems use the change in the frequency of radio waves that are reflected by a sprinting athlete (Doppler principle).

Based on a sampling frequency of 35–100 Hz, the radio wave signals are processed with software to determine sprinting speed (Simperingham et al., 2016). Laser systems utilize coherent light to capture the time delay of pulsed infrared light that is reflected by an athlete with a frequency of up to 4,000 Hz. Radar and laser devices are typically mounted behind the athlete (10–20 m) at a height of 100 cm to capture the athlete's lower back. Due to the high sampling rates, among other parameters, instantaneous velocity data can be calculated (Haugen & Buchheit, 2016; Simperingham et al., 2016). Both timing technologies are considered valid (Berthoin, Dupont, Mary, & Gerbeaux, 2001; Bezodis, Salo, & Trewartha, 2012; Clark et al., 2019; Di Prampero et al., 2005; Ferro, Floría, Villacieros, & Aguado-Gómez, 2012; Morin, Jeannin, Chevallier, & Belli, 2006) and reliable (Debaere, Jonkers, & Delecluse, 2013; Di Prampero et al., 2005; Ferro et al., 2012) methods to determine sprinting speed. Validation studies not only used motion capture (Clark et al., 2019) and high-speed video recording (Bezodis et al., 2012; Gander et al., 1994) as a reference method, but also timing lights (Berthoin et al., 2001; Di Prampero et al., 2005; Ferro et al., 2012; Morin et al., 2006). This is particularly interesting, as there also exist studies that validated timing lights using a radar system as a reference method (Roe et al., 2017). Despite this confusion in the literature, a study using high-speed video recordings as a reference method has shown that the validity of radar devices is reduced during the first meters of an acceleration sprint in comparison with longer distances (Bezodis et al., 2012). This is probably due to the lower back moving in relation to the center of mass as the sprinting posture becomes more upright (Simperingham et al., 2016). Another important point to consider when using radar systems is angle errors. Failing to run directly away or towards the device yields in substantial angle errors, expressed by slower sprinting speeds (Stalker Radar, 2010). While both radar and laser technologies are limited to linear sprints in principle, a new method employing two synchronized laser devices also enables the investigation of change-of-direction tasks (Hader, Palazzi, & Buchheit, 2015). In line with high-speed video recording, data processing is necessary to obtain results when using radar and laser systems. Therefore, these systems do not provide instant feedback (Simperingham et al., 2016).

GPS and LPS

Global positioning system (GPS) is based on a network of satellites that provides information regarding the location and time of the respective devices through trigonometry (Malone et al., 2017). Generally worn on the upper back, the sampling frequency of such devices varies between 1 and 15 Hz (Scott et al., 2016). Moreover, there exist differences regarding data collection and processing between different manufacturers. Due to high error rates for interdevice reliability, results from different GPS devices should not be used interchangeably (Malone et al., 2017). A large number of studies have investigated the reliability and validity of GPS, often using timing lights as a reference method (for reviews, see Haugen & Buchheit, 2016; Malone et al., 2017; Scott et al., 2016). Haugen & Buchheit (2016) summarize that the reliability and validity of GPS decreases with lower sampling frequency

(Aughey, 2011; Jennings, Cormack, Coutts, Boyd, & Aughey, 2010), higher sprinting speed (Johnston et al., 2012; Portas, Harley, Barnes, & Rush, 2010), shorter sprinting duration (Barr, Beaver, Turczyn, & Cornish, 2017; Coutts & Duffield, 2010; Jennings et al., 2010), and higher number of directional changes (Portas et al., 2010; Rawstorn, Maddison, Ali, Foskett, & Gant, 2014). While a main advantage of GPS is the simultaneous tracking of multiple athletes and real-time feedback (Scott et al., 2016), these systems should only be recommended for sprinting distances greater than 30 m and to assess maximal sprinting speed (Barbero-Alvarez, Coutts, Granda, Barbero-Alvarez, & Castagna, 2010; Haugen & Buchheit, 2016; Roe et al., 2017). More recently, **local positioning systems (LPS)** have been introduced into research and sports practice (Buchheit, 2017). Compared to GPS, LPS is based on a locally deployed infrastructure. LPS allows for higher sampling rates, thereby potentially increased validity and reliability of measurements (Hoppe, Baumgart, Polglaze, & Freiwald, 2018). However, as only a few studies have been conducted on this topic, robust evidence for using LPS is pending (Hoppe et al., 2018; Linke et al., 2018).

2.3.1.2 Timing Lights

As stated earlier, timing lights are the most common timing technology employed by scientists and sports coaches regarding speed testing (Comfort et al., 2018; Haugen & Buchheit, 2016; Rumpf et al., 2011). There exist a number of synonyms that are used in the scientific literature, such as light gates, photocells, photoelectric cells, and timing gates (Haugen & Buchheit, 2016; Simperingham et al., 2016; Young & Willey, 2010). For consistency, the term *timing lights* will be used throughout this thesis. Timing lights are affordable and relatively easy to set-up. Combined with higher accuracy and the elimination of human error compared to manual timing, these systems represent an attractive alternative for speed testing (Earp & Newton, 2012).

In terms of the function principle, timing lights generally consist of (a) an emitter and a receiver which are located in the same housing as well as (b) a reflector. The emitter sends an infrared light beam to the reflector at a distance of approximately 2 m. The light beam is bounced back to the receiver, thereby forming a „gate“ (Cronin & Templeton, 2008). When an athlete passes through and consequently breaks this gate, a signal is sent to a computer. In that way, sprint times and velocities can be calculated when multiple timing lights are set-up at defined distances, commonly at a resolution of 1,000 Hz. In addition, there also exist systems that do not require a reflector (Earp & Newton, 2012). However, they are not frequently employed and, therefore, will not be discussed further. Timing lights are available both as stationary and mobile systems (Shalfawi, Enoksen, Tønnessen, & Ingebrigtsen, 2012).

When using timing lights for speed testing purposes, a number of factors should be considered including the type of timing lights, (alternative) start triggering devices, starting procedures, and timing light height.

Conventional single-beam timing lights

Generally, timing lights can be divided into single-beam timing lights with or without error correction processing (ECP) and dual-beam timing lights. Conventional single-beam systems without ECP are frequently used, possibly due to their availability and relatively low costs (Haugen & Buchheit, 2016). The major limitation of these systems is that they are triggered as soon as any part of an athlete's body moves through it. Therefore, single-beam timing lights can be prematurely triggered by swinging arms or legs. This causes false signals and consequently measurement errors, as usually the torso is of interest (IAAF, 2017) thereby affecting both the validity and the reliability of the results obtained. While the occurrence of false signals indicates that other parts of the body than the torso triggered the timing lights, measurement errors quantify the time difference between the false (e.g., arm or leg) and the right signal (usually the torso). In this context, Earp & Newton (2012) reported false signals to occur in 32% of all sprints. However, there is a paucity in research quantifying these measurement errors in relation to a reference system such as motion capture or high-speed video recording (Whitting et al., 2013; Yeadon et al., 1999). For instance, Whitting et al. (2013) reported time differences of approximately 11% between single-beam timing lights and motion capture during sidestepping movements. Regarding the reliability of single-beam devices, standard errors of measurement (SEM) of 0.03 s and a coefficient of variation (CV) of 2% have been reported (Darrall-Jones, Jones, Roe, & Till, 2016a; Haugen & Buchheit, 2016; McMahon et al., 2017; Moir, Button, Glaister, & Stone, 2004).

Dual-beam timing lights

In order to overcome the issues relating to false signals using single-beam timing lights, dual-beam timing lights have been developed. These consist of two beams that are mounted with a vertical distance of approximately 20 cm. Here, both beams have to be broken simultaneously, for a signal to be sent to the computer. As an outstretched upper or lower limp might only break one beam at a time, dual-beam systems are thought to reduce the abovementioned false signals and increase validity and reliability (Haugen et al., 2014a; Haugen & Buchheit, 2016). In fact, a higher accuracy (Yeadon et al., 1999) and a reduction of false signals by 50% compared to single-beam devices have been shown (Earp & Newton, 2012). In line with this, reliability is increased (SEM of 0.02 s and CV of 1%) (Duthie et al., 2006; García-López et al., 2012; Haugen et al., 2014a). Haugen et al. (2014a) revealed absolute time differences ranging from -0.05 to 0.06 s for a 0–20-m sprint interval between single and dual-beam timing lights and identical results for a 20–40-m sprint interval. While the abovementioned research shows that dual-beam systems are clearly superior to single-beam systems, limitations associated with the double amount of light beams are higher costs and a more complex measurement set-up (Earp & Newton, 2012).

Single-beam timing lights with ECP

A third type of timing lights, which has become increasingly popular in recent years, are single-beam timing lights with ECP. Systems employing ECP algorithms, also known as post-processing timing lights (Haugen & Buchheit, 2016), make use of the different lengths of breaks as an athlete passes through the timing lights. While a single-beam system would always be triggered by the first break of the beam, ECP algorithms interpret all breaks (e.g., leading arm, torso, trailing arm) and take the beginning of the longest break as the correct trigger (Fusion-Sport, 2010; Haugen & Buchheit, 2016). This approach has also been described as the longest break criterion (Yeadon et al., 1999). In theory, arms and legs cause shorter break durations, while the longest break is assumed to always be the torso (see Figure 2.4 a) (Haugen & Buchheit, 2016). Supporting this hypothesis, in their study, Earp & Newton (2012) demonstrated that ECP eliminated all false signals during 10-m sprints. Consequently, the authors concluded that timing lights employing ECP are superior to dual-beam systems which did not detect half of the false signals that occurred due to swinging arms or legs in their study. Nevertheless, this conclusion is somewhat limited as the correct signal was not determined by motion capture or video recording. Conversely, in that study, the correct signal was defined as the longest break. As, unsurprisingly, ECP always took the longest break, authors concluded that the algorithm eliminated all false signals (Earp & Newton, 2012). In another study, D'Auria et al. (2006) reported enhanced reliability of ECP systems compared to dual-beam systems, which was particularly evident at shorter distances (e.g., 5m, 10 m). In contrast, other research showed reduced validity and reliability compared to high-speed video recording when using ECP systems during sprints of up to 18.28 m (Bond et al., 2017a; Bond et al., 2017b), thereby suggesting that some false signals due to outstretched limbs or forward lean of the trunk may not be detected. Possible scenarios where false signales could not be detected by ECP are illustrated in Figure 2.4 b and c (Haugen & Buchheit, 2016). In sum, research on single-beam timing lights with ECP is limited and shows inconsistent results. Therefore, further studies are needed to investigate their ability to eliminate false signals and to provide valid and reliable results during speed testing.

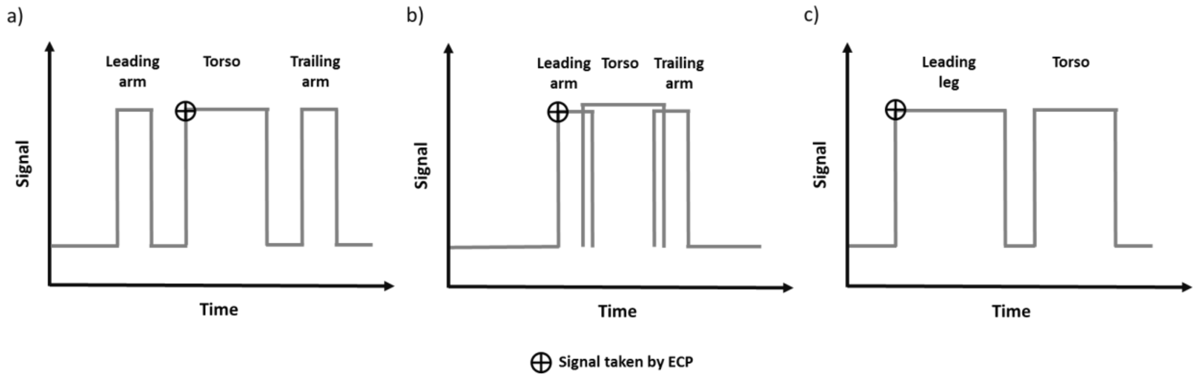


Figure 2.4 Possible constellations of signals, with ECP always taking the beginning of the longest break; a) the torso causes a longer break than the leading and trailing arm; b) permanent break from the leading arm over the torso to the trailing arm; c) the leading leg causes a longer break than the torso.

Alternative start-triggering devices

Independent from the specific type of timing lights applied, the highest potential for inaccurate and unreliable measurements is evident at short distances and especially at the sprint start (Bond et al., 2017a; Haugen et al., 2014a). Against this background, floor pods as well as audio and visual start-sensors are sometimes used as start-triggering devices, with the following (split) times being recorded with timing lights (Haugen et al., 2014a; Haugen & Buchheit, 2016). Regarding floor pods, a hand or a foot is placed on the pod at the start line. Timing begins when the hand or the foot (usually the front foot) is released (Haugen & Buchheit, 2016). Although floor pods produce reliable results (Duthie et al., 2006), starting from a three-point start with one hand at the ground is not common in team sports such as soccer. Furthermore, it remains to be explored whether placing the back foot on the floor pods instead of the front foot is advantageous (Haugen & Buchheit, 2016). A novel method similar to floor pods has been proposed by Healy et al. (2016). Here, two parallel bars consisting of several timing lights are placed on the ground at the start line. One bar acts as the emitter whereas the other acts as the receiver. The timer is triggered when the lights are disrupted by a foot or hand of an athlete. While high accuracy compared to high-speed video recording was shown, no data on reliability from this approach was reported (Healy et al., 2016).

Similar to fully-automatic timing, timing light systems can be combined with an audio sensor at the start that is triggered by a sound of a certain intensity. These devices produce practically the same results as fully-automatic timing (Haugen et al., 2012a). Albeit, relatively low reliability has been reported for a sprint test when using an acoustic starting signal (Impellizzeri et al., 2008). Again, reacting to an acoustic signal such as a start gun is only common in athletic events and less appropriate in team sports. A last type of an alternative start device is based on visual signals (Cometti, Maffiuletti, Pousson, Chatard, & Maffulli, 2001). Besides reliability data is lacking (Haugen & Buchheit, 2016) in line with acoustic signals, the stimulus used to initiate the start of the test should always be sport-specific. In contrast, the use of generic visual signals such as flashing lights seems rather inappropriate.

Starting procedures

Despite the existence of the abovementioned alternative start-triggering devices, timing lights are still commonly used at the start. As such, there are several aspects to consider regarding starting procedures, including starting position and starting distance. In relation to the starting position, different positions have been used in literature, e.g., four-point, three-point, and two-point positions (Haugen et al., 2012a). As starting position influences results (Haugen & Buchheit, 2016; Healy et al., 2016), different positions cannot be used interchangeably. The most common position employed in team sports involves a two-point standing start (Darrall-Jones et al., 2016a; Duthie et al., 2006; Haugen, Tønnessen, & Seiler, 2013b; Johnson et al., 2010). Even within a standing start, different positions can be adopted, such as a parallel or split stance (Johnson et al., 2010). Furthermore, in addition to rocking movements and leaning backward, a so-called „false-step strategy“ has been identified to be used by many athletes. That is, athletes first step back before stepping forward with the front foot. This procedure invokes the stretch-shortening cycle, which leads to enhanced force production and, consequently, performance (Cronin et al., 2007; Frost, Cronin, & Levin, 2008; Johnson et al., 2010). Different starting positions and movement regulations not only affect the times recorded but also reliability (Duthie et al., 2006; Johnson et al., 2010).

To avoid triggering the beam(s) accidentally due to leaning the upper body forward, athletes typically start at a certain distance behind the initial timing lights. This starting distance, sometimes also referred to a flying start (Haugen & Buchheit, 2016), usually varies between 0.2 m (Barbero-Alvarez et al., 2010), 30 cm (McMahon et al., 2017; Ramirez-Campillo et al., 2018), 0.5 m (Darrall-Jones et al., 2015; Frost et al., 2008), and 1.0 m (Meyer, Ohlendorf, & Kindermann, 2000). However, much greater starting distances of up to 20 m have also been reported (Haugen, Tønnessen, & Seiler, 2015b). Theoretically, the greater the starting distance, the lower the sprint times, because of a higher velocity when passing the initial timing lights. Conversely, little is known, to what extend starting distance affects sprint times. It is also unknown if a modified (i.e., more upright) running posture due to greater starting distances influences measurement accuracy and reliability.

Timing light height

Timing lights heights have been reported from as low as 0.4 m (Chaouachi, Manzi, Wong, Chaalali, & Laurencelle, 2010) to as high as 1.5 m above the ground (Henry, Dawson, Lay, & Young, 2012). Cronin & Templeton (2008) demonstrated that the height not only influences sprint times but also the reliability when using dual-beam systems. In order to reduce false signals caused by the lower limbs, all types of timing lights are recommended to be mounted at least at hip height, which corresponds to approximately 1.0 cm when testing adult men (Haugen & Buchheit, 2016; Yeadon et al., 1999). While timing light height is typically constant from start to finish, a reduced height at the start has also been used in order to improve timing accuracy (Haugen et al., 2012a). The theory behind that possibly is that athletes usually adopt a crouched starting position with a forward lean and become more upright with greater sprinting distance (Bond et al., 2017a). With the same purpose, Dyas & Kerwin (1995) even suggest mounting timing lights at head height. While this approach would likely reduce false signals, it appears to be inappropriate when testing larger groups, as the height would have to be adjusted for each athlete. As with starting distance, little is known about the effect of timing light height on sprint times and the measurement accuracy and reliability, especially when using single-beam systems.

In sum, the validity and reliability of speed testing results are dependent on a multitude of factors. While some of these factors have been well investigated, there remain questions about the influence of other methodological issues. Regarding timing lights, these include, but are not limited to, the effect of starting distance and timing light height on sprint times as well as the measurement accuracy and reliability over various distances. Furthermore, uncertainty exists as to whether single-beam timing lights with ECP are able to eliminate false signals and to provide valid and reliable speed testing results. Answering these questions could assist to provide information to researchers and practitioners about the most valid and reliable measurement set-up.

Now that speed testing has been discussed from a methodological perspective, the next subchapter will focus on the application of different speed tests to soccer.

2.3.2 Applications to Soccer

In the following, the rationale and purposes of speed testing as well as an overview of speed tests used in soccer will be provided. Indeed, there are several other aspects to consider that are particularly interesting from the view of a practitioner, such as data presentation and visualization (Buchheit, 2017; Comfort et al., 2018; Pyne, Spencer, & Mujika, 2014) and timing of testing during pre-, regular, and off-season (Comfort et al., 2018; Jemni, Prince, & Baker, 2018; Turner et al., 2011). However, this is beyond the scope of this thesis and the respective literature is recommended for further information on these topics.

2.3.2.1 Rationale and Purposes

As summarized in *Chapter 2.2*, modern match-analysis systems allow for capturing speed performance during competition (Sweeting et al., 2017). However, the distinct variability of speed performance in matches limits their suitability to determine what a player is able to accomplish (Brink & Lemmink, 2018; Carling et al., 2016). Appropriate speed tests can overcome this issue and, therefore, are advised in order to address the abovementioned purpose. Indeed, speed tests should reflect the demands of the game (Bradley et al., 2018; Brughelli et al., 2008). In doing so, data from match analysis should be used as a basis when developing speed tests.

Performance testing in general and speed testing in particular is applied for a number of purposes in soccer. Among the most prominent reasons rank the establishment of a baseline profile for individual players or the whole team and the identification of individual strengths and weaknesses. Furthermore, performance tests are used for talent identification purposes, the monitoring of rehabilitation progression after injuries or the readiness to return to competition as well as the conception and evaluation of the effectiveness of specific training interventions (Carling & Collins, 2014; Carling, Reilly, & Williams, 2008a; Haugen & Seiler, 2015; Jemni et al., 2018; Mendez-Villanueva & Buchheit, 2013; Svensson & Drust, 2005). To successfully address these multiple purposes, the collaboration of scientists, coaches, and their support staff as well as the individual players is required (Pyne et al., 2014).

2.3.2.2 Speed Tests Used in Soccer

Reflecting the manifold requirements in relation to speed during match-play (see *Chapter 2.2*), researchers and coaches can choose from a multitude of speed tests that are utilized in soccer. According to the speed skills relevant to this thesis outlined in *Chapter 2.1.1*, these tests can be categorized into linear sprinting, change-of-direction sprinting, repeated sprinting, agility, and combinations of these tests.

Linear-sprint tests

Linear or straight-line sprint tests are the most common speed tests used in soccer, probably due to the frequent occurrence of linear sprints during matches and the relatively easy test set-up. The tests either commence from a stationary or flying start. Typical distances investigated range from 5 m to 40 m, thereby aiming to cover both acceleration and maximum speed (Faude, Schlumberger, Fritsche T., Treff, & Meyer, 2010; Haugen et al., 2014a; Turner et al., 2011). To provide further insights into the linear sprinting skills of athletes, split times of 10 m, 20 m or 30 m are frequently reported. However, the time at a given distance (e.g., 30 m) is heavily influenced by the time at the proceeding split (e.g., 20 m). The calculation of interval times (e.g., 5–10 m, 20–30 m) can overcome this issue to at least some part (Meyer & Faude, 2006). An example of a 30-m linear-sprint test with splits at 5 m and 10 m using timing lights can be found in Figure 2.5.

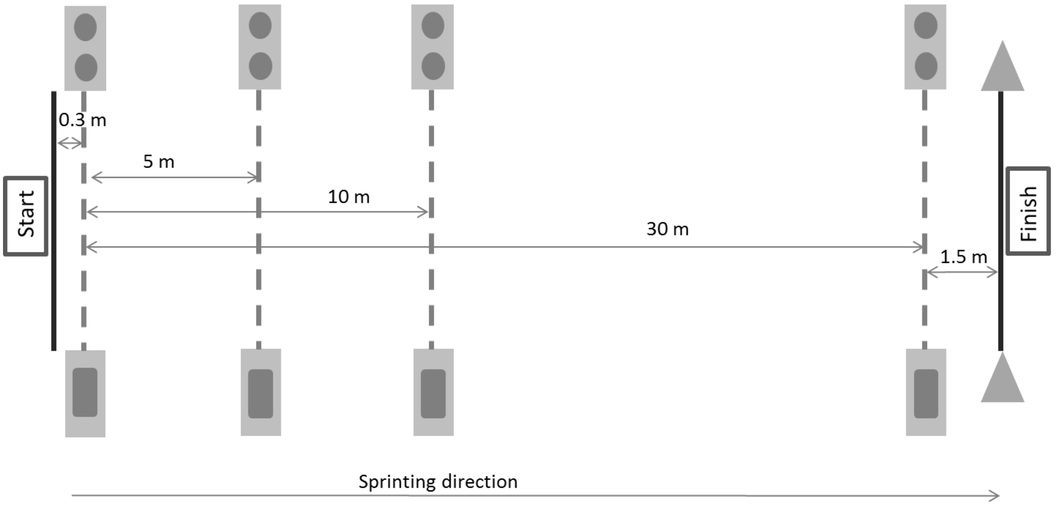


Figure 2.5 30-m linear-sprint test with splits at 5 m and 10 m (own illustration).

Change-of-direction sprint tests

Change-of-direction sprinting refers to a preplanned whole-body change of direction as well as rapid movement and direction change of limbs (Sheppard, Young, Doyle, Sheppard, & Newton, 2006; Young et al., 2015). Following the observation that, during matches, a substantial amount of sprints is not performed in a linear way but includes changes of direction (Rehhagel, 2011), this kind of tests has been introduced into soccer. There exist a plethora of change-of-direction sprint tests, differing in their total distance, number and angles of directional changes (see examples in Figures 2.6 and 2.7) (Sporis, Jukic, Milanovic, & Vucetic, 2010). Relating to some commonly used tests, on the one hand, the 505 test involves a single change of direction (180°) and a distance of 20 m (Draper, 1985). On the other hand, the Illinois run consists of 9 directional changes, approximately ranging between 45° and 270° over a distance of 60 m (Hachana et al., 2013). Obviously, the latter test lacks ecological validity, as sprints during matches are typically shorter and include fewer changes of direction at wider angles (Haugen et al., 2014a; Rehhagel, 2011). One reason that some change-of-direction sprint tests do not reflect the match demands is that they originally have been developed for other sports and have later been adapted to soccer. Importantly, the determining factors and the relationships between distinct change-of-direction tests differ according to their characteristics mentioned above (Chaouachi et al., 2012; Kadlubowski, Keiner, Hartmann, Wirth, & Frick, 2019; Sporis et al., 2010).

Most of the tests address all positions within a team. In order to account for positional differences during matches, position-specific change-of-direction tests have also been developed (Sporis et al., 2010). However, it seems that both researchers and practitioners apply the same test for all players, independent from playing position.

Parameters recorded during this kind of tests encompass total and split times as well as the time the complete the directional changes itself (Araujo et al., 2012; Turner et al., 2011). Some other authors also include a ball in the test and calculate a "skill index" by comparing the time needed to complete a test with and without dribbling with a ball (Mirkov, Nedeljkovic, Kukolj, Ugarkovic, & Jaric, 2008). The relationship between change-of-direction and linear-sprint tests is limited and depends on the similarity of tests (Young et al., 2001). It is, therefore, accepted that they represent relatively independent skills (Little & Williams, 2005). Despite this finding, as most of the change-of-direction sprint tests involve phases of linear sprinting, the latter accounts for some of the variance in the change-of-direction sprint tests (Nimphius et al., 2018). Hence, a relatively new approach called the "change-of-direction deficit" claims to provide a more isolated measure of change-of-direction performance. In this approach, the "deficit" is calculated by subtracting the time an athlete achieved in a linear-sprint test (e.g., 10-m sprint) from the time of a change-of-direction sprint test (e.g., 505 test) (Loturco et al., 2018).

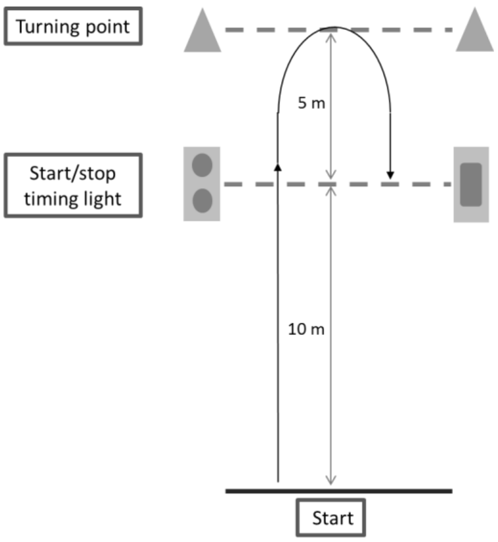


Figure 2.6 505 test
(adapted from Gabbett, Kelly, & Sheppard, 2008b).

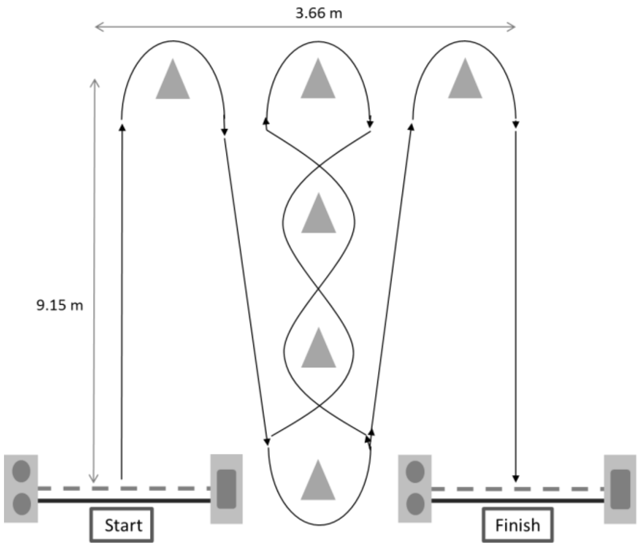


Figure 2.7 Illinois test
(adapted from Sheppard et al., 2006).

Repeated-sprint tests

Repeated sprinting is defined as sprints of short duration (<10 s) interspersed with brief recovery phases (<60 s) (Girard et al., 2011). Despite the observation that sequences of repeated sprinting occur rather seldom within matches, repeated-sprint tests are frequently employed in soccer (Haugen et al., 2014a). In doing so, most tests use repeated linear sprints (without changes of direction). Typically, the distances range between 15 m and 40 m and the number of sprints between 3 and 15 (Haugen et al., 2014a; Turner et al., 2011). Recovery phases can be of active or passive nature and usually last for 20 s to 30 s (Aziz, Mukherjee, Chia, & Teh, 2008; Meckel, Machnai, & Eliakim, 2009), but recovery phases of up to 1 minute have also been reported (Tønnessen, Shalfawi, Haugen, & Enoksen, 2011). When applying a repeated-sprint test, it is important that athletes do not adopt a pacing strategy but sprint as fast as possible from the first to the last repetition (Walker & Turner, 2009).

The performance achieved in repeated-sprint tests can be expressed through several parameters. According to the two main aims which the tested athletes pursue – achieving high sprint velocities and maintaining these velocities throughout the repetitions – these parameters include total and mean sprint time as well as measures of deterioration in performance (Haugen et al., 2014a; Turner & Stewart, 2013). The latter can be presented either as a fatigue index or as a performance decrement. While the fatigue index is calculated by subtracting the best time of the first 2 sprints from the slowest time of the last 2 sprints, the performance decrement represents the sum of all sprint times divided by the best possible total score multiplied by 100. The best possible total score is determined by multiplying the best sprint time by the number of repetitions (Turner et al., 2011; Walker & Turner, 2009). However, the use of total and mean sprint times has been somehow questioned since a strong relationship to single linear-sprint performance was evident in a study by Pyne, Saunders, Montgomery, Hewitt & Sheehan (2008). Conversely, in the same study, this was not true for measures of deterioration in performance which, consequently, represent parameters that are unique to repeated-sprint testing.

Agility tests

In terms of **agility**, soccer players are required to perform rapid movements with change of velocity or direction in response to a stimulus throughout a match (Paul et al., 2016; Sheppard & Young, 2006). Examples of such situations are evading an opponent, intercepting or reaching a pass, and creating or closing space between oneself and an opponent (Ade et al., 2016). While linear sprinting, change-of-direction sprinting, and repeated sprinting mainly represent physically-driven closed speed skills, agility is considered an open skill incorporating both physical and perceptual-cognitive aspects of speed (Girard et al., 2011; Paul et al., 2016).

A classic agility test for invasion sports (e.g., rugby, Australian football, basketball, soccer) has been developed by Sheppard et al. (2006). In this Y-shaped test, athletes face a tester who stands opposite them. When the tester initiates a movement, the timing begins. In response to this initial movement, the athletes have to sprint straight forward for 2 m and then react to the tester’s subsequent movement by either changing the direction to the left or the right for approximately 6 m (see Figure 2.8). According to the claim of Paul et al. (2016) to develop sport-specific agility tests, this test has been modified for the specific demands of several other sports including rugby (Serpell, Ford, & Young, 2010), Australian football (Veale, Pearce, & Carlson, 2010), basketball (Spiteri et al., 2015), tennis (Kraemer et al., 2003), netball (Farrow, D., Young, W., & Bruce, L., 2005), handball (Spasic, Krolo, Zenic, Delextrat, & Sekulic, 2015), and badminton (Loureiro & Freitas, 2016) by manipulating number and angels of directional changes as well as distances (Nimphius et al., 2018; Paul et al., 2016).

When using sport-specific stimuli (e.g., humans such as in the classic agility test or video projections of humans), athletes commonly are required to adopt the role of a defender by reacting to the (deceptive) movements of an opponent (Henry et al., 2012). Nevertheless, tests from an offensive perspective have also been proposed (Spiteri, Nimphius, & Wilkie, 2012). Besides sport-specific stimuli, some agility tests incorporate non-specific generic stimuli (e.g., arrows or flashing lights) (Paul et al., 2016). Regarding the latter, it has been argued that this kind of stimuli should not be used during agility tests because they do not allow athletes to deploy their anticipation skills (Young & Farrow, 2013). In line with this, Young et al. (2015) concluded in a brief literature overview that change-of-direction speed is relatively independent of agility when using sport-specific stimuli. Conversely, other researchers (Coh et al., 2018; Oliver & Meyers, 2009) reported moderate to large relationships between change-of-direction speed tests and agility tests incorporating a flashing light as a stimulus. According to the authors, this result can likely be attributed to the generic stimulus utilized in these tests. Moreover, no significant relationship seems to be evident between linear sprinting and agility (Sheppard et al., 2006).

Several parameters are of interest when analyzing agility tests. Regarding the classic Y-shaped test and using a human stimulus, besides the total time (duration from the movement initiation of the tester to the triggering of the finish timing lights by the athletes), response time is often reported. Response time reflects the time interval from the movement initiation of the tester until the triggering of the first set of timing lights by the athletes. This is usually positioned 0.3 m in front of the athletes’ starting position (Scanlan, Humphries, Tucker, & Dalbo, 2014). In addition, decision-making time is defined as the time from the tester’s first foot contact initiating a directional change to the athletes’ first foot contact initiating the response (Gabbett & Benton, 2009). If decision-making time wants to be determined, the application of high-speed video analysis is necessary (Paul et al., 2016). In cases where athletes anticipate the tester’s movement, thereby initiating the own movement before the tester does, decision-making time can be even negative. Furthermore, the response accuracy is determined by the proportion of right (right side) and wrong (wrong side) decisions (Scanlan et al., 2014). Lastly, movement time can be calculated as the time from the athletes' foot plant that initiates the directional change to the finish timing lights (Young & Willey, 2010). Based on this multitude of parameters assessing both physical and perceptual-cognitive aspects of speed, athletes can be distinguished into four classifications through an agility test: fast mover/fast thinker, fast mover/slow thinker, slow mover/fast thinker, and slow mover/slow thinker (Gabbett et al., 2008b). Interestingly, although short in duration compared to total time, both response time and decision-making time are important predictors of total time by explaining 57% and 33% of the shared variance, respectively (Scanlan et al., 2014).

The abovementioned results have predominantly been observed in sports other than soccer. However, in recent years, there have been some attempts to introduce agility tests into soccer. Some studies make use of the classic agility test developed by Sheppard et al. (2006) either with (Chaalali et al., 2016; Chaouachi et al., 2014) or without the inclusion of a ball (Jordan, Korgaokar, Farley, Coons, & Caputo, 2014; Trecroci, Longo, Perri, Iaia, & Alberti, 2018; Zois, Bishop, Ball, & Aughey, 2011). Subsequently, so-called soccer-specific agility tests have been developed by manipulating movement patterns and including "stop-and-go" scenarios (Pojskic et al., 2018) (see Figure 2.9). However, these tests have methodological limitations as they apply non-specific stimuli such as flashing lights or numbers on a screen (Bekris, Gissis, & Kounalakis, 2018; Benvenuti, Minganti, Condello, Capranica, & Tessitore, 2010; Fiorilli et al., 2017; Matlák et al., 2016; Pojskic et al., 2018; Rauter et al., 2018; Zouhal et al., 2019). Therefore, it might be concluded that soccer-specific agility research is still in its infancy.

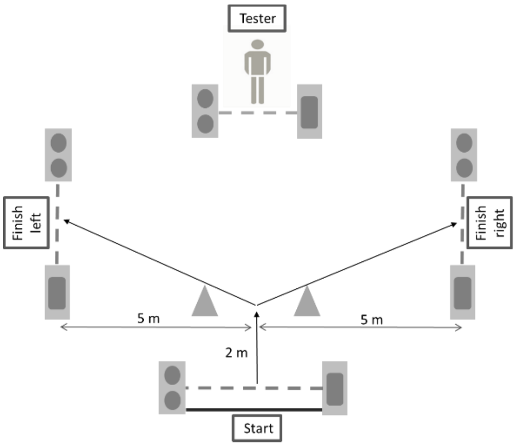


Figure 2.8 Classic agility test (adapted from Sheppard et al., 2006).

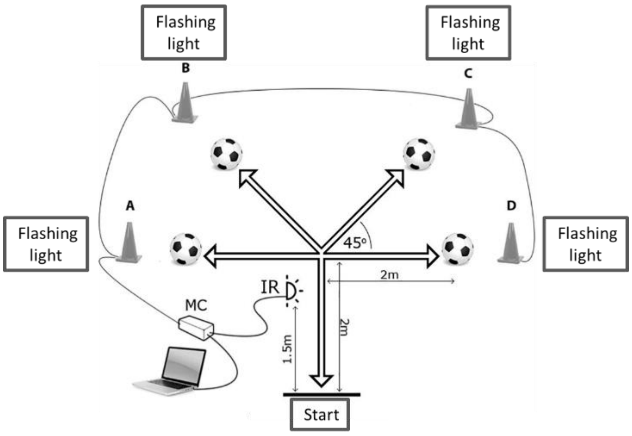


Figure 2.9 Soccer-specific agility test (adapted from Pojskic et al., 2018).

Combinations

Not all speed tests in soccer can be assigned to one of the abovementioned categories as they comprise characteristics of two or more categories. Examples are tests that combine repeated sprints with changes of direction at different angles (Buchheit et al., 2010; Impellizzeri et al., 2008). Furthermore, a “Reactive repeated sprint test” has been developed (Di Mascio, Ade, & Bradley, 2015). This test incorporates repeated sprints with changes of direction in response to a flashing light as a stimulus. A similar test has also been proposed by other authors (Martin, Sanchez-Sanchez, Ramírez-Campillo, Nakamura, & Gonzalo-Skok, 2018; Wragg, Maxwell, & Doust, 2000). A last example of a test that combines characteristics of several categories is a complex test by Bullock et al. (2012). Here, a linear sprint is followed by a passing test and subsequently by an agility test using video recordings of soccer-specific match scenarios as a stimulus.

To summarize, the test categories outlined represent relatively independent skills, depending on the parameter investigated (Coh et al., 2018; Little & Williams, 2005; Pyne et al., 2008; Young et al., 2015). Hence, specific tests in each category (linear sprinting, change-of-direction sprinting, repeated sprinting, agility, and combinations) should be applied in order to obtain a comprehensive picture of a player’s speed skills (Haugen et al., 2014a; Turner et al., 2011). While it is generally accepted that tests should mimic the match demands (Brughelli et al., 2008; Chaouachi et al., 2012; Jemni et al., 2018; Svensson & Drust, 2005), it seems that many widely-used tests do not account for this (Haugen et al., 2014a; Haugen & Seiler, 2015).

Scientists and practitioners working with soccer players can choose from a plethora of speed tests, while there is no accepted gold standard for each category. Thus, the selection of a specific test seems to result from experience or personal choice of the tester (Paul & Nassis, 2015a). From a scientific perspective, besides practicability, equipment needed, and economical aspects, the decision of which tests to choose should be based on their measurement properties such as validity and reliability (Currell & Jeukendrup, 2008; Paul & Nassis, 2015a). In terms of soccer, this is highlighted by Haugen & Seiler (2015) who stated that being 0.3 m to 0.5 m ahead or behind an opponent in a one-on-one situation might be enough to decide whether to win or lose the duel. Therefore, the speed skills needed in such but also other kinds of situations must be determined with a high degree of precision or validity, respectively, during speed testing. Moreover, as performance gains relating to speed skills are generally limited (Haugen, 2017; Haugen & Seiler, 2015), reliable measurements are mandatory. While recent reviews have been published that discuss tests of motor abilities such as endurance (Jemni et al., 2018) and strength (Paul & Nassis, 2015b) with regards to soccer, no overview of the validity and reliability of tests addressing speed skills is available.

In sum, *Chapter 2* provided a theoretical background for this thesis by introducing speed in general as well as speed demands in soccer as a foundation for the subsequent topic speed testing. As depicted before, several research questions surrounding the latter remain unsolved, which will be addressed in the following chapters. Consequently, *Chapter 3* focuses on the aims and scope of this thesis.

3 Aims and Scope of this Thesis

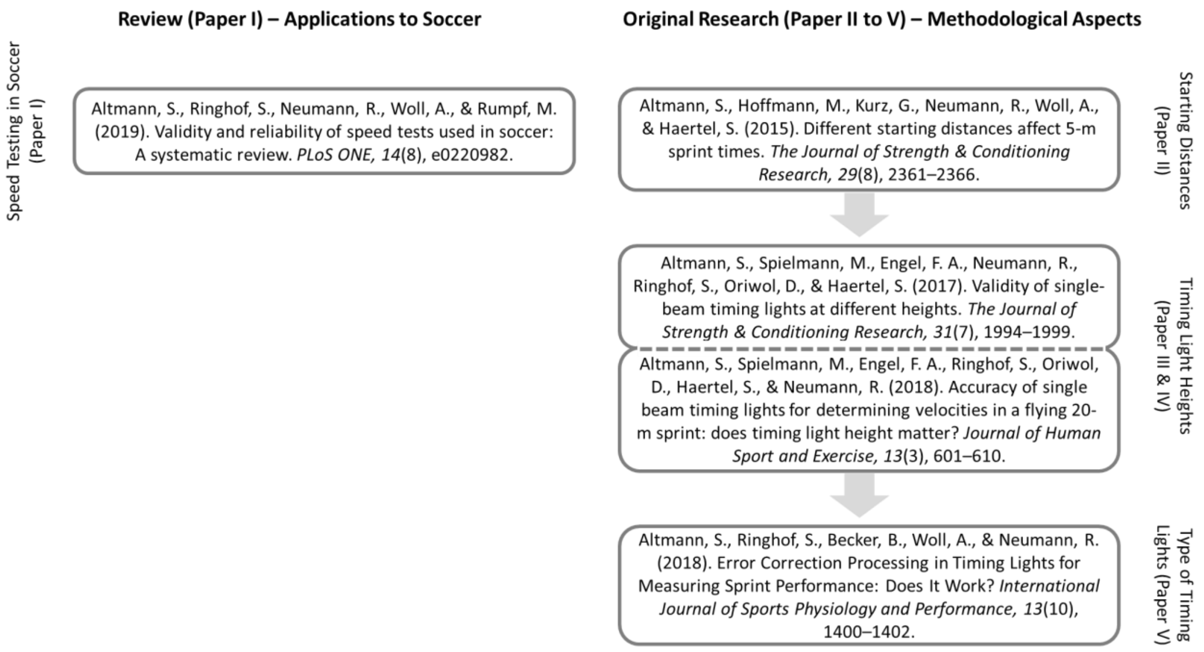
This chapter aims to bridge the gap between the theoretical background and the five papers presented in this thesis.

Based on the body of research presented in *Chapter 2.3*, there remain several questions relating to both soccer-specific and methodological aspects of speed testing. In terms of soccer-specific aspects, scientists and practitioners can choose from a multitude of speed tests that are used in soccer. However, these tests may differ in their psychometric properties, such as validity and reliability and, therefore, some may be more advisable than others. Currently, there exists no overview of the validity and reliability of speed tests applied in soccer. Moreover, once a test has been selected, there are several methodological issues to consider. When using timing lights as a timing technology, uncertainty is evident to which starting distance, timing light height, and timing light type to choose in order to achieve valid and reliable results.

This thesis intends to extend the knowledge on the abovementioned questions. Thereby, two main aims can be defined:

I. To comprehensively review the available literature on speed tests used in soccer with special reference to the tests‘ validity and reliability.
II. To investigate the effects of starting distance, timing light height, and timing light type with respect to speed testing results itself and their validity and reliability.

These two aims were addressed by a systematic review (Paper I) and four original investigations (Paper II to V). A schematic overview of the papers included in this thesis and how they address the different aims is illustrated in Figure 3.1.



Altmann, S., Ringhof, S., Neumann, R., Woll, A., & Rumpf, M. (2019). Validity and reliability of speed tests used in soccer: A systematic review. *PLoS ONE, 14*(8), e0220982.

Altmann, S., Hoffmann, M., Kurz, G., Neumann, R., Woll, A., & Haertel, S. (2015). Different starting distances affect 5-m sprint times. *The Journal of Strength & Conditioning Research, 29*(8), 2361–2366.

Altmann, S., Spielmann, M., Engel, F. A., Neumann, R., Ringhof, S., Oriwol, D., & Haertel, S. (2017). Validity of single-beam timing lights at different heights. *The Journal of Strength & Conditioning Research, 31*(7), 1994–1999.

Altmann, S., Spielmann, M., Engel, F. A., Ringhof, S., Oriwol, D., Haertel, S., & Neumann, R. (2018). Accuracy of single beam timing lights for determining velocities in a flying 20-m sprint: does timing light height matter? *Journal of Human Sport and Exercise, 13*(3), 601–610.

Altmann, S., Ringhof, S., Becker, B., Woll, A., & Neumann, R. (2018). Error Correction Processing in Timing Lights for Measuring Sprint Performance: Does It Work? *International Journal of Sports Physiology and Performance, 13*(10), 1400–1402.

Figure 3.1 Schematic overview of the papers included in this thesis. Applications to Soccer (Review) on the left side, Methodological Aspects (Original Research) on the right side.

As a whole, the current thesis aims to enable a deeper understanding of how to measure speed performance both from a soccer-specific and a methodological view. Subsequently, the results of this thesis could provide a solid scientific basis for research involving speed testing (e.g., for player performance monitoring or evaluation of training interventions).

In the following, the aims of each paper will be specified and the general methodology to achieve these aims will be outlined.

3.1 Review (Paper I) – Applications to Soccer

As depicted in *Chapter 2.2*, the speed demands placed upon soccer players are multifaceted. Throughout a match, players are challenged to perform various speed skills, including both physical and perceptual-cognitive aspects of speed. Given that speed is widely accepted to play a crucial role in soccer (Faude et al., 2012; Jeffreys et al., 2018), speed testing has become an integral part during performance assessments (Haugen et al., 2014a; Turner et al., 2011). For this purpose, a multitude of tests has been developed aiming to examine physical and perceptual-cognitive aspects of speed and have been implemented in research and practice (Paul & Nassis, 2015a) as outlined in *Chapter 2.3.2*. More specifically, these speed tests can be categorized into linear sprinting, change-of-direction sprinting, repeated sprinting, agility, and combinations of these categories. However, to be used with

confidence and to draw practical conclusions from test results, tests should possess appropriate levels of psychometric properties, including validity and reliability (Currell & Jeukendrup, 2008).
Therefore, the aim of the systematic review in *Chapter 4*, which is conducted in accordance with the Preferred reporting items for systematic reviews and meta-analysis (PRISMA) (Moher, Liberati, Tetzlaff, & Altman, 2009), is to provide a comprehensive overview of the available literature on speed tests used in soccer. Organized according to the test categories linear sprinting, change-of-direction sprinting, repeated sprinting, agility, and combinations, a special focus of this systematic review is on the tests‘ validity and reliability. The results of this review could help both scientists and practitioners to decide which test to choose depending on the specific aspects of speed being of interest.

3.2 Original Research (Paper II to V) – Methodological Aspects

Chapter 2.3.1 addressed several methodological issues related to speed testing which affect the test results and their validity and reliability (Haugen & Buchheit, 2016). This is particularly of interest as speed performance of elite athletes is usually homogeneous and that they are able to improve their speed performance by only small amounts during a period of several years (Haugen et al., 2015a; Haugen, 2017). Therefore, the procedures and equipment must allow for precise and repeatable measurements in order to compare the performance of athletes and to detect small performance changes (Haugen & Buchheit, 2016). Considering the timing technology used, timing lights are the most common (Rumpf et al., 2011). However, there remains uncertainty relating to a number of methodological aspects when using timing lights. These include the effect of starting distance and timing light height on sprint times and the validity and reliability of measurement over various distances. A further question relates to whether timing lights employing ECP are able to eliminate false signals, a common issue when utilizing conventional single-beam timing lights.

Consequently, the aim of the four original research articles in *Chapters 5–7* is to examine these questions. Answering these questions could assist to provide information to researchers and practitioners about the most valid and reliable measurement set-up during speed testing.

In each of the four original studies, a similar general methodology was applied. The measurement set-up of each study comprised two timing technologies, namely timing lights and high-speed video recordings. On the one hand, timing lights were used to examine the effects of starting distance, timing light height and timing light type with respect to speed testing results itself and their reliability. On the other hand, high-speed video recordings served as a reference method to validate the timing lights. High-speed video recordings were utilized as a reference method as it is considered a valid and reliable timing technology (see *Chapter 2.3.1.1*). The validity of the timing lights was addressed in two ways.

First, the sprint time over the respective distance in relation to the time achieved by video recording, and second, the measurement error caused by false signals at each set of timing lights in the respective study.

3.2.1 Starting Distances (Paper II)

In order to avoid breaking the beam of single-beam timing lights at the start by accident, athletes adopt a certain starting distance behind the initial timing lights. This starting distance varies largely between studies (commonly between 0.3 m and 1.0 m) and could affect both the test results and the validity of measurement. As little research has addressed this topic so far, the purpose of the study presented in *Chapter 5* (Paper II) was to investigate the effect of different starting distances on sprint times and measurement validity and reliability. To do so, 5-m sprint times were assessed by utilizing three commonly used starting distances (0.3 m, 0.5 m, and 1.0 m) and compared to each other. Furthermore, besides single-beam timing lights, athletes were recorded through a high-speed video camera that served as a reference method.

3.2.2 Timing Light Heights (Paper III & IV)

As with starting distance, there is a great variation between studies relating to timing light height, ranging from 0.4 m to 1.5 m. Aiming to reduce false signals that are associated with single-beam timing lights, recommendations have been made for optimal heights. Conversely, there is limited research examining the effect of timing light height on sprint times and the validity and reliability of measurement over various distances. These research issues were addressed in the two studies described in *Chapter 6* (Paper III & IV), with both studies using the same raw data. For this purpose, athletes performed 30-m sprints with splits at 5 m and 10 m. Sprints were recorded by two sets of single-beam timing lights at different heights, and the respective sprint times were compared to each other. The first system was set up at a height of 0.64 m and the second system at 0.25 m (initial timing lights) and 1.00 m (all following timing lights), respectively. The sprints were simultaneously captured by high-speed cameras that served as a reference method.

The first study in *Chapter 6* (Paper III) analyzed the effect of timing light height on 5-m, 10-m, and 30-m sprint times as well as their validity in relation to the high-speed video recordings. Based on this, the second study in *Chapter 6* (Paper IV) examined the effect of timing light height of sprinting velocity in the interval between 10 m and 30 m and the respective validity compared to high-speed video recordings. In the second study, the interval between 10 m and 30 m is termed a flying 20-m sprint.

Additionally, in the second study, the reliability of sprinting velocity for both timing light heights and the high-speed video recordings was analyzed.

3.2.3 Type of Timing Lights (Paper V)

The study presented in *Chapter 5* (Paper II) and the first study in *Chapter 6* (Paper III) revealed that neither the modification of the starting distance nor the timing light height enables a satisfactory validity of short sprint times (5 m and 10 m) using conventional single-beam timing lights. To avoid false signals due to swinging arms and legs that yield a reduced validity, single-beam timing lights employing ECP have been developed. Systems with ECP algorithms take the longest of multiple breaks as the correct trigger while an athlete passes through the timing lights. The longest break is thought to always represent the torso. Unfortunately, the limited research available on the validity and reliability of systems using ECP paints an inconsistent picture. Consequently, the study depicted in *Chapter 7* (Paper V) examined the ability of single-beam timing lights employing ECP to eliminate false signals and to provide valid and reliable results during short sprints. This was achieved by applying a controlled condition (dummy) to check if ECP generally works and a real condition in which athletes performed sprints over 5 m and 10 m that were recorded by single-beam timing lights employing ECP and a high-speed video camera serving as a reference method. In addition to validity analysis, the reliability of the measurement error caused by false signals was examined.

4 Speed Testing in Soccer (Paper I)

Published version of the review article

Altmann, S., Ringhof, S., Neumann, R., Woll, A., & Rumpf, M. (2019). Validity and reliability of speed tests used in soccer: A systematic review. *PLoS ONE 14*(8): e0220982.

4.1 Abstract

Introduction: Speed is an important prerequisite in soccer. Therefore, a large number of tests have been developed aiming to investigate several speed skills relevant to soccer. This systematic review aimed to examine the validity and reliability of speed tests used in adult soccer players.

Methods: A systematic search was performed according to the PRISMA guidelines. Studies were included if they investigated speed tests in adult soccer players and reported validity (construct and criterion) or reliability (intraday and interday) data. The tests were categorized into linear-sprint, repeated-sprint, change-of-direction sprint, agility, and tests incorporating combinations of these skills.

Results: In total, 90 studies covering 167 tests were included. Linear-sprint (n = 67) and change-of-direction sprint (n = 60) were studied most often, followed by combinations of the aforementioned (n = 21) and repeated-sprint tests (n = 15). Agility tests were examined fewest (n = 4). Mainly based on construct validity studies, acceptable validity was reported for the majority of the tests in all categories, except for agility tests, where no validity study was identified. Regarding intraday and interday reliability, ICCs > 0.75 and CVs < 3.0% were evident for most of the tests in all categories. These results applied for total and average times. In contrast, measures representing fatigue such as percent decrement scores indicated inconsistent validity findings. Regarding reliability, ICCs were 0.11–0.49 and CVs were 16.8–51.0%.

Conclusion: Except for agility tests, several tests for all categories with acceptable levels of validity and high levels of reliability for adult soccer players are available. Caution should be given when interpreting fatigue measures, e.g., percent decrement scores. Given the lack of accepted gold-standard tests for each category, researchers and practitioners may base their test selection on the broad database provided in this systematic review. Future research should pay attention to the criterion validity examining the relationship between test results and match parameters as well as to the development and evaluation of soccer-specific agility tests.

Keywords: football, athletic performance, fitness testing, linear sprint, repeated sprint, change of direction, agility, measurement properties

4.2 Introduction

The game structure of soccer has dramatically changed over the last decades towards a more and more dynamic and faster playing style (Wallace & Norton, 2014). Compared to years past, modern soccer is denoted by shorter ball contact times, increased passing rates, higher player density, and faster transitions (Wallace & Norton, 2014). The changes in game structure also place modified demands on the players. These alterations not only affect technical and tactical aspects but particularly the players' speed requirements. From a physical perspective, the players have to perform several accelerations and sprints at maximal speed with and without changes of direction throughout a match (Dellal et al., 2011; Haugen et al., 2014a; Varley & Aughey, 2013). Moreover, players are forced to possess rapid information processing and to make fast and accurate decisions in order to be successful (Wallace & Norton, 2014). This indicates that speed in soccer encompasses both physical and perceptual-cognitive components (Paul et al., 2016).

As indicated above, speed is widely accepted to play a crucial role in soccer (Faude et al., 2012; Jeffreys et al., 2018). Therefore, speed testing has become a standard component of performance assessments (Haugen et al., 2014a; Turner et al., 2011). For this purpose, a multitude of running-based tests has been developed aiming to examine several speed skills and have been implemented in research and practice (Haugen et al., 2014a; Paul & Nassis, 2015a). More specifically, these speed tests can be categorized into linear sprinting, change-of-direction sprinting, repeated sprinting, agility, and combinations of these categories. In this context, linear sprinting relates to straight-line sprinting over various distances, including acceleration and maximum speed phases (Rumpf et al., 2016). Moreover, change-of-direction sprinting comprises preplanned whole-body changes of directions as well as rapid movements and direction changes of the limbs (Sheppard & Young, 2006; Young et al., 2015). Repeated sprinting refers to short-duration sprints (< 10 s) interspersed with brief phases of recovery (< 60 s) (Girard et al., 2011). Finally, agility is considered an open skill and has been defined as a „rapid whole-body movement with change of velocity or direction in response to a stimulus" (Sheppard & Young, 2006). While linear sprinting, change-of-direction sprinting, and repeated sprinting mainly represent physically-driven speed skills, agility refers to both physical and perceptual-cognitive aspects of speed (Girard et al., 2011; Paul et al., 2016). These skills share a relatively low common variance with limited training transfer between each other being evident. Hence, they can be considered as rather independent (Buttifant et al., 2001; Coh et al., 2018; Little & Williams, 2005; Los Arcos et al., 2017; Pyne et al., 2008; Sassi et al., 2009; Shalfawi et al., 2013a; Šimonek et al., 2017; Vescovi & McGuigan, 2008; Young et al., 2015). Therefore, a comprehensive examination of speed should address all test categories.

From a practical perspective, the feasibility, equipment needed, and economical aspects represent important factors whether or not to choose a test. From a scientific perspective, however, tests should possess appropriate levels of psychometric properties, including validity and reliability, in order to be used with confidence and to be able to draw meaningful conclusions from test results (Currell & Jeukendrup, 2008; Robertson, Kremer, Aisbett, Tran, & Cerin, 2017). While recent reviews have been published focusing on tests of motor abilities such as endurance (Jemni et al., 2018) and strength (Paul & Nassis, 2015b) with regards to soccer, no overview of the validity and reliability of tests addressing speed skills is available.

Therefore, the aim of this systematic review is to review the available literature on speed tests used in soccer with a focus on the tests' validity and reliability. The results of this review could help both scientists and practitioners decide which test(s) to choose depending on the specific aspects of speed being of interest.

4.3 Methods

This systematic review was written according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The protocol was not registered prior to the initiation of the project.

4.3.1 Literature Search

A systematic review of the published literature was undertaken using the electronic databases PubMed and Web of Science during April and May 2018. An updated search regarding studies published after May 2018 was not conducted. The literature search was conducted by one researcher (SA). There was no restriction on publication date.

The following keywords were used to capture psychometric properties: psychometric, measurement.

The following keywords were used to capture validity: validity, logical, construct, convergent, discrimination, match performance, gold standard, level, standard.

The following keywords were used to capture reliability: reliability, repeatability, reproducibility, measurement error, consistency, smallest worthwhile change, minimal detectable change, typical error, usefulness.

The following keywords were used to capture speed testing and the different test categories: speed, quickness, sprint, acceleration, maximum speed, linear, change of direction, repeated sprint ability, agility, reactive agility, physical, unplanned, unanticipated, test, testing.

The following keywords were used to capture soccer: soccer, football.

Reference lists of retrieved full-text articles and recent reviews were examined to identify additional articles not identified by the initial search.

Eligibility criteria for study inclusion consisted of one of the following: (i) tests performed two or more times during one occasion (intraday reliability) or on two or more separate occasions (interday reliability); (ii) compared against other standards of play (construct validity); (iii) compared against match performance (criterion validity).

Except for reviews, all types of studies relating to at least one speed-test category (linear sprinting, repeated sprinting, change-of-direction sprinting, agility, and combinations) were taken into consideration. In addition, studies must have been published in English language in a peer-reviewed journal. As the present review focuses on adult players, only populations with a mean age of 17 years or older were considered. There was no restriction on gender (female and male) and playing level (e.g., recreational, amateur, semi-professional, professional). Complex tests incorporating passing or shooting were only considered when the part relating to speed was examined separately from the total test time. Studies investigating the factorial or convergent validity of speed tests were not included.

4.3.2 Literature Selection

The literature selection consisted of two screening phases. In phase one, duplicates, titles, and abstracts were screened. In phase two, the full papers were screened using the eligibility (inclusion) criteria noted above.

4.3.3 Data Extraction and Analyses

Data were extracted independently by four researchers (SA, SR, RN, and MR) and documented using a Microsoft Excel 2016 spreadsheet (Microsoft Corporation, Redmond, Washington, USA). Extracted data from each study included publication details, number of participants, demographic information (including gender, age, playing level, and country), test category, test name, short test description, type, outcome measures as well as results for validity or reliability, respectively, and the information required to assess the methodological quality of each study. If more than one group of players were investigated in a study, only the groups with a mean age of 17 years or older were considered.

For reliability (both intraday and interday), intraclass correlation coefficient (ICC), Pearson’s r, and coefficient of variation (CV) values were recorded. While ICC and Pearson’s r represent relative reliability, CV is a measure of absolute reliability. By reflecting the degree to which individuals in a specific sample maintain their position over the course of repeated trials (interindividual variability), measures of relative reliability are affected by group homogeneity. Conversely, measures of absolute reliability relate to the variation over repeated trials within individuals (intraindividual variability). Therefore, they do not depend on group homogeneity (Atkinson & Nevill, 1998). Considering the ICC, a range of different approaches exist on how to interpret these values (Atkinson & Nevill, 1998). Following the recommendations of a review with a similar objective (McCunn, Fünten, Fullagar, McKeown, & Meyer, 2016), in the present review, “good” reliability was considered ICC ≥ 0.75. This value was chosen as it appears to reflect a reasonable consensus as to what can be considered good reliability. The same value was applied for Pearson’s r. While a threshold of 10% for acceptable CV values has been suggested, this number seems rather arbitrary (Atkinson & Nevill, 1998). Therefore, CV values were interpreted in relation to each other.

Relating to construct validity, where possible, the percentage difference between playing levels and the respective effect sizes (ES) were calculated and rated according to Hopkins (2002). An ES less than 0.2 was considered a trivial effect; $0.2 \leq ES < 0.6$ a small effect; $0.6 \leq ES < 1.2$ a moderate effect; $1.2 \leq ES < 2.0$ a large effect; $2.0 \leq ES < 4.0$ a very large effect; and ≥ 4.0 an extremely large effect. In terms of criterion validity, the magnitude of the correlation coefficient between speed-test results and match parameters was considered as small ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), and nearly perfect ($r \geq 0.9$) (Hopkins, 2002).

Data were checked and verified by SA and discrepancies were resolved through discussion. The synthesis of the results was carried out descriptively.

4.3.4 Assessment of Methodological Quality

The methodological quality of the studies included in the review was assessed through a modified version of the critical appraisal tool (Brink & Louw, 2012). The modified checklist included nine items:

1. Subject characteristics were clearly described (validity and reliability studies)
2. Competence of the raters was clearly described (validity and reliability studies)
3. Reference (match data) was clearly described (criterion validity studies)
4. Raters were blinded to their own prior findings (reliability studies)

5. Time interval between the reference (match data) was suitable (criterion validity studies)
6. Time interval between repeated measures was suitable (reliability studies)
7. Test execution was described in sufficient detail to permit replication of the test (validity and reliability studies)
8. Methodological aspects (e.g., timing technology, starting position, surface) were described in sufficient detail to permit replication of the test (validity and reliability studies)
9. Statistical methods were appropriate for the purpose of the study (validity and reliability studies)

From the original checklist, the items 6 (Variation of the order of examination), 9 (Independence of reference standard from index test), and 12 (Explanation of withdrawals) were not included as they were thought to be not appropriate for the purpose of this review. Conversely, item 8 (Methodological aspects) was added to the checklist because of the considerable influence of methodological aspects on results, validity, and reliability of speed tests (Haugen & Buchheit, 2016). Due to the large absolute errors associated with manual timing through stopwatches, tests using this timing technology were excluded (Haugen & Buchheit, 2016).

The score for each item was determined as follows: 2 = clearly yes; 1 = to some extent; 0 = clearly no. Consequently, the maximal possible score was 14 (criterion) and 10 (construct) for validity studies, and 14 (intraday and interday) for reliability studies. In the case of more than one test being examined in a single study, the score was calculated for each test separately. According to Barrett et al. (2014), the methodological quality was rated as high when > 60% of the maximal possible score was obtained (corresponding to a score of > 6 for construct validity studies and > 8.4 for criterion validity, intraday, and interday reliability studies).

4.4 Results

4.4.1 Search Results

A flow diagram for the selection of the studies can be found in Figure 4.1. 10,656 records were retrieved through the initial search in the electronic databases. The removing of duplicates yielded 8,950 studies that were screened for the title. Subsequent abstract screening (1,270 records) led to the exclusion of further 1,131 studies. Consequently, the full-texts of 139 articles were assessed for eligibility, with 49 articles being excluded. The reasons for exclusion during full-text screening were

- no validity or reliability reported (16 studies),
- inappropriate timing technology (manual timing) used (12 studies),

- mean population age < 17 years (8 studies),
- reliability reported as a range over several tests (including strength and endurance tests) (5 studies),
- full-text not written in English language (3 studies),
- full-text not available (3 studies), and
- sports other than soccer included in calculations of validity or reliability (2 studies).

Ultimately, 90 studies were included in this review.

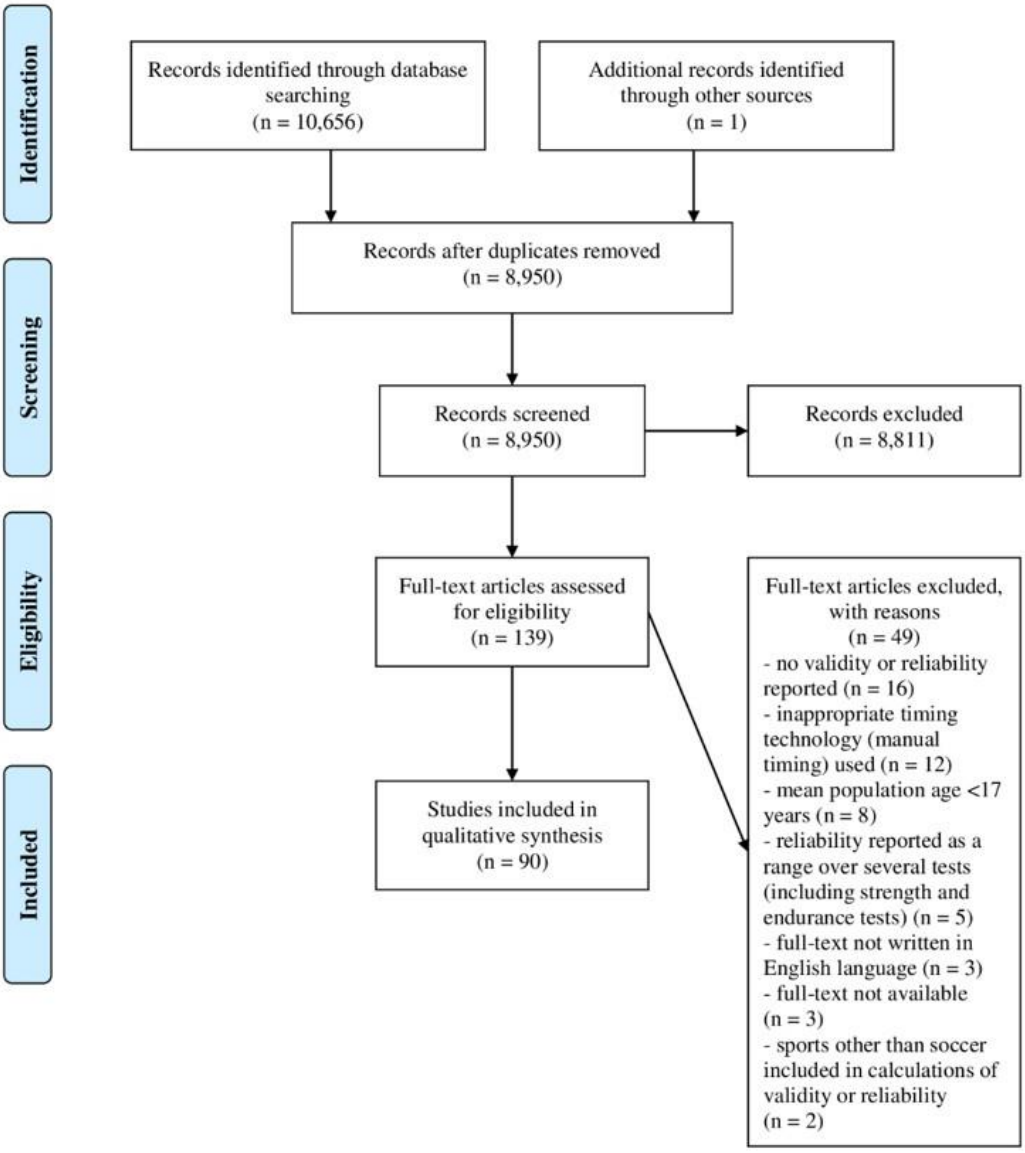


Figure 4.1 Flow diagram of the search and selection process for inclusion of articles.

4.4.2 Overview on Studies and Tests Included

From the 90 studies included, 20 referred to validity only, 60 to reliability only, and 10 to both validity and reliability. An overview of the number of the tests regarding validity and reliability in each category is presented in Table 4.1. Ball dribbling was included in change-of-direction sprint tests (4 validity, 3 reliability) and in combinations (1 validity). A total of 3,901 participants (mean ± standard deviation 56 ± 108, median 25, range 7–939) with an average age from 17 to 33 years (mean ± standard deviation 21 ± 3 years, median 21 years) were involved. Most studies examined male players (74), while female (13) and both male and female players (3) were studied less often. The playing level covered a wide range between recreational and national team players.

Table 4.1 Overview.

	Number of tests	
Test category	**Validity (Construct/Criterion)**	**Reliability (Intraday/Interday)**
Linear sprint	16 (14/2)	51 (26/22)*
Repeated sprint	6 (5/1)	9 (2/6)*
Change of direction	15 (14/1)	45 (27/16)*
Agility	0 (0/0)	4 (0/4)
Combinations	10 (8/2)	11 (2/8)*
Total	**47 (41/6)**	**120 (57/57)***

* – Deviating sum due to reliability type being not specified for each test

4.4.3 Assessment of Methodological Quality

Construct and criterion validity were reported for 41 and 6 tests, respectively. The mean score was 6.4/10 (range 4–10) and 9.8/14 (range 9–12) leading to a high rating of methodological quality.

Intraday and interday reliability were reported for 57 and 56 tests, respectively, with reliability type being not specified for 7 tests. The mean score was 7.9/14 (range 5–11) and 7.8/14 (range 5–11), which is below the threshold for a high rating of methodological quality (Tables 4.2–4.10, column ‘MQ’).

Subject characteristics and test execution were clearly depicted in most of the studies. In addition, the majority of studies used appropriate statistical methods at least to some extent. Conversely, only a small amount of studies stated the competence of the raters or described methodological aspects in sufficient detail, with blinding of the raters being stated in none of the studies.

Table 4.2 Linear-sprint tests (validity).

Study	**Population**				**Short description**	**Type**	**Results**	**MQ**
	N	**Gender**	**Age**	**Playing level (Country)**				
Silva et al. (2013b)	13	male	25.7 ± 4.6	Portuguese championship (Portugal)	30-m sprint, split at 5 m; high-intensity running and sprinting during matches	Criterion	5 m and high-intensity running during matches: r = -0.40 – -0.67 5 m and sprinting during matches: r = -0.56 – -0.62 30 m and high-intensity running during matches: r = -0.35 – -0.63 30 m and sprinting during matches: r = -0.46 – -0.73	10 (14)
Djaoui et al. (2017)	48	male	Professional: 24.3 ± 2.6 Elite amateur: 20.9 ± 2.9	Professional, elite amateur (France)	40-m sprint, with GPS; maximal sprinting speed during matches	Criterion	Maximal sprinting speed during 40-m sprint and matches: r = 0.52	9 (10)
					40-m sprint, with GPS	Construct	Elite amateur faster than professional (1.6%, ES (d) = 0.33)	6 (10)
Haugen et al. (2013a)	939	male	22.1 ± 4.3	National team, 1st division, 2nd division, 3rd to 5th division, junior national team, juniors (Norway)	40-m sprint, splits at 10, 20, and 30 m	Construct	20 m: National team faster than 2nd division (1.4%, ES (d) = 0.50), 3rd to 5th division (3.8%, ES (d) = 1.20), junior national team (1.8%, ES (d) = 0.60), and junior players (2.8%, ES (d) = 0.90) Fastest 10-m split: "similar results"	8 (10)
Ferro et al. (2014)	42	male	21.2 ± 1.70	Competitive, non-competitive (not specified)	30-m sprint, 10-m sections, with laser system	Construct	Competitive always better than non-competitive* 10 m: 0.7%, ES = 0.23 10–20 m: 1.4%, ES = 0.42 20–30 m: 1.8%, ES = 0.42 20 m: 1.1%, ES = 0.36 30 m: 1.3%, ES = 0.39 10–30 m: 1.6%, ES = 0.44	6 (10)
Silvestre et al. (2006a)	25	male	19.9 ± 1.3	Starters and non-starters of a division 1 team (USA)	36.5-m sprint, split at 9.1 m	Construct	Pre-Season 36.5 m: Starters better than non-starters (2%, ES (d) = 0.52) Pre-Season 9.1 m and Post-Season 9.1 m and 36.5 m: No differences between groups	5 (10)

Silvestre et al. (2006b)	27	male	19.9 ± 1.3	Starters and non-starters of a division 1 team (USA)	36.5-m sprint, split at 9.1 m	Construct	36.5 m: Starters better than non-starters (3.9%, ES (d) = 1.04) 9.1 m: No differences between groups	5 (10)
Cometti et al. (2001)	95	male	1st division: 26.1 ± 4.3 2nd division: 23.2 ± 5.6 amateurs: 25.8 ± 3.9	1st division, 2nd division, amateurs of regional standard (France)	30-m sprint, split at 10 m, visual stimulus as a starting signal	Construct	10 m: 1st division faster than 2nd division (0.8%, ES (d) = 0.24) and amateur (3.0%, ES (d) = 0.8) 30 m: 1st division faster than 2nd division (0.6%, ES (d) = 0.16) and amateur (1.7%, ES (d) = 0.43)	6 (10)
Risso et al. (2017)	22	female	Starters: 20.4 ± 1.3 Non-starters: 20.1 ± 1.2	Starters and non-starters of professional team (USA)	30-m sprint, splits at 5 m and 10 m	Construct	Starters always better than non-starters 5 m: 0.9%, ES (d) = 0.2 10 m: 0.5%, ES (d) = 0.16 30 m: 2.1%, ES (d) = 0.64	6 (10)
Vescovi (2012)	140	female	23.9 ± 2.8	Drafted and non-drafted players of try-outs of a professional women's soccer league (USA)	35-m sprint, splits at 5 m, 10 m, and 20 m	Construct	Drafted always better than non-drafted* 5 m: 4.1%; ES (d) = 0.55 10 m: 2.8%; ES (d) = 0.56 20 m: 2.9%; ES (d) = 0.67 35 m: 3%; ES (d) = 0.78	10 (10)
Rebelo et al. (2013)	180	male	18.2 ± 0.6	1st division elite, regional division non-elite (Portugal)	30-m sprint, split at 5 m	Construct	Elite better than non-elite** 5 m: 4.6%; ES (d) = 0.57 30 m: 1.48%; ES (d) = 0.38	7 (10)
Haugen et al. (2012b)	194	female	22 ± 4.1	Senior national-team, 1st division, 2nd division, highest junior division (Norway)	40-m sprint, splits at 10, 20, and 30 m	Construct	20 m: National team faster than 1st division (2%, ES (d) = 0.5) and 2nd division (5%, ES (d) = 1.30); 1st division faster than 2nd division (3%, ES (d) = 0.80); junior elite faster than 2nd division (3%, ES (d) = 0.80) 20–40 m: National team faster than 2nd division (5.0%, ES (d) = 1.10); 1st division faster than 2nd division (3.0%, ES (d) = 0.70)	8 (10)
Cotte & Chatard (2011)	14	male	International: 24.2 ± 6.1 National: 26.5 ± 5.9	International and national players of English premier league team (England)	30-m sprint, splits at 10 and 20 m	Construct	International always better than national, except for velocity 10–20 m Time: 10 m (1.2%, ES (d) = 0.25), 20 m (1.0%, ES (d) = 0.3), 30 m (1.2%, ES (d) = 0.32) Velocity: 0–10 m (1.2%, ES (d) = 0.26), 10–20 m (0.1%, ES (d) = 0.04), 20–30 m (1.2%, ES (d) = 0.29)	7 (10)
Nikolaidis et al. (2016)	179	male	U18–U35: 17.48 ± 0.23 – 32.58 ± 1.77	2nd, 3rd, and 4th national leagues (Greece)	20-m sprint	Construct	U19 better than U20 (0.6%), U25 (0.6%), U35 (2.8%), U21 (3.4%), U30 (3.7%), and U18 (4.0%)	7 (10)

Mujika et al. (2009b)	68	male, female	Female: 17 ± 1.6 (junior) 23.1 ± 2.9 (senior) Male: 18.4 ± 0.9 (junior), 24 ± 3.4 (senior)	Senior females of Spanish Super Liga, junior females of Primera Nacional, senior males of La Liga, junior of Tercera Division (Spain)	15-m sprint	Construct	Female: Senior better than junior (2.1%, ES (d) = 0.64) Male: Junior better than senior (0.1%, ES (d) = 0.05)	7 (10)
Kobal et al. (2016)	45	male	Professional: 22 ± 2.9 U20: 19 ± 0.6	Professional, U20 (Brazil)	20-m sprint, split at 10 m	Construct	10 m: U20 better than professional (ES (d) = 0.14) 20 m: Professional better than U20 (ES (d) = 0.38)	7 (10)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; GPS – Global positioning system; * – Selected parameters; ** – Pooled ES for several positions

Table 4.3 Linear-sprint tests (reliability).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Gelen (2010)	26	male	23.2 ± 3.2	Professionals from 3rd division (Turkey)	30-m sprint	Intraday	ICC = 0.87–0.91	7 (14)
Rouissi et al. (2017)	31	male	17.42 ± 0.55	Professionals from 1st division (Tunisia)	10-m sprint	Interday	ICC = 0.94; CV = 1.6%	9 (14)
Haugen et al. (2015b)	30 (m), 14 (f)	male, female	18.2 ± 1.0	Amateurs	25-m and 40-m sprint Flying start distances: 0.5, 1, 1.5, 2, 5, 10, 15 m	Intraday	20-m sprint time with flying start: 0.5 m: ICC = 0.99; CV = 1.2% 1 m: ICC = 0.99; CV = 1.3% 1.5 m: ICC = 0.99; CV = 1.3% 2 m: ICC = 0.99; CV = 1.4% 5 m: ICC = 0.99; CV = 1.0% 10 m: ICC = 0.99; CV = 1.0% 15 m: ICC > 0.99; CV = 0.9% 10-m sprint time with flying start: Similar trend but with slightly higher CV values across all flying-start distances (1.4–1.8%)	10 (14)
López-Segovia et al. (2015)	21	male	18.4 ± 0.8	Professional from Spanish national league division (Spain)	30-m sprint	Interday	ICC = 0.90; CV = 1.1%	8 (14)
Pareja-Blanco et al. (2016)	21	male	24.3 ± 4.6	Professional Moroccan soccer club (Morocco)	30-m sprint	Intraday	ICC = 0.98; CV = 0.8%	8 (14)
Sporis et al. (2009)	270	male	28.3 ± 5.9	Profesionals from 1st national league (Croatia)	20-m sprint, splits at 5 and 10 m	Intraday	5 m: ICC = 0.89 10 m: ICC = 0.80 20 m: ICC = 0.81	5 (14)
Zois et al. (2011)	10	male	23.3 ± 2.5	Amateurs from Serie D (Italy)	20-m sprint	Interday	CV = 0.8%	8 (14)
Emmonds et al. (2017)	10	female	25.4 ± 7.0	Professional from highest division (WSL1) (England)	30-m sprint, splits at 10 and 20 m	Intraday	10 m: ICC = 0.95; CV = 1.4% 20 m: ICC = 0.92; CV = 1.3% 30 m: ICC = 0.90; CV = 1.5%	8 (14)

Mujika et al. (2009a)	20	male	18.3 ± 0.6	Professional juniors at national level (not specified)	15-m sprint	Intraday	ICC = 0.94	9 (14)
Loturco et al. (2017) & Loturco et al. (2016)	27	male	18.4 ± 1.2	Professional U20, São Paulo state elite championship (Brazil)	30-m sprint	Intraday	ICC = 0.97; CV = 2.3%	8 (14) 9 (14)
Boone et al. (2012)	289	male	25.4 ± 4.9	Professionals from 1st division (Belgium)	10-m sprint, split at 5 m; auditory cue as a starting signal	Intraday	5 m: ICC = 0.88 10 m: ICC = 0.90	5 (14)
Manson et al. (2014)	33	female	U19: 17.8 ± 0.71 Senior: 23.3 ± 4.89	Professionals from national team (New Zealand)	Linear sprint for > 6 s on a nonmotorized treadmill	Intraday	Velocity: ICC = 0.79; CV = 2.0%	7 (14)
Meylan et al. (2017)	20	female	18.2 ± 0.7	Professionals from national team (Top 10 in the world)	40-m sprint, with timing lights and GPS	Intraday	Timing lights: ICC = 0.80–0.96; CV = 0.9–2.3% GPS: ICC = 0.86; CV = 2.1%	6 (14)
Sjökvist et al. (2011)	14	female	20.3 ± 2.3	Collegiate players from NCAA division 1 (USA)	20-m sprint	Interday	ICC > 0.93	8 (14)
Requena et al. (2011)	14	male	20.0 ± 3.6	Professional (not specified)	15-m sprint	Interday	ICC = 0.87–0.95	7 (14)
Ingebrigtsen et al. (2014)	57	male	22 ± 5	Professionals from 3 best leagues (Norway)	35-m sprint, splits at 10 and 20 m	Intraday	10 m: ICC = 0.94; CV = 0.7% 20 m: ICC = 0.97; CV = 1.4% 35 m: ICC = 0.96; CV = 1.9%	8 (14)
Yanci et al. (2014)	39	male	22.9 ± 2.8	Professionals from 3rd division (Spain)	15-m sprint, splits at 5 and 10 m	Intraday	5 m: CV = 2.5% 10 m: CV = 1.7% 15 m: CV = 1.2%	9 (14)
Comfort et al. (2014)	34	male	17.2 ± 0.6	Well-trained players (England)	20-m sprint, split at 5 m	Intraday	5 m: ICC = 0.87 20 m: ICC = 0.97	7 (14)
López-Segovia et al. (2011)	14	male	20.14 ± 0.4	Amateur (not specified)	30-m sprint, splits at 10 and 20 m	Intraday	10 m, 20 m, 30 m, 10–20 m, 10–30 m, 20–30 m: ICC: 0.92–0.99; CV: 1.2–2.6%	7 (14)
Chelly et al. (2010)	23	male	17.2 ± 0.7	Semi-professionals from national junior championship league (Tunesia)	10-m sprint, with camera at 25 frames per second	Intraday	Sprint velocities and accelerations: ICC = 0.87–0.96	8 (14)

Spierer et al. (2011)	15	male	22.1 ± 1.5	Professionals from Division 1 (USA)	20-m linear sprint with auditory stimulus as a starting signal	Intraday	ICC = 0.97	7 (14)
Caldwell & Peters (2009)	13	male	24 ± 4.4	Semi-professionals from nationwide conference north league (England)	15-m sprint	Interday	ICC = 0.80	7 (14)
Ronnestad et al. (2008)	21	male	IG1: 23 ± 2 IG2: 22 ± 2.5 CG: 24 ± 1.5	Professional (Norway)	40-m sprint, splits at 10 and 30 m	Intraday	10 m and 30–40 m: CV < 3.0%	7 (14)
Small et al. (2009)	9	male	21.3 ± 2.9	Semi-professional (United Kingdom)	10-m sprint, test is part of a soccer match simulation	Intraday	ICC > 0.83	6 (14)
Los Arcos et al. (2017)	42	male	23.2 ± 2.4	Professionals from 2nd and 3rd division (Spain)	15-m sprint, splits at 5 and 10 m	Intraday	5 m: ICC = 0.87 10 m: ICC = 0.93 15 m: ICC = 0.96	9 (14)
Gorostiaga et al. (2004)	19	male	17.2; range: 16–18.5	Amtaeurs at regional level (Spain)	15-m sprint	Intraday	CV < 1.5%	9 (14)
Gil et al. (2015)	20	male	23.3 ± 4.8	Professional (Brazil)	25-m sprint	Interday	ICC = 0.92; CV = 1.3%	6 (14)
Coelho et al. (2016)	138	male	U17: 17.3 ± 5.33 U20: 20.6 ± 3.66 Professional: 23.25 ± 6.42	Professionals from 1st division (Brazil)	30-m sprint, splits at 10 and 20 m	Interday	10 m: ICC = 0.98 20 m: ICC = 0.96 30 m: ICC = 0.96	9 (14)
Boussettaa et al. (2017)	11	male	21.82 ± 0.51	Healthy players (not specified)	10-m sprint	Interday	ICC = 0.88	7 (14)
Shalfawi et al. (2013b)	20	female	19.4 ± 4.4	Well-trained players from 2nd division (Norway)	40-m sprint	Intraday	ICC = 0.83	8 (14)
Sayers et al. (2008)	20	female	19.35 ± 0.99	Professional from women‘s professional socer league (not specified)	30-m sprint, splits at 10 and 20 m	Interday	30 m: ICC > 0.99 20–30 m: ICC = 0.99 10 m: ICC = 0.99	9 (14)
Thomas et al. (2009)	12	male	17.3 ± 0.4	Semi-professionals from soccer academy (United Kingdom)	20-m sprint	Interday	5 m: ICC = 0.93 10 m: ICC = 0.96 15 m: ICC = 0.94	8 (14)

							20 m: ICC = 0.98	
Iaia et al. (2015)	18	male	18.5 ± 1.0	Professionals at national level (Denmark)	200-m sprint	Interday	CV = 0.8%	8 (14)
Rey et al. (2017)	18	male	26.6 ± 3.7	Professional (Spain)	10-m sprint, split at 5 m	Interday	5 m: ICC = 0.96 10 m: ICC = 0.94	7 (14)
McGawley & Andersson (2013)	18	male	23.0 ± 4.0	Semi- and fully-professional from 1st division (Sweden)	10-m sprint	Interday	CV = 1.8%	7 (14)
Loturco et al. (2015)	24	male	18.2 ± 0.6 and 18.5 ± 0.8	High-level U20 players (Brazil)	20-m sprint, split at 10 m	Interday	10 m, 20 m, 10–20 m: ICC > 0.98	7 (14)
Rebelo et al. (2013)	180	male	18.2 ± 0.6	1st division elite, regional division non-elite (Portugal)	30-m sprint, split at 5 m	Intraday	5 m: ICC = 0.97 30 m: ICC = 0.97	6 (14)
Silva et al. (2013b)	13	male	25.7 ± 4.6	Professional Portuguese championship team (Portugal)	30-m sprint, split at 5 m	Not specified	5 m and 10 m: ICC: 0.76–0.87	6 (14)
Kobal et al. (2016)	45	male	Professional: 22 ± 2.9 U20: 19 ± 0.6	Professional, U20 (Brazil)	20-m sprint	Intraday	ICC = 0.88	7 (14)
Silva et al. (2011)	18	male	25.7 ± 4.6	Professionals from Portuguese elite championship (Portugal)	30-m sprint	Not specified	ICC = 0.71–0.87	6 (14)
Bullock et al. (2012)	18	male	18 ± 3	High-level amateurs from local soccer clubs (not specified)	5-m sprint; test is a part of a complex test	Interday	ICC = 0.55; r = 0.60; CV = 2.9%	8 (14)
Cotte & Chatard (2011)	14	male	International: 24.2 ± 6.1 National: 26.5 ± 5.9	International and national players of English premier league team (England)	30-m sprint, splits at 10 and 20 m	Intraday	10 m: CV = 5.2% 20 m: CV = 4.8% 30 m: CV = 4.5%	9 (14)
Williams et al. (2010)	15	male	26.1 ± 4.6	Amateurs from local league (not specified)	20-m sprint, split at 12 m, test is part of a soccer match simulation	Interday	12 m: CV = 1.8–3.2% 20 m: CV = 0.9–3.3%	8 (14)
Mirkov et al. (2008)	20	male	20.4 ± 1.8	Professionals from 1st selection of a premier	30-m sprint, split at 10 m	Intraday	10 m: ICC = 0.81; CV = 3.2% 10–30 m: ICC = 0.93; CV = 2.1%	9 (14)

				national league team (Serbia)				
Silva et al. (2013a)	7	male	22–31	Professionals from Portuguese soccer league (Portugal)	30-m sprint	Intraday	CV = 3.5%	7 (14)
Kutlu et al. (2017)	34	female	20.8 ± 1.9	Amateurs from university soccer team (Turkey)	20-m sprint	Interday	ICC = 0.94; CV = 4.0%	9 (14)
Harper et al. (2016)	10	male	22 ± 3	University-standard (England)	20-m sprint, test is part of a soccer match simulation	Interday	CV = 0.5–3.5%	7 (14)
Sonderegger et al. (2016)	72	male	17.1 ± 0.6	Highly-trained U18 top level teams (Switzerland)	50-m sprint, velocity at the start line: 0 km/h, 6 km/h, 10.8 km/h, and 15 km/h	Interday	0 km/h: CV = 6.7% 6 km/h: CV = 5.4% 10.8 km/h: CV = 6.1% 15 km/h: CV = 10.9%	9 (14)
Ispirlidis et al. (2008)	24	male	21.1 ± 1.2	Elite (Greece)	20-m sprint	Not specified	CV = 3.5%	5 (14)
Yanci et al. (2017)	12	male	21.08 ± 1.57	Amateur (Spain)	20-m sprint, with timing lights and GPS	Interday	Timing lights: ICC = 0.73; CV = 1.9% GPS: ICC = 0.17; CV = 7.8%	9 (14)
Haugen et al. (2012b)	194	female	22 ± 4.1	Senior national-team, 1st division, 2nd division, highest junior division (Norway)	40-m sprint, splits at 10, 20, and 30 m	Interday	Long-term reliability (6–12 months) 10 m: r = 0.77; CV = 2.9% 10–20 m: r = 0.82; CV = 2.6% 20–30 m: r = 0.85; CV = 3.3% 30–40 m: r = 0.81; CV = 1.8% 20 m: r = 0.90; CV = 2.1% 20–40 m: r = 0.80; CV = 3.3%	9 (14)

MQ – Methodological quality, maximal possible score in parenthesis; ICC – Intraclass correlation coefficient, r – Pearson's r; CV – Coefficient of variation; IG – Intervention group; CG – Control group; GPS – Global positioning system

Table 4.4 Repeated-sprint tests (validity).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Carling et al. (2012)	12	male	Senior (not specified	1st French league (France)	6 x 6-s sprints, 20 s passive recovery, on a non-motorized treadmill	Criterion	Test: AV, HAV, PV, %Dec Match: High-intensity actions (% of total distance covered, average number, average recovery time, % of recovery time < 20 s and < 30 s), repeated high-intensity bouts (average number, average velocity, maximum velocity) %Dec and % of high-intensity actions with recovery times ≤ 20 s: r = -0.51 Average velocity and recovery time between high-intensity actions: r = 0.42 No further notable correlations between repeated-sprint test parameters and match parameters*	9 (14)
Dellal & Wong (2013)	26	male	Senior, U19 (not specified)	2nd senior team of a professional club, U19 (France)	10 x 20-m sprints, 25 s active recovery	Construct	2nd team always better than U19 FT: 2.7%; ES (d) = 0.90 AT: 2.6%; ES (d) = 0.88 TT: 2.6%; ES (d) = 0.89 %Dec: 6.0%; ES (d) = 0.15	5 (10)
Wong et al. (2012)	34	male	23.3 ± 3.6	Professional, college (not specified)	6 × 20-m sprints, 25 s active recovery	Construct	Professional always better than college: FT: 2.2%; ES (d) = 0.69 AT: 2.4%; ES (d) = 0.77 TT: 2.6%; ES (d) = 0.84 %Dec: 14.5%; ES (d) = 0.39	5 (10)
Gabbett (2010)	19	female	18.1 ± 2.9	Professional, semi-professional (Australia)	Game-specific test of repeated-sprint ability for elite women's soccer players: 6 × 20-m sprints, starting every 15 s, 20 m active recovery	Construct	Professional always better than semi-professional: IT: 8.3%; ES (d) = 3.17 TT: 10.3%; ES (d) = 5.50 %Dec: 8.8%; ES (d) = 0.30	5 (10)
Aziz et al. (2008)	52	male	Professional: 20.4 ± 1.6	Professional U23 players, amateur	6 × 20-m sprints, 20 m active recovery	Construct	Professional always better than amateur: FT: 0.3%, ES (d) = 0.14 TT: 2.3%, ES (d) = 0.83	7 (10)

			Amateur: 23.5 ± 0.8	players from a university (Singapore)				
Ingebrigtsen et al. (2012)	51	male	Elite: 26 ± 7 Sub-elite: 20 ± 3	Elite 1st division players, Sub-elite 3rd division players (Norway)	7 x 35-m sprints, 25 s active recovery	Construct	AT: Elite better than sub-elite (0.4%; ES (d) = 0.1) %Dec: Sub-elite better than elite: (22.9%; ES (d) = 0.4)	4 (10)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; * – Selected parameters; AV – Average velocity; HAV – Highest average velocity; PV – Peak velocity; %Dec – Percent decrement; FT – Fastest time; AT – Average time; TT – Total time; IT – Initial time

Table 4.5 Repeated-sprint tests (reliability).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Chaouachi et al. (2010)	23	male	19 ± 1	Professionals from national leagues (Tunisia)	7 x 30-m sprints, 25 s recovery	Not specified	TT: ICC = 0.92; CV = 2.7%	9 (14)
Haugen et al. (2014b)	25	male female	17 ± 1	1st junior division high school (Norway)	12 x 20-m sprints, starting every 60 s	Intraday	TT: CV = 0.8%	5 (14)
Shalfawi et al. (2013b)	20	female	19.4 ± 4.4	Well-trained from 2nd division (Norway)	7 x 30-m sprint, 30 s recovery	Interday	TT: ICC = 0.91	8 (14)
Iaia et al. (2015)	18	male	18.5 ± 1.0	Professionals at national level (Denmark)	15 x 40 m-sprint, 30 s passive recovery	Interday	TT: CV = 1.2% %Dec: CV = 16.8%	6 (14)
McGawley & Andersson (2013)	18	male	23.0 ± 4.0	Semi- and fully-professional from 1st division (Sweden)	6 x 30 m-sprints, starting every 20 s	Interday	TT: CV = 0.8%	7 (14)
López-Segovia et al. (2014)	19	male	21.2 ± 2.1	Semi-professional from 3rd division (Spain)	Repeated 40-m sprints, splits at 10 and 20 m, until there was a 3% decrease in performance, 2 min passive recovery	Interday	TT: 10 m, 20 m, and 40 m: ICC = 0.92–0.99; CV = 1.2–2.6%	7 (14)
Wong et al. (2012)	34	male	23.3 ± 3.6	Professional, college (not specified)	6 × 20-m sprints, 25 s active recovery	Interday	FT: ICC = 0.88; CV = 5.0% AT: ICC = 0.90; CV = 5.0% TT: ICC = 0.90; CV = 5.0% %Dec: ICC = 0.11; CV = 46.0%	7 (14)
Gabbett (2010)	19	female	18.1 ± 2.9	Professional, semi-professional (Australia)	Game-specific test of repeated-sprint ability for elite women's soccer players: 6 × 20-m sprints, starting every 15 s, 20 m active recovery	Interday	TT: ICC = 0.91; CV = 1.5% %Dec: ICC = 0.14; CV = 19.5%	7 (14)
Ruscello et al. (2013)	17	male	21.9 ± 3.6	Professionals from Italian lega pro (Italy)	7 x 30-m sprints, exercise to rest ratio 1:5, passive recovery	Intraday	TT: ICC = 0.75	6 (14)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; * – Selected parameters; %Dec – Percent decrement; FT – Fastest time; AT – Average time; TT – Total time, ICC – Intraclass correlation coefficient, r – Pearson's r; CV – Coefficient of variation

Table 4.6 Change-of-direction sprint tests (validity).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Silva et al. (2013b)	13	male	25.7 ± 4.6	Professional Portuguese championship team (Portugal)	T Test (36.6 m): Linear sprinting (9.1 m), COD of 90° to the left (4.6 m), COD of 180° (9.1 m), COD of 180° to the left (4.6 m), COD of 270° to the left (9.1 m)	Criterion	T Test and high-intensity running during matches: r = -0.01 – -0.56 T Test and sprinting during matches: r = -0.15 – -0.34	10 (14)
Mujika et al. (2009b)	68	male, female	Female: 17 ± 1.6 (junior) 23.1 ± 2.9 (senior) Male: 18.4 ± 0.9 (junior), 24 ± 3.4 (senior)	Senior females of Spanish Super Liga, junior females of Primera Nacional, senior males of La Liga, junior of Tercera Division (Spain)	15-m sprint: Linear sprinting (3 m), slalom section (3 m), clearing a hurdle (2 m), linear sprinting (7 m) to the finish	Construct	Male: Senior better than junior (5.1%, ES (d) = 1.27) Female: Senior better than junior (7.8%, ES (d) = 1.47)	7 (10)
					15-m ball dribbling: 15-m sprint, while dribbling and kicking a ball	Construct	Male: Senior better than junior (0.8%, ES (d) = 0.11) Female: Senior better than junior (12.2%, ES (d) = 1.41)	7 (10)
Risso et al. (2017)	22	female	Starters: 20.4 ± 1.3 Non-starters: 20.1 ± 1.2	Starters and non-starters of professional team (USA)	Pro agility shuttle: 4.57-m sprint, COD of 180°, 9.14-m sprint, COD of 180°, 4.57-m sprint to the finish	Construct	Starters better than non-starters (1.0%, ES (d) = 0.29)	8 (10)
					60-yard shuttle: 4.57-m sprint, COD of 180°, 4.57-m sprint, COD of 180°, 9.14-m sprint, COD of 180°, 9.14-m sprint, COD of	Construct	Starters better than non-starters (0.4%, ES (d) = 0.17)	8 (10)

					180°, 13.72-m sprint, COD of 180°, 13.72-m sprint to the finish			
Huijgen et al. (2014)	113	male	17.1 ± 0.7	Selected and deselected players of talent development programmes of professional soccer clubs (Netherlands)	Slalom Sprint: 30-m slalom section with 12 cones placed in a zig-zag pattern (horizontal and lateral displacement: 2 m)	Construct	Selected better than deselected (1.9%; ES (d) = 0.40)	7 (10)
					Slalom Dribbling Slalom sprint while dribbling a ball	Construct	Selected better than deselected (2.6%; ES (d) = 0.37)	7 (10)
Rebelo et al. (2013)	180	male	18.2 ± 0.6	1st division elite, regional division non-elite (Portugal)	T Test (40 m): Linear sprinting (10 m), COD of 90° to the left (5 m), COD of 180° (10 m), COD of 180° to the left (5 m), COD of 90° to the left (10 m)	Construct	Elite better than non-elite (3.2%; ES (d): 0.90)	7 (10)
					Slalom Dribbling (approx. 32 m): 9 cones, each cone 2 m apart, slalom dribbling around the cones, COD of 180° and slalom dribbling back to the start	Construct	Elite better than non-elite (3.6%; ES (d): 0.42)	7 (10)
Kutlu et al. (2012)	70	male	21.2 ± 3.0	Professional, amateur (Turkey)	T Test: Several CODs, forward sprinting, left- and right-side shuffling, and back pedaling; no further information on test procedures given	Construct	Professional faster than amateur (5.27%, ES (d) = 1.5)	5 (10)
					T Test with Ball: No information on test procedures given	Construct	Professional faster than amateur (3.92%; ES (d) = 0.81)	4 (10)

					Zig-Zag: No information on test procedures given	Construct	Professional faster than amateur (9.11%; ES (d) = 1.64)	4 (10)
					Illinois test: Accelerating, decelerating, several CODs of different angles; no further information on test procedures given	Construct	Professional faster than amateur (1.81%; ES (d) = 0.5)	5 (10)
Russel et al. (2010)	20	male	19 ± 4	Recreational university reserve team, Professional Championship team (England)	Slalom Dribbling (approx. 20 m): 7 cones, each cone 3 m apart, 1st cone 1 m from start, slalom dribbling around the cones, finish 1 m from 7th cone	Construct	Professional better than recreational (2.4%; ES (d) = 0.37)	7 (10)
Keiner et al. (2014)	111	male	U19, U21, Senior (not specified)	U19 and U21 of elite club, professional players of 1st and 2nd German division (Germany)	Equilateral triangle, 5 m side length 10-m sprint, 2 CODs of 60° after 2.5 m and 7.5m, 2.5-m sprint to the finish, split at 5 m	Construct	5 m: U21 (STG) better than U21 (CG) (3.1–3.4%, ES (d) = 1.0–1.4), U19 (STG) (3.4–4.1%, ES (d) = 0.85–0.94), professional (3.5–5.4%, ES (d) = 1.16–1.89), and U19 (CG) (5.6–7.0%, ES (d) = 1.42–2.01) 10 m: U21 (STG) better than U21 (CG) (3.1–4.6%, ES (d) = 1.25–1.33), U19 (STG) (3.2–3.5%, ES (d) = 0.85–0.98), professional (3.8–4.3%, ES (d) = 1.34–1.50), and U19 (CG) (6.6–7.9%, ES (d) = 2.06–2.42)	5 (10)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; COD – change of direction; STG – Strength training group; CG – Control group

Table 4.7 Change-of-direction sprint tests (reliability).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Gelen (2010)	26	male	23.2 ± 3.2	Professionals from 3rd division (Turkey)	Slalom Dribble (10 m): 4 cones, each cone 2 m apart, slalom dribbling around the cones	Intraday	ICC = 0.87–0.91	7 (14)
Bendiksen et al. (2013)	11	female	21.0 ± 4.5	Professionals from 2nd best league (Norway)	Shuttle Sprint (40 m) 40-sprint, COD of 180° after 20 m, test is part of a soccer match simulation	Interday	10 m: ICC = 0.91; CV = 2.3% 20 m: ICC = 0.91; CV = 2.9%	8 (14)
Currell et al. (2009)	11	male	21.4 ± 1	Recreational (not specified)	Running through a series of markers as quickly as possible, test is part of a soccer match simulation; no further information on test procedures given	Interday	CV = 1.2%	7 (14)
					Ball dribbling: Each participant had to negotiate a course of five cones set out directly behind one another as quickly as possible, test is part of a soccer match simulation	Interday	CV = 2.2%	7 (14)
Rouissi et al. (2017)	31	male	17.42 ± 0.55	Professionals from 1st division (Tunisia)	10-m sprint, COD of 45° after 5 m	Interday	ICC = 0.88–0.89; CV = 1.2–1.8%	9 (14)
					10-m sprint, COD of 90° after 5 m	Interday	ICC = 0.87–0.88; CV = 1.5%	9 (14)
					10-m sprint, COD of 135° after 5 m	Interday	ICC = 0.92; CV = 1.2–2.2%	9 (14)
					10-m sprint, COD of 180° after 5 m	Interday	ICC = 0.89–0.94; CV = 1.6–1.9%	9 (14)
Emmonds et al. (2017)	10	female	25.4 ± 7.0	Professional from highest division (WSL1) (England)	505 test (20 m): COD of 180° after 15 m, time taken 10–20 m	Intraday	ICC = 0.99; CV = 2.2%	8 (14)

Mujika et al. (2009a)	20	male	18.3 ± 0.6	Professional juniors at national level (not specified)	15-m sprint: Linear sprinting (3 m), slalom section (3 m), clearing a hurdle (2 m), linear sprinting (7 m)	Intraday	ICC = 0.92	9 (14)
Loturco et al. (2017) & Loturco et al. (2016)	27	male	18.4 ± 1.2	Professional U20, São Paulo state elite championship (Brazil)	Zig-zag test: 20-m sprint, 3 CODs of 100° every 5 m	Intraday	ICC = 0.96; CV = 2.4%	8 (14) 9 (14)
Miller et al. (2011)	16	male	19.6 ± 0.8	NCAA Division III national championship (USA)	T Test (36.6 m) with contact mat: 9.1 m linear sprinting, 4.6 m shuffling to the left, 9.1 m shuffling to the right, 4.6 m shuffling to the left, 9.1 m backpedaling	Intraday	ICC = 0.86	6 (14)
Boone et al. (2012)	289	male	25.4 ± 4.9	Professionals from 1st division (Belgium)	Shuttle sprint (5 x 10 m): 50-m sprint, 5 CODs of 180° every 10 m	Intraday	ICC = 0.81	5 (14)
Castillo-Rodríguez et al. (2012)	42	male	20.11 ± 3.68	Amateur (Spain)	10-m sprint, COD of 90° after 5 m	Intraday	ICC = 0.81–0.88	5 (14)
					10-m sprint, COD of 180° after 5 m	Intraday	ICC = 0.83	5 (14)
Caldwell & Peters (2009)	13	male	24 ± 4.4	Semi-professionals from nationwide conference north league (England)	Illinois test: Start from a lying position; no further information on test procedures given	Interday	ICC = 0.78	7 (14)
Thomas et al. (2009)	12	male	17.3 ± 0.4	Semi-professionals from soccer acamedy (United Kingdom)	505 test	Interday	ICC = 0.99	7 (14)
Rey et al. (2017)	18	male	26.6 ± 3.7	Professional (Spain)	T Test (36.6 m): 9.1 m linear sprinting, 4.6 m shuffling to the left, 9.1 m shuffling to the right, 4.6 m	Interday	ICC = 0.91	5 (14)

					shuffling to the left, 9.1 backpedaling			
Rebelo et al. (2013)	180	male	18.2 ± 0.6	1st division elite, regional division non-elite (Portugal)	T Test (40 m): Linear sprinting (10 m), COD of 90° to the left (5 m), COD of 180° (10 m), COD of 180° to the left (5 m), COD of 90° to the left (10 m)	Intraday	ICC = 0.95	6 (14)
					Slalom Dribbling (approx. 32 m): 9 cones, each cone 2 m apart, slalom dribbling around the cones, COD of 180° and slalom dribbling back to the start	Intraday	ICC = 0.99	6 (14)
Russel et al. (2010)	20	male	19 ± 4	Recreational university reserve team, Professional Championship team (England)	Slalom Dribbling (approx. 20 m): 7 cones, each cone 3 m apart, 1st cone 1 m from start, slalom dribbling around the cones, finish 1 m from 7th cone	Interday	Mean ball speed during dribbling: ICC = 0.78; r = 0.78; CV = 2.4%	9 (14)
Di Mascio et al. (2015)	11	male	17 ± 1	Elite U18 EPL (England)	Arrowhead Agility Test: Cones in an arrowhead shape, cones to indicate the start and finish line; no further information on test procedures given	Interday	CV = 0.8%	7 (14)
Silva et al. (2013b)	8	male	25.7 ± 4.6	Portuguese championship (Portugal)	T Test (36.6 m): Linear sprinting (9.1 m), COD of 90° to the left (4.6 m), COD of 180° (9.1 m), COD of 180° to the left (4.6 m), COD of 270° to the left (9.1 m)	Not Specified	ICC: 0.75–0.85	6 (14)
Mirkov et al. (2008)	20	male	20.4 ± 1.8	Professionals from 1st selection of a premier national league team (Serbia)	Shuttle sprint (10 × 5 m): 50-m sprint, 10 CODs of 180° every 5 m	Intraday	ICC = 0.94; CV = 1.2%	9 (14)
					Zig-zag test: 20-m sprint, 3 CODs of 100° every 5 m	Intraday	ICC = 0.84; CV = 2.5%	9 (14)
					Zig-zag test with ball	Intraday	ICC = 0.81; CV = 3.3%	9 (14)

Meylan et al. (2017)	20	female	18.2 ± 0.7	Professionals from national team (Top 10 in the world)	20-m sprint, COD of 90° after 10 m, with timing lights and GPS	Intraday	Timing lights: ICC = 0.81–0.93; CV = 1.1–2.4% GPS: ICC = 0.37–0.77; CV = 3.7–13.0%	6 (14)
Yanci et al. (2014)	39	male	22.9 ± 2.8	Professionals from 3rd division (Spain)	Modified T Test (20 m): 5 m linear sprinting, 2.5 m shuffling to the left, 5 m shuffling to the right, 2.5 m shuffling to the left, 5 m sprinting back to the start line	Intraday	CV = 2.3%	9 (14)
					505 test (10 m): COD of 180° after 5 m, 5 m sprinting back to the start	Intraday	CV = 3.3%	9 (14)
					20-yard test (18.3 m): 4.6-m sprint, COD of 180°, 9.1-m sprint, COD of 180°, 4.6-m sprint	Intraday	CV = 1.8%	9 (14)
Shalfawi et al. (2013b)	20	female	19.4 ± 4.4	Well-trained players from 2nd division (Norway)	Sprint 9–3–6–3–9 m with 180° turns (30 m): 4 CODs of 180° every 3–9 m, 9-m sprint to the finish	Interday	ICC = 0.63	8 (14)
Los Arcos et al. (2017)	42	male	23.2 ± 2.4	Professionals from 2nd and 3rd division (Spain)	Modified T Test (20 m): 5 m linear sprinting, 2.5 m shuffling to the left, 5 m shuffling to the right, 2.5 m shuffling to the left, 5 m sprinting back to the start line	Intraday	ICC = 0.80	9 (14)
					505 test (10 m): COD of 180° after 5 m, 5 m sprinting back to the start	Intraday	ICC = 0.87	9 (14)
					20-yard test (18.3 m): 4.6-m sprint, COD of 180°, 9.1-m sprint, COD of 180°, 4.6-m sprint	Intraday	ICC = 0.72	9 (14)
Pojskic et al. (2018)	20	male	17.0 ± 0.9	Professionals at highest level of competition at their age (Sweden)	Soccer-specific test of change-of-direction speed (5 x 8 m): Sprinting to one of 4 cones, rebounding a ball in front of the	Intraday	ICC = 0.92; CV = 5.9%	8 (14)

					cone, and returning to the start, 5 sprints per trial			
Kutlu et al. (2017)	34	female	20.8 ± 1.9	Amateurs from university soccer team (Turkey)	Change-of-Direction and Acceleration Test (24 m): Linear sprinting (5 m), COD of 45°, linear sprinting (3 m), COD of 90°, linear sprinting (3 m), COD 90°, linear sprinting (3 m), COD of 45°, linear sprinting (10 m)	Interday	ICC = 0.98; CV = 4.0%	9 (14)
					Illinois test (approx. 60 m): Start from a standing position, linear sprinting (10 m), COD of approx. 180°, linear sprinting (10 m), COD of approx. 180°, slalom section (approx. 10 m), COD of 180°, slalom section (approx. 10 m), COD of approx. 180°, linear sprinting (10 m), COD of 180°, linear sprinting (10 m)	Interday	ICC = 0.98; CV = 4.0%	9 (14)
					T Test: No information on test procedures given	Interday	ICC = 0.95; CV = 4.0%	8 (14)
Silva et al. (2011)	18	male	25.7 ± 4.6	Professionals from Portuguese elite championship (Portugal)	T Test (36.6 m): 9.1 m linear sprinting, 4.6 m shuffling to the left, 9.1 m shuffling to the right, 4.6 m shuffling to the left, 9.1 backpedaling	Not specified	ICC = 0.70–0.85	6 (14)
Sporis et al. (2010)	150	male	19.1 ± 0.6	Professionals from 1st junior league (Croatia)	T Test (36.6 m): 9.1 m linear sprinting, 4.6 m shuffling to the left, 9.1 m shuffling to the right, 4.6 m shuffling to the left, 9.1 backpedaling	Intraday	ICC = 0.93; CV = 3.3%	11 (14)
					Slalom Test (approx. 22 m): 6 cones, each cone 2 m apart, 1st cone 1 m from start, slalom	Intraday	ICC = 0.99; CV = 2.9%	11 (14)

sprinting around the cones, COD of 180° and slalom sprinting back to the start			
Sprint 4 x 5 m (20 m): 3 CODs of 90° or 180° every 5 m, 2-m sprint to the finish	Intraday	ICC = 0.98; CV = 4.3%	11 (14)
Sprint with 90° turns (21 m): 6 CODs of 90° every 2–5 m, 5-m sprint to the finish	Intraday	ICC = 0.98; CV = 2.9%	11 (14)
Sprint 9–3–6–3–9 m with 180° turns (30 m): 4 CODs of 180° every 3–9 m, 9-m sprint to the finish	Intraday	ICC = 0.95; CV = 5.1%	11 (14)
Sprint 9–3–6–3–9 m with backward and forward running	Intraday	ICC = 0.95; CV = 5.6%	11 (14)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; COD – change of direction, ICC – Intraclass correlation coefficient; CV – Coefficient of variation; GPS – Global positioning system; EPL – English premier league

Table 4.8 Agility tests (reliability).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Bullock et al. (2012)	18	male	18 ± 3	High-level amateurs from local soccer clubs (not specified)	Reactive Agility Test (approx. 9.4 m): Reacting to a video of a life-size soccer player dribbling the ball towards the player by sprinting in the same direction as the video; test is a part of a complex test	Interday	ICC = 0.70; r = 0.71; CV = 2.3%	8 (14)
Zois et al. (2011)	10	male	23.3 ± 2.5	Amateurs from Serie D (Italy)	Reactive Agility Test (approx. 8 m): Reacting to a tester displaying different movements by sprinting in the same direction as the tester	Interday	CV = 0.8%	8 (14)
Pojskic et al. (2018)	20	male	17.0 ± 0.9	Professionals at highest level of competition at their age (Sweden)	Soccer-specific test of reactive agility (5 x 8 m): Reacting to one of 4 LEDs on a cone by sprinting to and rebounding a ball in front of the cone, and returning to the start, 5 sprints per trial	Intraday	Protocol 1: ICC = 0.70; CV = 3.7% Protocol 2: ICC = 0.88; CV = 4.7% Protocol 3: ICC = 0.87; CV = 4.9%	10 (14)
McGawley & Andersson (2013)	18	Male	23.0 ± 4.0	Semi- and fully-professional from 1st division (Sweden)	Modified T Test (40 m): Linear sprinting (10 m), random COD to the left or the right – example left side – COD of 90° to the left (5 m), COD of 180° (10 m), COD of 180° to the left (5 m), COD of 90° to the left (10 m)	Interday	CV = 0.8%	7 (14)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; * – Selected parameters; %Dec – Percent decrement; FT – Fastest time; AT – Average time; TT – Total time, ICC – Intraclass correlation coefficient, r – Pearson's r; CV – Coefficient of variation

Table 4.9 Combinations (validity).

Study	Population				Short description	Type	Results	MQ
	N	**Gender**	**Age**	**Playing level (Country)**				
Rampinini et al. (2007a)	18	male	26.2 ± 4.5	1st national league (one of the most important European leagues)	Repeated Shuttle-Sprint Test: 6 x 40-m sprints, COD of 180° after 20 m, 20 s passive recovery	Criterion	Test: FT, AT, %Dec Match: sprinting distance, very high-speed running distance AT and sprinting distance: r = -0.65 AT and very high-speed running distance: r = -0.60 No further significant correlations between FT and %Dec, and match parameters*	9 (14)
Di Mascio et al. (2015)	48	male	Elite U18 EPL: 17 ± 1 Elite U18 EFL: 17 ± 1 Sub-elite U18: 17 ± 1	Elite U18 EPL, elite U18 EFL, sub-elite U18 (England)	Soccer-specific reactive repeated-sprint test: 8 x 30-m sprints, 3 random CODs to the left or the right of 45°, 135°, and 180°, 2 curved sprints, 30 s active recovery	Criterion	Test: TT Match: High-speed running (most intense 5-min period, whole match), total distance High-speed running most intense 5-min period: r = -0.55 – -0.74 High-speed running whole match: r = -0.55 – -0.67 Total distance: r = -0.25 – -0.66*	12 (14)
	106	Female, male	Elite U18 EPL: 17 ± 1 Elite U18 EFL: 17 ± 1 sub-elite U19: 18 ± 1 sub-elite U18: 17 ± 1 Elite senior female: 21 ± 3	Elite U18 EPL, Elite U18 EFL, sub-elite U19, sub-elite U18, Elite senior female (England)		Construct	TT: Elite U18 EPL better than sub-elite U19 (4.8%), sub-elite U18 (5.9%), and elite senior female (9.7%) Elite U18 EFL better than sub-elite U19 (3.5%), sub-elite U18 (4.6%), and elite senior female (8.3%)**	7 (10)
Huijgen et al. (2014)	113	male	17.1 ± 0.7	Selected and deselected players of talent development programmes of professional soccer clubs (Netherlands)	Repeated Shuttle Sprint: 3 x 30-m sprints, starting every 20 s, 3 CODs of 180° after 5 m, 10 m, and 20 m	Construct	Selected always better than deselected FT: 1.7%; ES (d) = 0.55 TT: 1.4%; ES (d) = 0.47	7 (10)

					Repeated Shuttle Dribbling: Repeated Shuttle Sprint while dribbling with a ball	Construct	Selected better than deselected FT: 2.4%; ES (d) = 0.66 TT: 2.9%; ES (d) = 0.60	7 (10)
Dellal & Wong (2013)	49	male	Senior, U19 (not specified)	Second team of a professional club, U19 (France)	Repeated change-of-direction test: 10 x 20-m sprints, 4 CODs of 100° every 4 m, 25 s active recovery	Construct	FT: Senior better than U19 (0.6%; ES (d) = 0.72) AT: Senior better than U19 (0.4%; ES (d) = 0.41) TT: Senior better than U19 (0.4%; ES (d) = 0.43) %Dec: U19 better than Senior (23.4%; ES (d) = 0.74)	5 (10)
Rampinini et al. (2009)	23	male	professional: 25 ± 4 amateur: 26 ± 6	Professional from 3rd division, amateur from 6th division (not specified)	Repeated Shuttle-Sprint Test: 6 x 40-m sprints, COD of 180° after 20 m, 20 s passive recovery	Construct	Professional always better than amateur FT: 1.6%; ES (d) = 0.82 AT: 3.2%; ES (d) = 1.72 %Dec: 25%; ES (d) = 0.83	7 (10)
Wong et al. (2012)	34	male	23.3 ± 3.6	Professional, college (not specified)	Repeated Change-of-Direction Test: 6 x 20-m sprints, 4 CODs of 100° every 4 m, 25 s active recovery	Construct	FT: Professional faster than college (1.8%; ES (d) = 0.47) AT: Professional faster than college (1.8%; ES (d) = 0.46) TT: Professional faster than college (1.8%; ES (d) = 0.48) %Dec: College faster than professional (0.8%; ES (d) = 0.02)	5 (10)
Impellizzeri et al. (2008)	108	male	24 ± 4	Top-professional, mid-professional, amateur (not specified)	Repeated-shuttle-sprint ability test: 6 x 40-m sprints, COD of 180° after 20 m, 20 s passive recovery	Construct	FT: Top-professional better than mid-professional (1.1%; ES (d) = 0.44) and amateur (5.7%; ES (d) = 2.03) AT: Top-professional better than mid-professional (0.7%; ES (d) = 0.28) and amateur (2.8%; ES (d) = 0.96) %Dec: Top-professional better than mid-professional (35.3%; ES (d) = 1.08) and amateur (45.9%; ES (d) = 1.60)	8 (10)

Abrantes et al. (2004)	146	male	1st national: 26 ± 3 2nd national: 24 ± 2 1st regional: 29 ± 5	1st national level professional, 2nd national level professional, 1st regional level semi-professional (Portugal)	Bangsbo sprint test: 7 x 34.2-m sprints, 3 CODs of 45° after 10 m, 90° after 17.1 m, and 45° after 24.2 m, 10-m sprint to the finish, 25 s active recovery	Construct	AT: 1st national better than 2nd national (6.1%; ES (d) = 4.37) and 1st regional (15.4%; ES (d) = 15.24)	6 (10)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; * – Selected parameters; ** – Data required to calculate ES not available; %Dec – Percent decrement; FT – Fastest time; AT – Average time; TT – Total time; COD – change of direction; EPL – English premier league; EFL – English football league

Table 4.10 Combinations (reliability).

Study	Population				Short description	Type	Results	MQ
	N	Gender	Age	Playing level (Country)				
Kaplan (2010)	85	male	20.95 ± 3.8	Different amateur clubs (Turkey)	Bangsbo sprint test: 7 x 34.2-m sprints, 3 CODs of 45° after 10 m, 90° after 17.1 m, and 45° after 24.2 m, 10-m sprint to the finish, 25 s active recovery	Not Specified	TT: ICC = 0.94	5 (14)
Wong et al. (2012)	34	male	23.3 ± 3.6	Professional, college (not specified)	Repeated Change-of-Direction Test: 6 x 20-m sprints, 4 CODs of 100° every 4 m, 25 s active recovery	Interday	FT: ICC = 0.79; CV = 9.0% AT: ICC = 0.80; CV = 10.0% TT: ICC = 0.80; CV = 10.0% %Dec: ICC = 0.17; CV = 51.0%	7 (14)
Impellizzeri et al. (2008)	22	male	22 ± 1	Professional (not specified)	Repeated shuttle-sprint test: 6 x 40-m sprints, COD of 180° after 20 m, 20 s passive recovery	Interday	Short-term reliability (2–7 days) FT: ICC = 0.15 AT: ICC = 0.81 %Dec: ICC = 0.17	11 (14)
	30	male	25 ± 5	Professionals from national league (not specified)	see above	Interday	Long-term reliability (3 months) FT: ICC = 0.63, CV = 1.2% AT: ICC = 0.58; CV = 0.9% %Dec: ICC = 0.49; CV = 29.8%	10 (14)
Wragg et al. (2000)	7	male	23 ± 4	National level student players (United Kingdom)	Modified Bangsbo sprint test: 7 x 34.2-m sprints, 3 random CODs to the left or to the right of 45° after 10 m, 90° after 17.1 m, and 45° after 24.2 m, 10-m sprint to the finish, 25 s active recovery	Interday	CV = 1.8%	9 (14)
Di Mascio et al. (2015)	14	male	18 ± 1	Sub-Elite U19 (England)	Soccer-specific reactive repeated-sprint test: 8 x 30-m sprints, 3 random CODs to the left or the right of 45°, 135°, and 180°, 2 curved sprints, 30 s active recovery	Interday	TT: CV = 0.8% FT: CV = 1.1%	9 (14)
Brahim et al. (2016)	27	male	17.6 ± 0.5	National team U19 (Norway)	Bangsbo sprint test: 7 x 34.2-m sprints, 3 CODs of 45° after 10 m, 90° after 17.1 m, and	Interday	TT: ICC = 0.93	6 (14)

					45° after 24.2 m, 10-m sprint to the finish, 25 s active recovery			
					12 x 20-m sprints, 3 CODs in a zig-zag pattern after 4.3 m, 12.5 m, and 15.7 m, 4.3-m sprint to the finish, 40 s active recovery	Interday	TT: ICC = 0.93	6 (14)
					Repeated shuttle-sprint test: 6 x 40-m sprints, COD of 180° after 20 m, 20 s passive recovery	Interday	TT: ICC = 0.89	6 (14)
Ruscello et al. (2013)	17	male	21.9 ± 3.6	Professionals from Italian lega pro (Italy)	Shuttle sprint (2 x 15 m): 7 x 30-m sprints, COD of 180° after 15 m, exercise to rest ratio 1:5, passive recovery	Intraday	TT: ICC = 0.89	6 (14)
					Zig-zag: 7 x 30-m sprints, 5 CODs of 120° every 5 m, exercise to rest ratio 1:5, passive recovery	Intraday	TT: ICC = 0.89	6 (14)

MQ – Methodological quality, maximal possible score in parenthesis; ES – Effect size; %Dec – Percent decrement; FT – Fastest time; AT – Average time; TT – Total time; COD – change of direction

4.4.4 Study Characteristics and Main Findings

Linear-sprint tests

Linear-sprint tests were examined 67 times. The distances investigated ranged from 5 to 200 m. The most frequent studied distances were 10, 20, and 30 m. In terms of construct validity, the test results between the playing levels differed between -1.6 and 5% (ES = -0.33–1.3), whereas positive values indicate that the higher-level players performed better than the lower-level players. Negative values indicate the opposite. Regarding criterion validity, the highest correlation coefficient found between test results and match parameters was r = -0.73.

Intraday reliability ranged from 0.17 to 0.99 (ICC) and from 0.7 to 7.8% (CV), whereas interday reliability ranged from 0.77 to 0.98 (ICC) and from 0.5 to 10.9% (CV).

Study findings in relation to the validity and reliability of linear-sprint tests are illustrated in Tables 4.2–4.3.

Repeated-sprint tests

Repeated-sprint tests were examined 15 times. The investigated tests incorporated 3 to 15 repetitions over distances ranging from 15 to 40 m with active and passive recovery between approximately 15 s and 1 min. The most frequent utilized tests comprised of 6 x 20-m sprints with approximately 20–25 s of active recovery (n = 3) and 7 x 30-m sprints with approximately 20–30 s of active or passive recovery (n = 3).

In terms of construct validity, the test results between the playing levels ranged from 0.3 to 2.7% (ES = 0.14–0.9) for the fastest time, between 0.4 and 2.6% (ES = 0.1–0.88) for the average time, and between 2.3 and 10.3% (ES = 0.83–5.5) for the total time. Results for the percent decrement ranged from -22.9 to 14.5% (ES = -0.4–0.39). Positive values indicate that the higher-level players performed better than the lower-level players. Negative values indicate the opposite. Regarding criterion validity, the highest correlation coefficient found between test results and match parameters was r = -0.51.

Intraday reliability was ICC = 0.75 and CV = 0.8% for the total time. Interday reliability was ICC = 0.88 and CV = 5.0% for the fastest time as well as ICC = 0.90 and CV = 5.0% for the average time. Moreover, ICCs and CVs ranged from 0.91 to 0.99 and from 0.8 to 5.0% for the total time and from 0.11 to 0.14 and from 16.8 to 46.0% for the percent decrement, respectively.

Study findings in relation to the validity and reliability of repeated-sprint tests are illustrated in Tables 4.4–4.5.

Change-of-direction sprint tests

Change-of-direction sprint tests were examined 60 times. The investigated distances ranged from 10 to 60 m including 1 to 9 directional changes of 45° to 270°. The most frequent studied tests were the T Test (n = 10), 505 test (n = 4), and zig-zag tests in various modifications (n = 5).

In terms of construct validity, the test results between the playing levels differed between -5.4 and 12.2% (ES = -1.89–1.64). Positive values indicate that the higher-level players performed better than the lower-level players. Negative values indicate the opposite. Regarding criterion validity, the highest correlation coefficient found between test results and match parameters was r = -0.56.

Intraday reliability ranged from 0.37 to 0.99 (ICC) and from 1.1 to 13.0% (CV), whereas interday reliability ranged from 0.63 to 0.98 (ICC) and from 0.8 to 4.0% (CV).

Study findings in relation to the validity and reliability of change-of-direction sprint tests are illustrated in Tables 4.6–4.7.

Agility tests

Agility tests were examined 4 times. The investigated distances ranged from 8 to 40 m with 1 to 9 directional changes of 45° to 180°. Flashing light, video, and human stimuli were applied to indicate the directional changes. Each test was investigated once.

There were no studies investigating the construct or criterion validity of agility tests. Intraday reliability ranged from 0.70 to 0.88 (ICC) and from 3.7 to 4.9% (CV), whereas interday reliability was 0.70 (ICC) and ranged from 0.8 to 2.3% (CV).

Study findings in relation to the reliability of agility tests are illustrated in Table 4.8.

Combinations

Combinations of the other test categories were examined 21 times. The investigated tests ranged from 3 to 10 repetitions over distances from 20 to 40 m with 1 to 5 directional changes of 45° to 180°. Both active and passive recovery ranging from approximately 15 to 40 s were utilized. Light stimuli were applied in all tests. The most frequent studied tests were the Bangsbo sprint test and the repeated shuttle-sprint test.

In terms of construct validity, the test results between the playing levels differed between 0.6 and 2.4% (ES = 0.44–0.82) for the fastest time, between 0.4 and 15.4% (ES = 0.28–15.24) for the average time, and between 0.4 and 9.7% (ES = 0.16–0.60) for the total time. Results for the percent decrement ranged from -23.4 to 45.9% (ES = -0.74–1.60). Positive values indicate that the higher-level players performed better than the lower-level players. Negative values indicate the opposite. Regarding criterion validity, the highest correlation coefficient found between test results and match parameters was r = -0.74.

Intraday reliability was ICC = 0.89 for the fastest time. Interday reliability ranged from 0.15 to 0.79 (ICC) and from 1.1 to 9.0% (CV) for the fastest time as well as from 0.58 to 0.81 (ICC) and from 0.9 to 10.0% (CV) for the average time. Moreover, ICCs and CVs ranged from 0.89 to 0.94 and from 0.8 to 10.0% for the total time, and from 0.17 to 0.49 and from 29.8 to 51.0% for the percent decrement, respectively.

Study findings in relation to the validity and reliability of combinations are illustrated in Tables 4.9–4.10.

4.5 Discussion

4.5.1 Overview

This review examined the validity and reliability of different speed tests used in soccer, categorized into linear-sprint tests, repeated-sprint tests, change-of-direction sprint tests, agility tests, and combinations of these tests. In general, the high number of total studies and single tests included in this review highlights the importance of speed and speed testing in soccer. The majority of studies examined male players, which corresponds to the gender distribution of soccer players (FIFA, 2015). The tests were applied in a variety of performance levels, thereby allowing for both general and playing-level specific considerations.

Several different tests were identified in each category, while no accepted gold-standard tests seem to exist. The most studied tests were classified as linear-sprint tests and change-of-direction sprint tests, followed by combinations and repeated-sprint tests. Agility tests were the least studied. The amounts of tests in each category might be explained by differences relating to the complexity of the measurement set-up, test execution, and data analysis. For example, a 30-m linear sprint is relatively easy to conduct, while agility tests require the application of a stimulus which must be achieved through specific timing equipment incorporating flashing lights, life-size video clips or experienced humans (Paul et al., 2016; Turner et al., 2011).

Regardless of the test category, construct validity was investigated more frequently than criterion validity. This may be due to the additional match data needed for the same players in the latter case. Conversely, intraday and interday reliability were studied equally, although these approaches differ markedly in their organizational effort. However, in order to get a more holistic insight into the measurement properties of the tests, both types of validity and reliability should be assessed.

In the following paragraphs, the tests in each of the categories are discussed in relation to their validity and reliability. Based on this, recommendations for test selection in each category are given.

4.5.2 Study Characteristics and Main Findings

Linear-sprint tests

In terms of construct validity, the majority of studies report faster sprint times in favor of the higher-level players compared to the lower-level players. Such results have been found for both the comparison within professional players, e.g., national team vs. 1st division players (trivial to small ES) (Cotte & Chatard, 2011; Haugen et al., 2012b), and the comparison between professional and amateur players (trivial to large ES) (Cometti et al., 2001; Ferro et al., 2014; Haugen et al., 2013a; Rebelo et al., 2013). In addition, drafted players in try outs of a professional women's soccer league demonstrated faster sprint times than non-drafted players (small to moderate ES) (Vescovi, 2012). In line with this, starters outperformed non-starters of the same team (trivial to moderate ES), with a tendency to larger ES over longer distances (Risso et al., 2017; Silvestre et al., 2006a; Silvestre et al., 2006b).

However, tendencies for larger performance differences with increasing sprinting distance were not evident when all abovementioned studies were taken into consideration. Therefore, it might be concluded that all distances investigated (from 5 to 40 m) seem to be equally important in soccer, even though short sprints and accelerations (e.g., 10 m) occur more frequently than longer sprints (e.g., 40 m) during matches (Di Salvo et al., 2010; Haugen et al., 2014a; Varley & Aughey, 2013).

Some investigations reported faster sprint times for the players assigned to the lower playing level compared to those of the higher playing levels (Djaoui et al., 2017; Kobal et al., 2016; Mujika et al., 2009b). Besides the only trivial to small ES, in two studies, this finding was only obtained for a 10-m distance (Kobal et al., 2016) and for males (Mujika et al., 2009b) with contrary results being obtained for a 20-m distance and females, respectively. Furthermore, in the third study (Djaoui et al., 2017), the lower-level players consisted of young elite amateur players who were training every day. Thus, both groups of players were considered "high-level" players by the authors of that study.

In terms of criterion validity, only two studies were identified. Djaoui et al. (2017) found a large relationship between the results of a 40-m sprint test and the maximal sprinting speed during matches. In addition, moderate to large relationships were reported for 5-m and 30-m sprints on the one side and high-intensity and sprinting distances during several periods of matches on the other side (Silva et al., 2013b).

Considering both intraday and interday reliability, 40 studies report ICCs > 0.75 and CVs < 3.0% (e.g., Kobal et al., 2016; Los Arcos et al., 2017; Loturco et al., 2015; Rebelo et al., 2013; Silva et al., 2013b). The studies obtaining lower reliability (ICC ≥ 0.55 and CV ≤ 10.9%) integrated linear-sprint testing into complex tests (Bullock et al., 2012) or match-simulation protocols (Small et al., 2009; Williams et al., 2010) or required the players to adopt a defined running velocity at the start line (Sonderegger et al., 2016). In addition, it seems that the reliability decreases when considering longer terms, such as 6–12 months between measurements, with Pearson’s r and CV being 0.77–0.90 and 1.8–3.3%, respectively (Haugen et al., 2012b).

While more consistent reliability indices were obtained whilst utilizing established timing technologies such as timing lights and radar guns, varying results have been obtained for global positioning systems (ICC = 0.17–0.86; CV = 2.1–7.8%) (Meylan et al., 2017; Yanci et al., 2017). Although not consistent over all studies, both intraday and interday reliability have been reported to be higher with increasing sprinting distance (Comfort et al., 2014; Cotte & Chatard, 2011; Los Arcos et al., 2017; Mirkov et al., 2008; Thomas et al., 2009; Yanci et al., 2014).

Given the results of the abovementioned studies, linear-sprint tests over distances up to 40 m possess acceptable construct validity and high intraday and interday reliability to assess linear-sprinting skills in soccer players.

Repeated-sprint tests

The identified repeated-sprint tests differ in their number of repetitions (3 to 15), the distance per repetition (15 to 40 m), and the type (active and passive) and duration (approximately 15 s to 1 min) of recovery per repetition. Common parameters derived from such tests include the fastest time, average time, total time, and percent decrement. The initial sprint time was reported less frequently.

The construct validity of repeated-sprint tests has been investigated in few studies (n = 5). In the majority of the studies, the higher-level players outperformed the lower-level players for all abovementioned parameters when comparing professional vs. semi-professional, college, university or regional level players; however, with considerably varying ES (trivial to very large) (Aziz et al., 2008; Dellal & Wong, 2013; Gabbett, 2010; Wong et al., 2012). Only one study (Ingebrigtsen et al., 2012) found the lower-level players outperforming the higher-level players. However, this was true for percent decrement only. This result might be related to the low reliability of this parameter, which will be discussed later. Except for percent decrement, no parameter was superior to another in its ability to distinguish between playing levels. Interestingly, the largest ES between higher- and lower-level players were reported in a study with females (Gabbett, 2010). This finding mirrors the observation that repeated-sprint bouts occur more frequent during matches of professional females in comparison with those of professional males (Gabbett, 2010; Schimpchen et al., 2016; Taylor et al., 2016).

Only one study examined the criterion validity of a repeated-sprint test (6 x 6-s sprints, 20 s passive recovery) in professional male players. A large correlation was found between percent decrement in the test and the frequency of high-intensity actions interspersed by recovery times ≤ 20 s during matches. In addition, a moderate correlation was reported between average velocity in the test and recovery time between high-intensity actions during matches (Carling et al., 2012). Given the lack of further notable relationships between the test parameters and the frequency of repeated high-intensity bouts during matches, the authors question the criterion validity of this and similar tests. Indeed, more investigations using a similar study design are needed to confidentially draw conclusions with respect to criterion validity.

As a repeated-sprint test elicits considerable degrees of fatigue, multiple testing on one occasion (intraday reliability) appears to be rather inappropriate. Therefore, most of the studies reported interday reliability values (n = 6). Intraday reliability was examined less often (n = 2) and one study did not state the reliability type. ICCs for the average and total time exceeded 0.75 in all studies and were mostly higher than 0.90 while CVs were lower than 3.0% in 7 out of 9 studies (Chaouachi et al., 2010; Gabbett, 2010; Haugen et al., 2014b; Iaia et al., 2015; López-Segovia et al., 2014; McGawley & Andersson, 2013; Shalfawi et al., 2013b; Wong et al., 2012). The reliability of the fastest time was 0.88 and 5.0% for ICC and CV, respectively (Wong et al., 2012). Conversely, the percent decrement as a measure of fatigue was markedly less reliable (ICC ≥ 0.11, CV ≤ 46.0%) (Gabbett, 2010; Iaia et al., 2015). Pacing strategies of the players throughout the sprints was stated as a possible reason (Dawson, 2012).

No differences between different recovery durations and modes were obvious regarding validity and reliability. However, the recovery duration should be short enough (e.g., < 30 s) to provoke the occurrence of fatigue (Girard et al., 2011). Additionally, the recovery mode should be active in order to replicate the match demands (Carling et al., 2012).

The use of repeated-sprint tests has been criticized by some authors (Haugen et al., 2014a; Haugen & Seiler, 2015). Their criticism is based on the very large correlations between the fastest time, average time and total time of such tests on the one side and results of single linear-sprint tests on the other side. Additionally, the low reliability of fatigue measures such as the percent decrement questions the additional benefits derived from repeated-sprint tests compared to linear-sprint tests. Nevertheless, based on the studies included in this review, repeated-sprint tests differing in the number of repetitions, the distance per repetition, and the recovery phases possess acceptable levels of construct validity and high levels of reliability for examining repeated-sprinting skills in adult soccer players regarding all parameters, except for percent decrement.

Change-of-direction sprint tests

A plethora of change-of-direction sprint tests has been developed and introduced into soccer. Some of these tests carry the word "agility" in their name (e.g., “Illinois agility run”, “Agility T Test”) but do not contain a response to a stimulus. Therefore, they were classified as change-of-direction sprint tests in this review. Change-of-direction sprint tests vary in their total distance (10–60 m) as well as number (1–9) and angles (45–270°) of directional changes. A frequently applied type of test involves shuttle sprints, where players sprint to a line, change the direction by 180°, and sprint back. Furthermore, test set-ups using zig-zag or slalom patterns are common. In addition, some popular tests were originally developed for sports other than soccer, such as the 505 test, Illinois test, and T Test.

The construct validity of change-of-direction sprint tests has been evaluated in a number of investigations (n = 14). As with linear-sprint tests and repeated-sprint tests, the higher-level players obtained faster times than the lower-level players in the vast majority of studies (n = 13). This applied to the comparison of starters vs. non-starters in a professional team (trivial to small ES) (Risso et al., 2017), professional vs. amateur players (small to large ES) (Kutlu et al., 2012), 1st division vs. regional division players (moderate ES) (Rebelo et al., 2013), seniors vs. juniors of the same professional club (large ES) (Mujika et al., 2009b) and selected vs. deselected players in talent a program (small ES) (Huijgen et al., 2014). Similar results were obtained when players were required to dribble a ball, commonly in a slalom or zig-zag manner (trivial to large ES) (Huijgen et al., 2014; Kutlu et al., 2012; Mujika et al., 2009b; Rebelo et al., 2013; Russell et al., 2010).

In contrast, the study of Keiner et al. (2014) showed superior performance of U21-players of a professional soccer club compared to professional adult players. However, this was particularly evident for a group of U21-players who had performed a specific strength training program for the two proceeding years. In contrast, no detailed information was provided relating to the training contents of the professional adult players.

Only one study addressing the criterion validity of change-of-direction sprint tests met the inclusion criteria (Silva et al., 2013b). This study investigated the relationships between the results of the T Test and match parameters. Compared to 5-m and 30-m sprints, as depicted above, markedly lower relationships were evident. This finding particularly applied for the correlation between the T Test and sprinting distances during several periods of the match (Silva et al., 2013b). Therefore, it might be concluded that a high change-of-direction performance translates into sprinting behavior during matches only to a limited extent. Possibly, other match parameters that reflect change-of-direction behavior more directly might represent a more suitable alternative.

A considerable number of studies (n = 27, encompassing 45 tests) reported intraday or interday reliability of various change-of-direction sprint tests with ICCs usually exceeding 0.75 and CVs lower than 3.0% (e.g., Bendiksen et al., 2013; Gelen, 2010; Miller et al., 2011; Rebelo et al., 2013; Rouissi et al., 2017; Silva et al., 2013b). Similar reliability was demonstrated in the four studies that included ball dribbling into the test (Currell et al., 2009; Mirkov et al., 2008; Rebelo et al., 2013; Russell et al., 2010).

Conversely, some studies report high relative reliability (ICCs 0.92–0.99) and somewhat lower absolute reliability (CVs 2.9–5.9%) (Pojskic et al., 2018; Sporis et al., 2010). Lower reliability was reported for shuttle sprints over 18.2 m (ICC = 0.72) (Los Arcos et al., 2017) and 30 m (ICC = 0.63) (Shalfawi et al., 2013a).

As with linear-sprint testing, a change-of-direction sprint test using a global positioning system was reported less reliable (ICCs 0.37–0.77; CVs 3.7–13.0%) (Meylan et al., 2017), supporting the utilization of appropriate timing technologies during speed testing (Haugen & Buchheit, 2016).

The high number of change-of-direction sprint tests and the large differences in test design highlight the lack of an accepted gold standard (Chaouachi et al., 2012). However, some popular tests have been evaluated in several studies, such as the 505 test or the T Test. Several modifications of these tests have been applied. For example, the linear-sprint phase prior to the directional change of 180° in the 505 test varies between 5 m and 15 m in the literature (Emmonds et al., 2017; Los Arcos et al., 2017; Thomas et al., 2009; Yanci et al., 2014). Regarding the T Test, as many as six different types of this test have been used, differing in the total distance (20–40 m), the type of locomotion (shuffling, backpedaling, and sprinting), and the inclusion or exclusion of ball dribbling (Kutlu et al., 2012; Kutlu et al., 2017; Los Arcos et al., 2017; Miller et al., 2011; Rebelo et al., 2013; Rey et al., 2017; Silva et al., 2011; Silva et al., 2013b; Sporis et al., 2010; Yanci et al., 2014). One study even added a visual stimulus prior to changing direction, leading this modification to be classified as an agility test (McGawley & Andersson, 2013). Despite these modifications, all types of the 505 test and the T Test have been shown to be valid (T Test: ES = 0.62–1.50 in favor of the higher-level players) and/or reliable (505 test: ICC = 0.87–0.99, CV = 2.2–3.3%; T Test: ICC = 0.70–0.95, CV = 0.8–4.0%).

While many tests, including the 505 test and the T Test, do not mimic the match demands (Haugen et al., 2014a), the confirmed validity and reliability of these two tests for assessing change-of-direction sprinting skills through a number of studies allow their application until more game-specific tests are thoroughly evaluated.

Agility tests

Since the introduction of a classic agility test for invasion sports by Sheppard et al. (2006), this test has been evaluated and modified for the specific demands of different sports, such as Australian football, basketball, netball or rugby (Nimphius et al., 2018; Paul et al., 2016).

With respect to the inclusion criteria of this review, no study was identified that evaluated the validity of an agility test in soccer players. This is somewhat surprising as agility tests have been shown to possess high levels of construct validity by discriminating between playing levels in Australian football and rugby league, while change-of-direction sprint tests did not (Young et al., 2015). This finding is mainly attributed to the superior anticipation and decision-making skills of higher-level players (Paul et al., 2016). It should be noted that studies examining the construct validity of such tests in soccer exist. However, either the (sub-)sample investigated for this specific outcome was too young to be considered for this review (Pojskic et al., 2018) or the population also included sports other than soccer (e.g., futsal) (Benvenuti et al., 2010). Although more complex than capturing the number of sprints or maximum speed during matches, methods for analyzing decision-making during training and matches have already been applied to soccer and might serve as a foundation for evaluating the criterion validity of agility tests (Gabbett et al., 2008a; González-Víllora et al., 2015).

Conversely, the reliability of agility tests has been addressed in four studies, all of them relating to interday reliability (Bullock et al., 2012; McGawley & Andersson, 2013; Pojskic et al., 2018; Zois et al., 2011). Two of the tests used flashing lights as a stimulus (ICCs 0.70–0.87; CVs 0.8–4.9%) (McGawley & Andersson, 2013; Pojskic et al., 2018). One study (Zois et al., 2011) adopted the classic agility test by Sheppard et al. (2006), which requires the players to respond to different movements of a tester (human stimulus) by sprinting in the same direction as the tester (CV = 0.8%). The last study examined agility as a part of a complex test (Bullock et al., 2012). Here, players respond to a video of a life-size soccer player dribbling the ball towards the player by sprinting in the same direction as the video (ICC = 0.70; CV = 2.3%). The slightly lower reliability of agility tests compared to the other test categories might be attributed to the complexity of such tests, incorporating both physical and perceptual-cognitive aspects of speed. While several parameters can potentially be investigated during agility tests, such as the response time at the start, the decision-making time or the response accuracy (Paul et al., 2016), the abovementioned studies were limited to the total time to complete the test.

In terms of the applied stimuli, it has been shown in other sports (e.g., Australian rules football, field hockey) that humans or video sequences appear to be more appropriate than flashing lights when examining construct validity (Paul et al., 2016). This seems reasonable as the latter does not allow higher-level players to utilize their anticipation and decision-making skills, but simply to react to a non-specific signal (Young & Farrow, 2013). Given the small total number of investigations and the lack of studies using humans or video sequences as a stimulus, it can be concluded that the soccer-specific agility research is still in its infancy.

Combinations

This test category combines elements of two or more of the abovementioned test categories. Most of the studies examined pre-planned repeated change-of-direction sprint tests with or without ball dribbling (10 studies encompassing 12 tests), while two studies analyzed repeated change-of-direction sprint tests in response to a stimulus. Thereby, such tests comprise elements of repeated-sprint tests and change-of-direction sprint tests, and sometimes even those of agility tests. Similar to repeated-sprint tests, the fastest time, average time, total time, and percent decrement are commonly investigated during such tests. The most utilized tests were the (modified) Bangsbo sprint test (Abrantes et al., 2004; Brahim et al., 2016; Kaplan, 2010; Wragg et al., 2000) and the repeated shuttle-sprint test (Brahim et al., 2016; Impellizzeri et al., 2008; Rampinini et al., 2007a; Rampinini et al., 2009).

The construct validity of combination tests was supported in the vast majority of studies for most of the parameters in question. Specifically, the higher-level players performed better than their lower-level counterparts when comparing professional vs. semi-professional players (small to very large ES) (Abrantes et al., 2004; Impellizzeri et al., 2008), professional vs. amateur players (trivial to very large ES) (Impellizzeri et al., 2008; Rampinini et al., 2009; Wong et al., 2012), 2nd team vs. U19 players of a professional club (small to moderate ES) (Dellal & Wong, 2013) or selected vs. deselected players of a talent development program (small to moderate ES) (Huijgen et al., 2014). Similarly to the results of the repeated-sprint tests, the percent decrement was not always able to discriminate between playing levels, with the lower-level players obtaining better scores in some studies (trivial to moderate ES) (Dellal & Wong, 2013; Wong et al., 2012). All other parameters were able to distinguish between playing levels.

The criterion validity of combination tests has been evaluated in two studies (Di Mascio et al., 2015; Rampinini et al., 2007a). In the study of Rampinini et al. (2007a), the average time of a repeated shuttle-sprint test was largely correlated to the sprinting distance and very high-intensity running distance during professional matches. However, no notable relationships were evident between the fastest time or percent decrement and match variables. The second study analyzed a reactive repeated-sprint test involving changes of direction in response to a light stimulus (Di Mascio et al., 2015). The authors found large to very large correlations between the total time of the test and match parameters related to high-speed running. Small to large associations were reported for the total distance covered during matches (Di Mascio et al., 2015).

In terms of reliability, the interday reliability of combination tests was addressed in a number of studies (5 studies encompassing 7 tests), while the intraday reliability was examined less frequent (1 study encompassing 2 tests). Varying results were obtained for different parameters. ICCs and CVs for the average time and total time were > 0.75 and < 2.0%, respectively, in most studies (Brahim et al., 2016; Di Mascio et al., 2015; Impellizzeri et al., 2008; Kaplan, 2010; Ruscello et al., 2013; Wragg et al., 2000). However, high CVs of 10.0% have also been found for these parameters (Wong et al., 2012). Moreover, one study reported low relative reliability for the fastest time (ICC = 0.15) (Impellizzeri et al., 2008), while high absolute reliability (CV = 1.1%) was evident for the same parameter in another study (Di Mascio et al., 2015). More consistently, percent decrement was found to not be reliable (ICC = 0.17, CV = 51.0%) (Impellizzeri et al., 2008; Wong et al., 2012). In addition, the relative reliability in long-term (3 months between occasions) seems to be somewhat lower compared to short-terms (ICC for average time 0.58), while the absolute reliability remains high (CV for average time 0.9%) (Impellizzeri et al., 2008).

In sum, the total and average time possess the highest degree of validity and reliability. Specifically, this was confirmed for the Bangsbo sprint test and the repeated shuttle-sprint test in a number of studies. Moreover, it should be noted that although evaluated in a single study only, the validity and reliability were confirmed for the reactive repeated-sprint test, which has been designed on the basis of match analysis.

4.5.3 Limitations

The findings of this systematic review should be interpreted in light of its limitations. We did not conduct an updated search that included studies published after May 2018. In addition, only studies examining soccer players with an average age of 17 years or above were considered. This automatically excludes investigations in younger age groups (Paul & Nassis, 2015a), which could have broadened the database. However, the number of included articles (n = 90) was already high in this review and results from other sports, although related, or differing age groups may not always be transferable (Pyne et al., 2014).

We excluded investigations applying manual timing due to large absolute errors and issues relating to inter-rater reliability with this timing technology (Haugen & Buchheit, 2016). While this approach further reduces the available database, it ensures that an appropriate timing technology has been used in the studies, thereby accounting for adequate methodological quality in this regard.

The methodological quality of the construct and criterion validity studies was rated as high, while the scores of the intraday and interday reliability studies were somewhat lower. The latter finding might be explained by the inclusion criteria, as there was no restriction on the type of studies. Therefore, studies in which the reliability assessment was not the main aim were also included. While being well-designed for their primary aim (e.g., the evaluation of a training intervention), the necessary information for the reliability assessment were not always given.

In addition, the assessment of methodological quality itself should be viewed critically. Unfortunately, no assessment tool was applicable without modifications for the purpose of this review. In this context, another frequently used tool for the evaluation of measurement properties, the COSMIN checklist (Terwee et al., 2011), seems more appropriate in relation to questionnaire-based studies (Chiwaridzo et al., 2017) than for performance testing. Therefore, we made use of the critical appraisal tool by Brink & Louw (2012) including some modifications, which promised a more suitable assessment of methodological quality of performance testing.

Another limitation might be position-specificity. We reported study results for all players of a team as a whole, thereby not accounting for position-specific demands which could lead to differing validity and reliability of speed tests and, therefore, specific test recommendations for each position (Mirkov et al., 2008; Slimani & Nikolaidis, 2017).

4.5.4 Further Considerations and Future Research

Although a test may have shown to be valid and reliable, it does not automatically guarantee that the derived results provide new and useful information to the coach and the individual players (Mendez-Villanueva & Buchheit, 2013). While this issue seems still to be discussed (Simperingham et al., 2016), methodological barriers to data collection and analysis are overcome by modern technologies. As a result, researchers can better identify crucial factors of (speed) performance in soccer and consequently to develop tests with direct impact on coaches and players (Mendez-Villanueva & Buchheit, 2013). One solution might be the implementation of test designs based on detailed analysis of match demands. In fact, few studies clearly stated such an approach (e.g., Di Mascio et al., 2015; Gabbett, 2010). However, this seems promising for future studies. Based on this, more studies are needed examining the relationship between test results and match parameters (criterion validity) throughout all test categories.

Besides intraday and interday reliability, it is of further interest to know if small performance changes can be identified using a specific test (Darrall-Jones et al., 2016a; Hopkins, 2004). In particular, this becomes a matter at a professional level, where performance gains are usually small (Haugen, 2017). This test property, commonly referred to as usefulness, is determined through the ratio of the intra-individual variability and the so-called smallest worthwhile change (SWC) (Hopkins, 2004). While the intra-individual variability is usually expressed as a CV, the SWC can either be calculated as 0.2 x standard deviation of a given population, representing a small effect, or a pre-defined threshold. Given the example of a 20-m linear-sprint test, Haugen et al. (2014a) stated that the SWC relates to approximately 0.02 s when expressed as a small effect. Considering a real-world scenario, a gap of 0.3 m to 0.5 m might be decisive in a sprint duel of two players. In this case, the SWC as a pre-defined threshold corresponds to 0.04–0.06 s over a 20-m distance. These approaches might not only be applied to linear-sprint testing, but also to the other test categories. However, being reported scarcely in the identified studies, the usefulness was not included in this review. Indeed, it has been highlighted that this test property is population-specific to great extends and, therefore, should be determined for each investigation or team separately (Darrall-Jones et al., 2016a).

Although demonstrating good validity and reliability, the value of repeated-sprint tests has been questioned, as mentioned above. As repeated accelerations have been found to occur much more frequently during matches (Varley & Aughey, 2013), the concept of repeated-acceleration bouts has recently been introduced (Barberó-Álvarez et al., 2013; Taylor et al., 2016). Therefore, the development and evaluation of repeated-acceleration tests should be subject of further investigations.

Lastly, agility tests are underrepresented compared to the other test categories. Based on the promising results from related sports evaluating such tests (Paul et al., 2016) and the increasing overall game speed (Wallace & Norton, 2014), requiring the players to make fast decisions and perform an adequate motor response, more research with respect to agility tests is recommended. Particularly, tests using scenarios close to the game and specific stimuli seem appropriate.

4.5 Conclusion

Speed is considered a crucial factor for overall performance in soccer. As most of the test categories evaluated in this review share a relatively low common variance, they represent rather independent skills. Therefore, no single test is appropriate to measure all aspects of speed concurrently, thus, a comprehensive examination of speed should cover all test categories.

Linear-sprint tests over various distances (5 to 40 m) can be used to determine acceleration and maximal speed. Thereby, such tests have been shown to be able to distinguish between playing levels, to correlate with sprint-related parameters during matches, and to possess high levels of reliability. Although criticized for not replicating the match demands, repeated-sprint tests of different number of repetitions, distances per repetition as well as types and durations of recovery have been reported to be valid in terms of discriminating playing levels and to be highly reliable. However, this specifically applies to the total time and the average time of such tests, while the use of percent decrement should be treated with caution. A high number of studies identified addressed change-of-direction sprint tests. Such tests vary dramatically in their total distance, number and angles of directional changes, and often do not mimic the match demands. Nevertheless, a number of tests, including the 505 test and T Test, possess high construct validity and reliability, thereby supporting their utilization in soccer. Conversely, agility tests have been investigated scarcely. While no information on the validity of agility tests is currently available, acceptable but slightly lower reliability compared to the other categories has been reported for tests applying flashing lights, video sequences, and humans as a stimulus. Combinations include elements of two or more test categories, commonly those of repeated-sprint and change-of-direction sprint tests and sometimes even agility tests. The total and average time possess the highest degree of validity and reliability, most frequently reported for the Bangsbo sprint test and the repeated shuttle-sprint test.

As currently stated, there is a lack of an accepted gold standard test in most of the categories. Researchers and practitioners might base their test selection on the comprehensive validity and reliability database provided in this review.

5 Starting Distances (Paper II)

Published version of the original research article

Altmann, S., Hoffmann, M., Kurz, G., Neumann, R., Woll, A., & Haertel, S. (2015). Different starting distances affect 5-m sprint times. *The Journal of Strength & Conditioning Research, 29*(8), 2361–2366.

5.1 Abstract

The purpose of this study was to quantify the effect of different starting distances on 5-m sprint time and the accuracy of the initial timing lights. A single-beam timing light system (1 m high) was used to measure 5-m sprint time in 13 male sports students. Each subject performed three valid trials for three starting distances: 0.3, 0.5, and 1.0 m from the initial timing lights, respectively. A high-speed video camera was used to track a reflective marker placed on the subjects' hip within a field of view around the initial timing lights. Accuracy of the initial timing lights was defined as the time between the initial timing light trigger and passing of the reflective marker by the initial timing lights. Sprint times were significantly faster for the 1.0-m starting distance (0.98 ± 0.06 s) than for the 0.5-m (1.05 ± 0.07 s) and the 0.3-m (1.09 ± 0.08 s) starting distances ($p < .001$). There were no differences in initial timing lights error between starting distances ($p = .078$). Hence, starting distance influenced sprint times but not the accuracy of the initial timing lights. Researchers and coaches should consider the effect of starting distance on 5-m sprint time and ensure consistent testing protocols. Based on the results of this study, we recommend a starting distance of 0.3 m that should be used for all sprint performance tests.

Keywords: sprint performance, single-beam timing lights, starting distance, accuracy, video analysis, precision

5.2 Introduction

Sprinting is an important athletic skill in many field and court sports such as soccer, field hockey or tennis. Although representing only a small percentage of total game time, the ability to accelerate can contribute to winning or losing (Faude et al., 2012; Little & Williams, 2005). Consequently, testing sprint performance has become a standard component of performance diagnostics in many professional soccer clubs (Gonzalez-Balzar, 2007).

Several factors have been identified to influence sprint performance including starting stance and first-step strategy (Cronin et al., 2007; Frost et al., 2008; Frost & Cronin, 2011; Haugen et al., 2012a; Johnson et al., 2010; Kraan, van Veen, Snijders, & Storm, 2001), running surface (Faude, Meyer, Buchmann, & Kindermann, 2007.) or the type of timing-light system (Cronin & Templeton, 2008; Earp & Newton, 2012). While timing lights are more accurate and reliable for measuring sprint times than manual systems such as stop watches (Ebben et al., 2009; Hetzler et al., 2008; Houser et al., 2010; Mayhew et al., 2010), timing lights are not free of timing lights errors. Timing lights may consist of single, double or triple light beams. The most important error of a single-beam timing light is caused by premature triggering of the system by a swinging arm or leg. This error affects both the validity and the reliability of the measurement. To avoid this problem, more expensive double and triple beam systems and systems employing signal processing algorithms have been developed (Earp & Newton, 2012). Further, contact mats are used which are activated when the athlete‘s foot leaves the mat (Duthie et al., 2006). But even when using such systems differences in measurement set-up can influence results and single-beam timing lights are still frequently used for sprint performance testing.

Sprint time measurements not only depend on factors related to the accuracy of the measurement system but also on the testing procedure. For instance, different starting distances ranging from 0.3 to 1.0 m from the placement of the initial timing lights are used in sprint performance testing (Chaouachi et al., 2010; Meckel et al., 2009; Meyer et al., 2000). However, depending on the specific starting distance, athletes start to accelerate before reaching the initial timing lights and hence are sprinting at greater speeds within the 5-m timing distance. This may result in faster 5-m sprint times. Moreover, starting before the initial timing lights might change the body’s configuration when reaching the timing lights and thus affect the error caused by premature triggering of the timing lights by swinging arms or legs.

To date, the effect of starting distance on 5-m sprint times and initial timing lights error has not been investigated. Hence, the purpose of this study was to investigate this effect. We hypothesized that greater distances between the starting position and single-beam timing light placement would reduce 5-m sprint times and the initial timing lights errors due to a higher acceleration compared to smaller starting distances.

5.3 Methods

5.3.1 Experimental Approach to the Problem

In this cross-sectional experimental laboratory study, experienced athletes performed acceleration sprint trials from three starting positions: 0.3, 0.5, and 1.0 m from the initial timing lights. These distances cover the range of starting distances commonly used in sprint performance testing (Chaouachi et al., 2010; Meckel et al., 2009; Meyer et al., 2000). 5-m sprint times were measured using two sets of single-beam timing lights. We used a high-speed video camera to simultaneously capture the initial timing light beam and a reflective marker on the subjects' hip. The accuracy of the initial timing lights was defined as the time difference between the initial timing lights trigger and the reflective marker passing the timing lights.

5.3.2 Subjects

Thirteen male sports students (age, 25.6 ± 1.8 years; age range, 22-29 years; height, 181 ± 7 cm; mass, 79.4 ± 7.3 kg) participated in this study. All subjects had a team-sport background and were injury-free at the time of the investigation. The study was exempt from full ethics review by the institutional review board and conducted in accordance with the Declaration of Helsinki (World Medical Association (WMA), 2013). All subjects gave written informed consent prior to participation.

5.3.3 Procedures

All tests were conducted indoors on a PVC running surface. Two pairs of wireless single-beam timing lights (TAG Heuer, La-Chaux-de-Fonds, Switzerland) were placed 5 m apart. The gates were adjusted to a height of 1 m approximately matching the subjects' hip height. A high-speed camera (Weinberger Deutschland GmbH, Erlangen, Germany; 100 frames per second) was positioned behind the initial timing lights aligned with the timing light beam. Hence, the subject and the timing light beam were within the camera's field of view (Figure 5.1). A reflective marker was placed on the subjects' left hip representing the body close to the height of the center of mass.

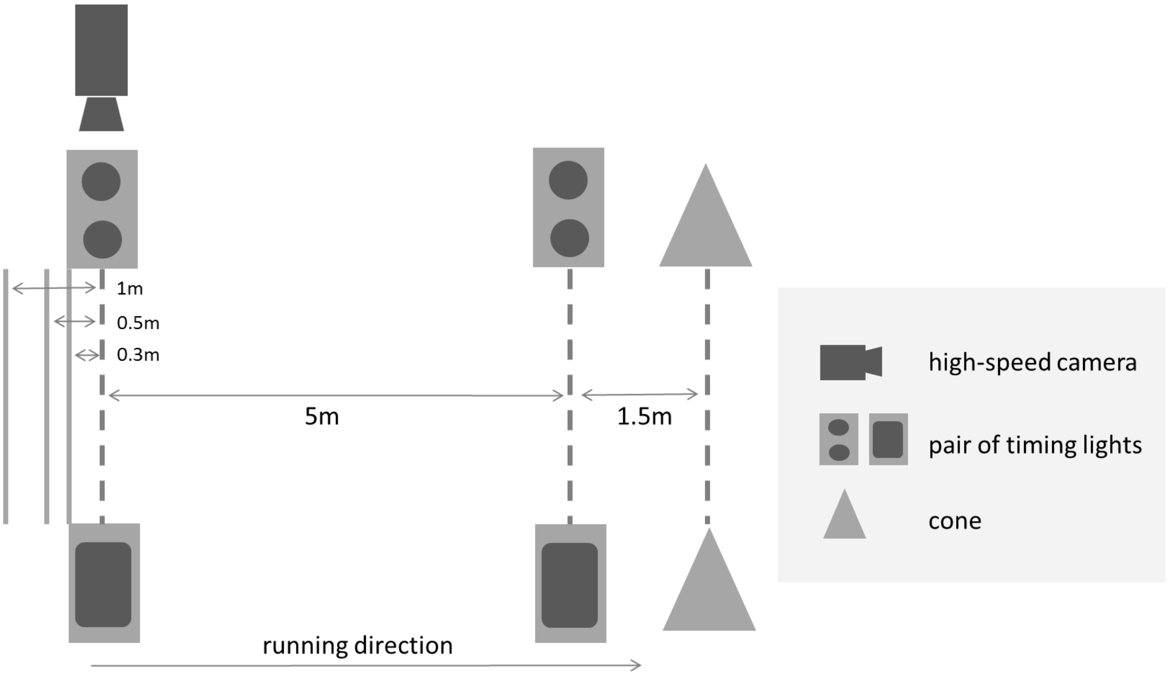


Figure 5.1 Measurement set-up.

Subjects completed a 10-minute warm-up including light jogging, short accelerations, and dynamic stretching exercises before performing a familiarization trial. Subsequently, subjects performed three valid trials for each starting distance (0.3, 0.5, 1.0 m). The order of starting distances was randomized to avoid any possible effects of fatigue. The rest period between sprints of the same starting distance was 90 s and between different starting distances 3 min. Subjects were asked to sprint past a cone placed 1.5 m behind the second timing lights to avoid a finishing dip or an early deceleration. Subjects were instructed to perform a split start (Figure 5.2) and allowed to choose the leading foot but had to use the same starting position for all trials. A starting signal was not given. Rocking or leaning back prior to sprinting was not allowed.

Timing began when the initial timing lights were triggered. All subjects wore the same model of an athletic running shoe (Puma Cell). The video sequences were processed using Vicon Motus Version 9.2 (Vicon Peak, Los Angeles, CA). The accuracy of the initial timing lights (time [s]) was defined as the number of frames between the frame when the timing light beam first appeared in the video image (Figure 5.3) and the frame when the reflective marker passed the timing lights line divided by 100 and could be interpreted as timing lights error. Corrected 5-m time was calculated by subtracting timing lights error from 5-m time gained by the timing lights.

Figure 5.2 Starting position.

Figure 5.3 The athlete's right hand breaks the beam (marked by the flashing of the timing light at the bottom of the picture) before the hip does.

5.3.4 Statistical Analysis

All statistical analysis were performed in SPSS statistical software version 19.0 (SPSS, Inc., Chicago, IL). Mean and SD of 5-m sprint time and timing lights error of three valid trials were calculated for each starting distance. Significant differences in 5-m time and timing lights error between starting distances were detected using one-way repeated measures analysis of variance (ANOVA) and paired t-tests. Pearson correlation coefficients were used to determine the correlation between measured and corrected 5-m sprint times and the correlation of 5-m sprint time and timing lights error between starting distances. Within-trial reliability was assessed using coefficients of variation (CV) and intraclass correlation coefficients (ICC). The significance level for all statistical tests was set a priori to 0.05.

5.4 Results

5-m sprint times differed significantly between the different starting distance conditions (ANOVA $p < .001$). Sprint times were significantly faster for the 1.0-m starting distance than for the 0.5-m and the 0.3-m starting distances (-0.11 ± 0.05 s and -0.07 ± 0.08 s, respectively; Table 5.1). The reliability of 5-m sprint times was lower for larger starting distances indicated by greater coefficients of variation and smaller intraclass correlation coefficients (Table 5.1). 5-m sprint times for the 1.0-m starting distance correlated with 5-m sprint times for the 0.3-m starting distance (Table 5.2). Pearson correlations between corrected and measured 5-m time were 0.91, 0.70, and 0.73 for the 0.3-, 0.5-, and 1.0-m starting distance, respectively.

While the ANOVA did not show any differences in initial timing lights errors between starting distances ($p = .078$) the t-test revealed that timing lights errors were smaller for the 1.0-m compared to the 0.3-

m starting distance (-0.02 ± 0.04 s; Table 5.1). CVs for the initial timing lights error were not interpreted because the mean errors were close to zero, and in this case the CV values are not meaningful. The reproducibility of the initial timing gait errors was smaller than that for the 5-m sprint times (Table 5.1). Initial timing lights errors for the 1.0-m starting distance correlated with initial timing lights errors for the 0.3-m starting distance (Table 5.2).

Table 5.1 Mean, SD, CV, and ICC for 5-m sprint time and initial timing lights error (time between the first break of the beam to the point where the reference point on the hip actually passed the timing lights) for each starting distance.

	Starting distance			***p*-value**		
Variable	**0.3 m**	**0.5 m**	**1.0 m**	**0.3 vs. 0.5 m**	**0.3 vs. 1.0 m**	**0.5 vs. 1.0 m**
5-m sprint time						
Mean (s)	1.09	1.05	0.98	.175	**<.001**	**.007**
SD (s)	0.08	0.07	0.06			
CV (%)	2.44	3.46	3.15			
ICC	0.84	0.65	0.64			
Initial timing lights error						
Mean (s)	0.18	0.16	0.16	.397	**.022**	.639
SD (s)	0.04	0.05	0.04			
CV (%)[a]	13.78	19.88	15.01			
ICC	0.46	0.51	0.67			

CV – coefficient of variation; ICC – intraclass correlation coefficient; [a] CVs for the initial timing lights error were not interpreted because the mean errors were close to zero, and in this case the CV values are not meaningful.

Table 5.2 Pearson correlation coefficients and p-values for correlations in 5-m sprint times and timing lights errors between different starting distances.

	5-m sprint time		**Timing lights error**	
Condition	**0.3 m**	**0.5 m**	**0.3 m**	**0.5 m**
0.5 m	.246	-	-.085	-
p-value	.418		.783	
1.0 m	**.750**	.224	**.624**	.222
p-value	**.004**	.410	**.019**	.467

5.5 Discussion

The purpose of this study was to test the hypothesis that greater distances between the starting position and single-beam timing light placement will reduce 5-m sprint times and the initial timing lights error. As expected, 5-m sprint times were faster with increasing starting distance presumably because the athletes already accelerated before passing the initial timing lights. Hence results gained by different starting distances are not comparable. The small correlations between starting distances concerning 5-m time and timing lights error support this finding: While an athlete is among the best for 0.3 m he might be rather weak for 0.5 m starting distance. However, starting distance did not systematically reduce timing lights errors. These results suggest that starting distances should be standardized to allow for comparison between tests and studies but that the specific starting distance does not improve the accuracy of assessing sprint performance using single-beam timing lights.

The reliability of 5-m sprint times in this study was acceptable (CV, 2.44–3.15%; ICC, 0.64–0.84). However, coefficients of variation in this study were slightly higher than values reported in the literature for dual beam timing lights (2.15%) (Cronin et al., 2007). In our study, the criteria for a valid trial were very strict. Thus, some outliers caused by rocking movements or a backwards step were not used for analysis. This approach probably leads to a higher stability of measurement. While the reliability of this setup may be adequate for assessing sprint performance in athletes in their early career when performance improvements are relatively high, this may not detect small improvements of about 1% which can be crucial for winning or losing at an elite level (Earp & Newton, 2012; Whitting et al., 2013).

Although the timing lights errors were smallest for the 1.0-m starting distance, the differences in timing lights errors between conditions are too small to be of practical relevance. Independent of the starting distance, the timing light beam was broken by the leading arm before the hip passed the timing lights for all trials, and the timing lights error was approximately 16% of the 5-m sprint times. Moreover, timing lights error varied between participants and the ICCs showed high levels of variability. Although 5-m sprint times measured using timing lights correlated with the corrected 5-m time measured by the initial video trigger, the shared variance was only between 49 and 83%. Hence, the results obtained with the two systems are not comparable, especially for the 0.5-m and 1.0-m starting distances. These results support findings in the literature. For instance, Whitting et al. (2013) found that 6-m sidestep times measured using single-beam timing lights and using a motion capture system differed by approximately 11%.

The small ICCs for the initial timing lights error suggest that the movement of the arm relative to the subject's hip differ between trials and that even slight differences in arm movement can affect the timing lights error considerably. Moreover, the timing light error might also depend on the athlete's height and the specific running technique. This variability may be reduced by asking subjects to place their hands on head height (Whitting et al., 2013). However, this unnatural posture would likely affect the results of the 5-m sprint times. Yeadon et al. (1999) recommend placing single-beam timing lights on head height. While this setup would avoid inaccurate measurements due to swinging arms or legs, it would be rather time-consuming to adjust timing light height for each subject. Additional inspection of our video data suggested that for 0.3 m and 0.5 m starting distances the ankle of the back foot of the starting stance passes the initial timing lights line at the same time as the hip. However, further research is necessary to determine if placing the initial timing lights below the knee would improve the accuracy of single-beam timing lights for measuring 5-m sprint times.

The results of this study are based on sprint performance of 13 subjects. Although the mean difference in 5-m sprint time between the 0.3-m and the 0.5-m starting distances was not statistically significant, a sprint time difference of 0.04 s is a relevant time difference regarding sprint performance. Power analysis revealed a required effect size of 0.05 s to reach a power of 80%, and that the power for an effect size of 0.04 s was only 63%. Hence, including more subjects may have resulted in statistically significant differences of performance relevant differences in sprint time. Moreover, in this study, we only investigated the accuracy of the initial timing lights by comparing data to those obtained with a high-speed video camera. It is unknown if the accuracy of the finish timing lights would also affect 5-m sprint times. Because of the small sample size and the characteristics of the sample results cannot be generalized (e.g., different types of sports, women, children). Further investigation is warranted to analyze possible effects of the final timing lights and differences between other samples.

5.6 Practical Applications

Starting distance affected 5-m sprint times but not the accuracy of the initial timing lights. Researchers and coaches should consider the effect of starting distance on 5-m sprint time. Based on the results of this study, we recommend a starting distance of 0.3 m that should be used for all sprint performance tests. Single-beam timing lights may be acceptable for assessing intrapersonal changes at early career level. This study emphasizes the importance of precisely reporting experimental methods and using standardized testing protocols for measuring sprint performance using single-beam timing lights.

6 Timing Light Heights (Paper III & IV)

Paper III

Published version of the original research article

Altmann, S., Spielmann, M., Engel, F. A., Neumann, R., Ringhof, S., Oriwol, D., & Haertel, S. (2017). Validity of single-beam timing lights at different heights. *The Journal of Strength & Conditioning Research, 31*(7), 1994–1999.

6.1 Abstract

The purpose of this study was to quantify the effect of different timing light heights on sprint time and the validity of measurement. Two single-beam timing light systems were used to measure 30-m sprint time (splits at 5 m and 10 m) in 15 healthy and physically active male subjects. System 1 was set up at a height of 0.64 m, system 2 at 0.25 m (initial timing light) and 1.00 m (each following timing light), respectively. Participants performed three valid trials. The recordings of a high-speed video camera were used as a reference. Sprint times of system 1 and system 2 differed significantly between each other and from the reference system at all distances (p <0.001). ICC and Pearson's r values between both timing light systems and the reference system were low to moderate at 5 m and 10 m, and moderate to high at 30 m. Bland & Altman analysis revealed that the agreement intervals were considerably higher for the comparison between system 1 and the reference system than for system 2 and the reference system. A valid measurement of splits at 5 m and 10 m via the systems used in this study is questionable, while 30-m times have an acceptable validity, especially when using system 2. This study confirms the influence of methodological approaches on sprint times. Coaches and researchers should consider that results gained by single-beam timing lights at different heights are not comparable.

Keywords: sprint performance, single-beam timing lights, accuracy, video analysis, timing light height, photocells

6.2 Introduction

Linear-sprint testing is an elementary part of performance testing of team sport athletes. A review recently published by Haugen & Buchheit (2016) investigated methodological issues associated with sprint performance monitoring. Accordingly, there are various factors that affect sprint performance, e.g., starting position (Cronin et al., 2007; Johnson et al., 2010), running surface (Brechue et al., 2005), footwear (Stefanyshyn & Fusco, 2004), environmental factors (Linthorne, 1994), and timing technology (Earp & Newton, 2012; Haugen et al., 2012a; Hetzler et al., 2008; Mayhew et al., 2010). In terms of timing technology, among professional team sports timing lights are frequently employed. Single-beam timing lights can be triggered prematurely by a swinging arm or leg, which leads to measurement errors (Altmann et al., 2015). In order to improve accuracy, more expensive double and triple beam systems and systems employing signal processing algorithms have been developed (Earp & Newton, 2012). However, due to greater availability and lower costs many scientists and practitioners continue to use single-beam systems (Haugen, Tønnessen, Svendsen, & Seiler, 2014c). Literature reveals inconsistent procedures regarding timing light heights, varying between knee (Cronin & Templeton, 2008; Earp & Newton, 2012), hip (Yeadon et al., 1999), and even head height (Dyas & Kerwin, 1995). Conversely, there is limited research examining the effect of timing light height on sprint times (Cronin & Templeton, 2008; Yeadon et al., 1999), especially when applying single-beam systems.

Therefore, the purpose of this study was to investigate whether timing light height might affect sprint times as well as the validity of single-beam systems on the basis of high-speed cameras in order to give recommendations for the practitioner if these systems can be used for measuring (short) sprints. We hypothesized that timing light height would influence both sprint times and timing accuracy.

6.3 Methods

6.3.1 Experimental Approach to the Problem

As described before, timing light heights are usually positioned at knee (Shalfawi et al., 2012) or hip height (Yeadon et al., 1999). In a recent study, Altmann et al. (2015) investigated the effect of starting distance on 5-m sprint times and initial timing lights accuracy at a height of 1.00 m. While there was no significant difference between timing accuracy for 0.30, 0.50, and 1.00 m distance from the first timing lights, authors suggested that for 0.30 m starting distance the ankle of the back foot could pass the initial timing lights simultaneously with the hip. Therefore, authors claimed that placing initial timing lights below the knee could possibly improve the accuracy of the initial timing lights.

In the present cross-sectional experimental laboratory study single-beam timing light systems were placed at two different heights, each at the start line, 5, 10, and 30 m. System 1 was set up at a height of 0.64 m (approx. knee height), system 2 at 0.25 m (approx. ankle height; initial timing light) and 1.00 m (approx. hip height; each following timing light), respectively. With regards to system 2, variations of timing light height within a measurement set-up were also previously performed by Haugen et al. (2012a). Experienced athletes performed sprint trials over 30 m with splits recorded at 5 and 10 m. High-speed video cameras were used to simultaneously capture the timing light beam and a reflective marker on the subjects' right hip. Measurement error (ME) of the timing lights was defined as the time difference between the timing lights trigger and the reflective marker passing the timing lights.

6.3.2 Subjects

Fifteen healthy and physically active male subjects (age, 24.3 ± 1.8 years; age range, 20–27 years; height, 178.5 ± 7.4 cm; mass, 74.6 ± 8.7 kg) volunteered to participate in this study. All subjects had a team-sport background (e.g., soccer, handball, volleyball) and were free from injuries at the time of testing. The study was approved from full ethics review by the institutional review board and was conducted in accordance with the Declaration of Helsinki (World Medical Association (WMA), 2013). All subjects gave their written informed consent before participation.

6.3.3 Procedures

The tests took place indoors on a PVC running surface. The wireless single-beam timing light systems (TAG Heuer, La-Chaux-de-Fonds, Switzerland) were placed at the start line, 5, 10, and 30 m. To assess the effects of timing light heights, timing lights were set up at two different heights and simultaneously covered the sprint times. System 1 was set up at a height of 0.64 m, matching approx. subjects' knee height. Relating to system 2 the initial timing light was mounted at 0.25 m, matching approx. the ankle of the back foot of the starting stance. All following timing lights of system 2 were set at 1.00 m (approx. hip height). High-speed cameras (Weinberger Deutschland GmbH, Erlangen, Germany) recording at a frequency of 100 frames per second were positioned behind each timing light to provide a reference value, adjusted with the timing light beam. Thus, the timing light beam as well as the subjects were captured by the cameras (Figure 6.1). A reflective marker representing the body close to the height of the center of mass was placed on subjects' right hip.

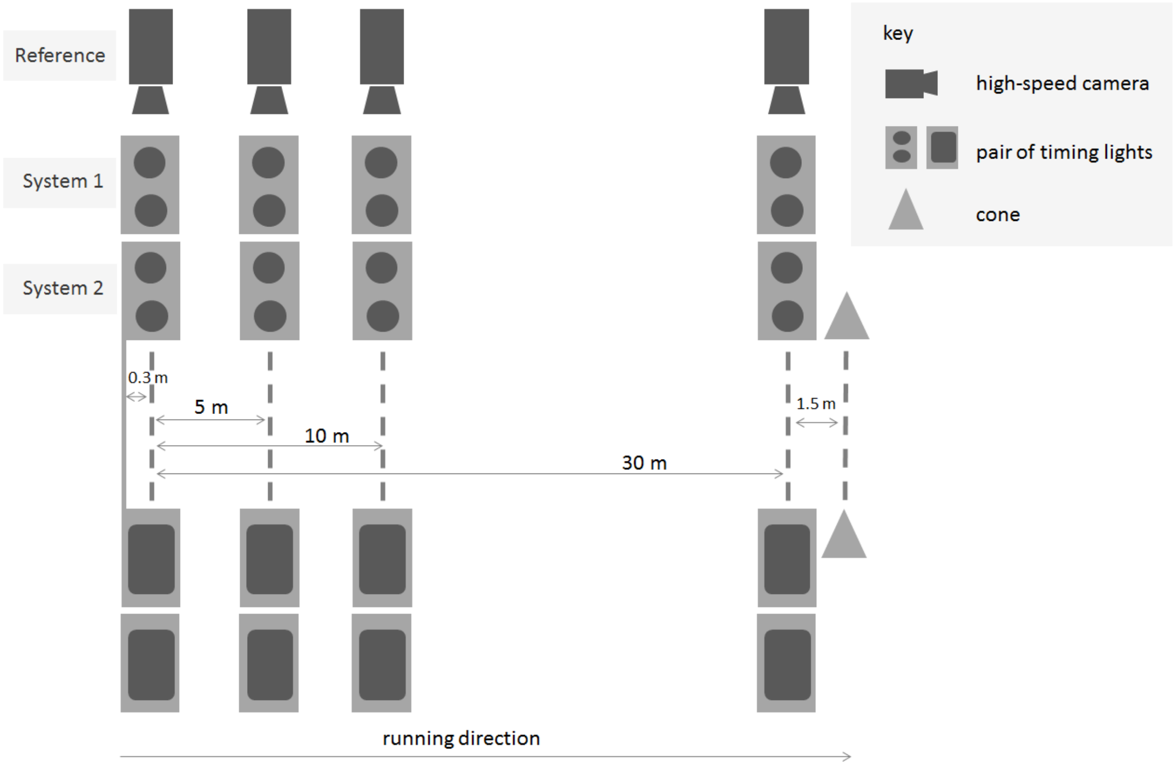


Figure 6.1 Measurement set-up.

After a standardized 10-minute warm-up protocol including jogging, short accelerations and movement preparation exercises subjects performed a familiarization trial. Subsequently, all participants completed 3 valid sprint trials over 30 m with 2 min recovery between trials. Subjects were instructed to sprint as fast as possible past a cone placed 1.50 m behind the finish timing lights in order to avoid a finishing dip or an early deceleration. Prior to sprinting, participants received a standardized briefing concerning the starting procedures. The starting distance from the first timing lights was set at 0.30 m. The starting position was a split start (Figure 6.2).

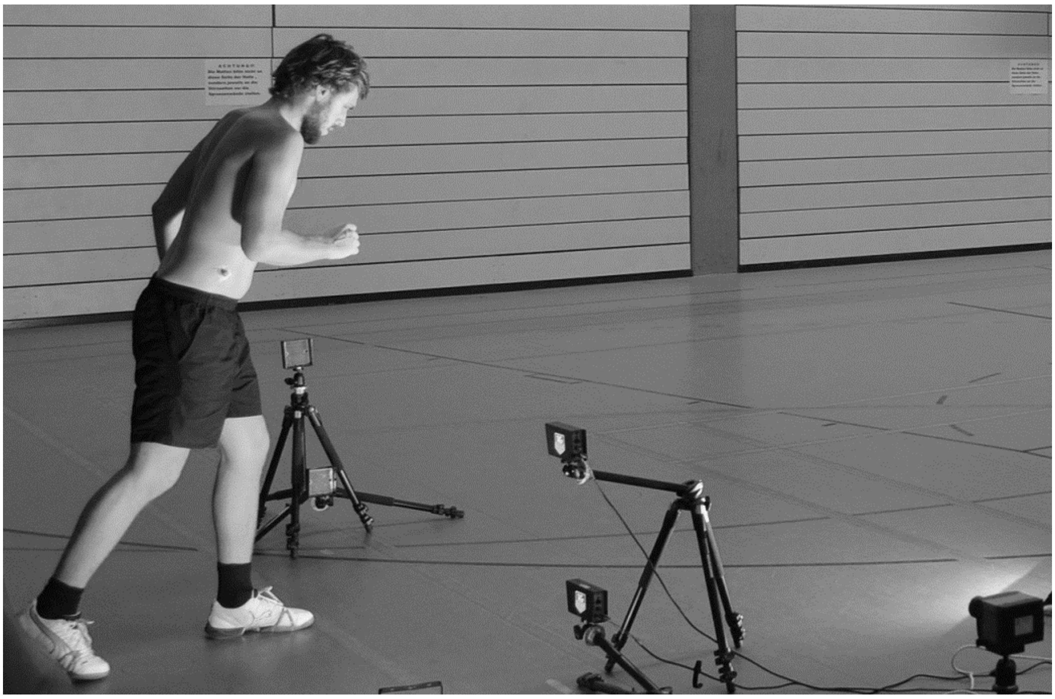


Figure 6.2 Starting position.

Athletes were free to choose the leading foot but had to use the same starting position for all trials. Leaning back or rocking movements prior to sprinting were prohibited. A starting signal was not given. The same model of a running shoe (Puma Cell) was provided for all subjects.

6.3.4 Data Analysis

The timing started automatically for both systems when the initial timing lights were triggered. The video sequences covered by the high-speed cameras were processed using Windows Media Player Version 12.0.7601.17514 (Microsoft Corporation, Redmond, Washington, USA). In order to calculate the times of the reference system, a measurement error (ME $_{\text{Initial Timing Lights, 5, 10 or 30 m}}$) was determined by capturing the number of frames between the frame when the timing light beam first appeared in the video image (Figure 6.3) and the frame when the reflective marker passed the timing lights for each system at each timing light. This value was divided by 100. The times of the reference system were calculated as follows:

$$\textit{Reference System}_{(5,\,10\text{ or }30\text{ m})} =$$

$$\textit{Timing Light System Time}_{(5,\,10\text{ or }30\text{ m})} - \textit{ME}_{\text{Initial Timing Lights}} + \textit{ME}_{(5,\,10\text{ or }30\text{ m})}$$

These calculations were done for both systems in order to ensure the reference system time.

As an absolute measure of within-trial reliability of the reference system root mean square errors (RMSE) were calculated (Atkinson & Nevill, 1998; Bland & Altman, 1996). There was considerable unsystematic biological variability for the reference system (RMSE 0.037, 0.062, and 0.062 s, representing 3.52, 3.48, and 1.45% of total running time for 5, 10, and 30 m, respectively). Therefore, we used the best trial revealed by the reference system, as this trial represents the best performance of the athletes, and corresponding trials of system 1 and 2.

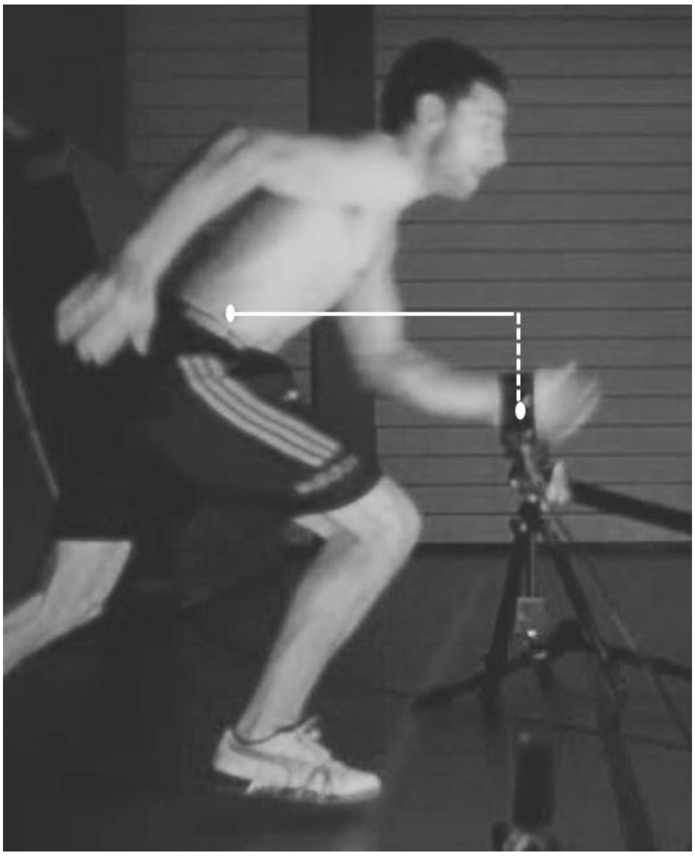


Figure 6.3 The athlete's left hand breaks the beam of system 1 at the initial timing lights (marked by a flashing of the timing light) before the hip does.

6.3.5 Statistical Analysis

The data were analyzed using SPSS statistical software version 22.0 (SPSS, Inc., Chicago, IL). For each subject, the best trial (30-m time) of the reference system and corresponding trials of system 1 and 2 were included in the analysis. Mean values and standard deviations (SD) were calculated for the whole sample. One-way repeated measures analysis of variance (ANOVA) and subsequent pairwise comparisons with Bonferroni corrected p-values were used to determine differences in sprint times between system 1, system 2, and reference system. Intraclass correlation coefficients (ICC; absolute agreement, single measures), Pearson correlation coefficients, and Bland & Altman's 95% limits of agreement (LOA) were used as additional measures of validity (Atkinson & Nevill, 1998; Bland & & Altman, 1999). The agreement intervals were defined as the range between the upper and the lower LOA. Low ICC and Pearson correlation coefficients indicate the existence of systematic and unsystematic bias, respectively. LOA are able to detect both types of bias.

Normal distribution as an assumption for the here used statistical procedures was given. The significance level for all statistical tests was set a priori to 0.05.

6.4 Results

Descriptive statistics of sprint times for each system can be seen in Table 6.1. ME (± SD) for each timing light can be found in Table 6.2. All sprint times differed significantly between the 3 timing systems (ANOVA and pairwise comparisons *p* <0.001).

Table 6.1 Mean values (± SD) over the best trial per subject for the whole sample of the reference system and corresponding trials of system 1 and 2 of 30-m sprints with splits at 5 m and 10 m.

Distance	**Reference**	**System 1**	**System 2**
5 m	1.051 ± 0.035 s	1.139 ± 0.097 s	0.936 ± 0.040 s
10 m	1.783 ± 0.051 s	1.883 ± 0.113 s	1.700 ± 0.053 s
30 m	4.280 ± 0.126 s	4.385 ± 0.163 s	4.216 ± 0.130 s

SD – standard deviation; Reference – High-speed video analysis; System 1 – 0.64 m; System 2 – 0.25 m and 1.00 m, respectively

Table 6.2 ME (± SD) of corresponding trials of system 1 and system 2 for each timing light (best trial per subject of the reference system for the whole sample of 30-m sprints with splits at 5 m and 10 m).

Timing lights	**System 1**	**System 2**
Initial	0.130 ± 0.085 s	-0.058 ± 0.024 s
5 m	0.043 ± 0.017 s	0.057 ± 0.030 s
10 m	0.035 ± 0.014 s	0.025 ± 0.018 s
30 m	0.029 ± 0.012 s	0.005 ± 0.011 s

ME – measurement error; SD – standard deviation; Reference – High-speed video analysis; System 1 – 0.64 m; System 2 – 0.25 m and 1.00 m, respectively

All sprint times were significantly faster for system 2 than for system 1 as well as the reference system and faster for the reference system compared to system 1 (Table 6.3). Results for LOA, ICC, and Pearson's r between the systems can be found in Table 6.3.

Table 6.3 ANOVA between all systems and pairwise comparisons (Bonferroni corrected p-values, level of significance = 0.05), LOA, ICC and Pearson's r for the best trial of the reference system and corresponding trials of system 1 and 2 of 30-m sprints with splits at 5 and 10 m.

Distance	Overall	System 1 vs. Reference	System 2 vs. Reference	System 1 vs. System 2
5 m				
ANOVA	<0.001	0.006	<0.001	<0.001
LOA (95%)	–	-0.267 – 0.089 s	0.037 – 0.193 s	–
ICC	0.026	0.134	0.008	-0.029
Pearson's r	–	0.351 (y = 0.128x + 0.905)	0.449 (y = 0.399x + 0.677)	–
10 m				
ANOVA	<0.001	0.003	<0.001	<0.001
LOA (95%)	–	-0.280 – 0.080 s	0.038 – 0.128 s	–
ICC	0.209	0.278	0.400	0.126
Pearson's r	–	0.597 (y = 0.270x + 1.274)	0.904 (y = 0.872x + 0.300)	–
30 m				
ANOVA	<0.001	0.001	<0.001	<0.001
LOA (95%)	–	-0.276 – 0.066 s	0.006 – 0.120 s	–
ICC	0.632	0.657	0.869	0.491
Pearson's r	–	0.848 (y = 0.657x + 1.400)	0.905 (y = 0.946x + 0.290)	–

ANOVA – Analysis of variance; LOA (95%) – Bland & Altman's 95% limits of agreement; ICC – Intraclass correlation coefficient; Reference – High-speed video analysis; System 1 – 0.64 m; System 2 – 0.25 m and 1.00 m, respectively

Exemplarily, Bland & Altman plots with bias and limits between the reference system and system 1 and 2 at 5 m are illustrated in Figures 6.4 and 6.5, respectively.

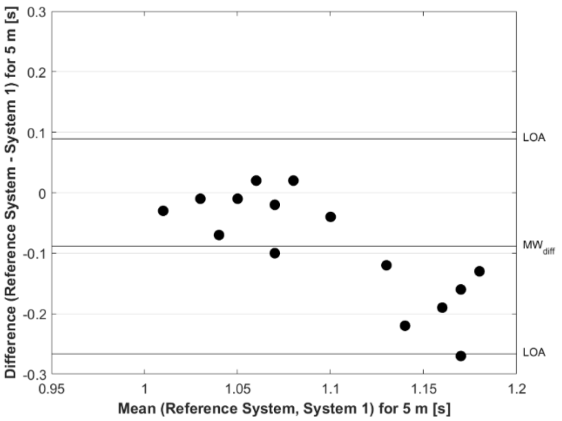


Figure 6.4 Bland & Altman plot with bias and limits between the reference system and system 1 at 5 m.

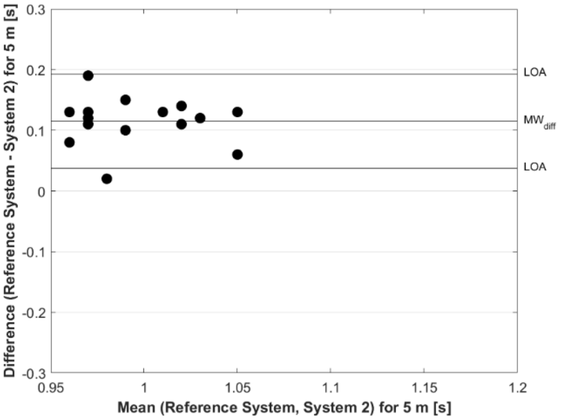


Figure 6.5 Bland & Altman plot with bias and limits between the reference system and system 2 at 5 m.

6.5 Discussion

The purpose of this study was to examine the validity of single-beam timing light systems and the effect of timing light height on 30-m sprints in trained team sports athletes.

As described before, the best trial of the reference system was used for analysis. In addition, analysis was also run for the best trials of the two timing light systems and corresponding reference times and comparable results were obtained.

With regard to the best reference system trial, ANOVA showed a main effect of timing systems. All sprint times were faster for system 2 than for system 1 and the reference system, and faster for the reference system compared to system 1. Hence, results gained by the three systems are not interchangeable. This finding is in line with previous research by Cronin & Templeton (2008), who found that the height of double beam timing lights affects sprint times.

In this study these results are supported by low to moderate ICC and Pearson's r values, especially for 5 and 10 m, indicating both systematic and unsystematic bias between the 3 systems.

Moreover, Bland & Altman plot analysis revealed that the agreement intervals were considerably higher for the comparison between system 1 and the reference system (0.356, 0.360, and 0.342 s for 5, 10, and 30 m, respectively) than for system 2 and the reference system (0.156, 0.090, and 0.114 s). The finding that different timing light heights affect the measurement accuracy is in agreement with previous research by Yeadon et al. (1999). They found single-beam timing lights mounted at hip height

(1.05 m) to be more accurate than timing lights at 1.25 m when compared to a three-dimensional video analysis.

As ME varied between participants in our study, again in a higher extent for system 1 than system 2, the introduction of correction factors (Haugen et al., 2012a) is not applicable in this case.

The synthesis of the presented results suggests that the use of both timing light systems is questionable for measuring short sprints (5 and 10 m) as previously suggested by Haugen & Buchheit (2016). Anyway, as validity increased with running distance, the timing light systems, especially system 2, could be used for longer distances such as 30 m. According to Rumpf et al. (2016), for this distance performance improvements due to specific sprint training interventions are 3.63 ± 2.37% on average. In relation to an assumed 30-m time of 4.300 s this corresponds to a time improvement of 0.156 ± 0.102 s, and therefore, could be detected by timing light system 2 as LOA were 0.006–0.120 s.

In a recent study (Altmann et al., 2015), initial single-beam timing lights were set up at a height of 1.00 m. Using the same study design, the authors found a ME of 0.180 s. After additional inspection of video material, authors suggested that the ankle of the back foot of the starting stance could pass the initial timing lights at the same time as the hip. Hence placing initial timing lights below the knee could possibly improve the accuracy of the initial timing lights. In this study ME at the initial timing lights were lower for both timing light heights (0.130 ± 0.085 s and -0.058 ± 0.024 s for system 1 and system 2, respectively). Furthermore, ME decreased continuously to 0.029 ± 0.012 s and 0.005 ± 0.01 s at 30 m for system 1 and system 2, respectively. The decrement of ME with greater running distances can be explained by higher running speeds and subsequent smaller time frames between prematurely triggering of the gates and passing of the reflective marker on the subjects' hip. These results are supported by research of Haugen et al. (2012a) who demonstrated that the highest potential for differences between timing methods is in the start. Therefore, using interval times (e.g., 5–10 or 10–30 m) could provide more valid results with regards to the reference system (Haugen et al., 2014c).

In order to avoid false triggering of timing lights by swinging arms (see Figure 6.3) or legs, some authors recommend placing single-beam timing lights on head height (Dyas & Kerwin, 1995). Most likely, this setup would do so. However, the buildup would be rather time-consuming and therefore be uneconomic for regular measurements. Furthermore, start triggering devices like pressure sensitive floor pods (Haugen & Buchheit, 2016) and infra-red photoelectric measurement systems as described in Healy et al. (2016) have been developed. However different influencing factors when using these systems have yet to be examined. Therefore, systems where accuracy has been proven, like dual-beam or post-processing timing lights, are recommended for measuring short sprints (Earp & Newton, 2012; Haugen & Buchheit, 2016).

Finally, it should be mentioned that all these effects were measured in young and healthy males with a team-sport background. Therefore, no conclusions about generality can be drawn on this basis. Further investigation is advised to analyze if results can be transferred to other populations.

6.6 Practical Applications

Coaches and researchers should consider that results measured by single-beam timing lights at different heights are not comparable. A valid measurement of splits at 5 m and 10 m via the systems used in this study is questionable, while 30-m times have an acceptable validity, especially when using system 2 (at a height of 0.25 m and 1.00 m, respectively). In order to measure short sprints, dual-beam timing lights or post-processing systems are recommended. In line with other research (Haugen & Buchheit, 2016), this study confirms the influence of methodological approaches on sprint times and thus the importance of precisely reporting experimental methods for measuring sprint performance using single-beam timing lights.

Paper IV

Published version of the original research article

Altmann, S., Spielmann, M., Engel, F. A., Ringhof, S., Oriwol, D., Haertel, S., & Neumann, R. (2018). Accuracy of single beam timing lights for determining velocities in a flying 20-m sprint: does timing light height matter? *Journal of Human Sport and Exercise, 13*(3), 601–610.

6.7 Abstract

Background: The purpose of this study was to evaluate the accuracy of timing lights (TL) at different heights for measuring velocities during sprinting.

Methods: Two sets of single-beam TL were used to determine velocities reached in a flying 20-m sprint in 15 healthy and physically active male participants. In TL_{64}, all TL were set up at a height of 64 cm, and in TL_{100}, all TL were set up at 100 cm, respectively. Participants performed three valid trials. The recordings of high-speed video cameras were used as a reference.

Results: ICC and Pearson's r values between both timing light heights and the reference system were almost perfect (0.969–0.991). Bland & Altman's LOA (95%) indicated low systematic and unsystematic errors, with somewhat smaller LOA for TL_{100} (-0.013–0.121 m/s) than for TL_{64} (-0.060–0.120 m/s). Measures of between-trial reliability of running velocities showed a high relative (ICC) and absolute (RMSE) reliability, with the reference system showing slightly better values in all reliability measures (ICC=0.935; RMSE<0.001 m/s) compared to TL_{64} and TL_{100} (ICC=0.894, 0.887; RMSE=0.107 m/s, 0.124 m/s, respectively). The usefulness, determined by comparing the typical error (TE) with the smallest worthwhile change (SWC), was considered as "OK" (TE ≈ SWC) for all three systems.

Conclusions: Results suggest that TL at both heights (TL_{64} and TL_{100}) can be considered as accurate, reliable, and useful in computing velocities during a flying 20-m sprint, and therefore can be recommended to both coaches and researchers.

Keywords:

Sprint performance; Timing gates; Validity; High-speed video analysis; Photocells

6.8 Introduction

Linear-sprint testing plays a key role in the assessment of physical abilities in different sports (Haugen & Buchheit, 2016). Regarding timing technology, timing lights are commonly employed in order to capture split or total sprint times (e.g., 5 m, 10 m, 30 m) as well as interval times (e.g., 10–30 m) and sprinting velocities over a given interval (e.g. velocity between 10 m and 30 m) (Rumpf et al., 2016).

Despite the development of progressive technologies such as dual-beam or post-processing timing lights, the use of single-beam systems is still widespread (Darrall-Jones et al., 2016a; Darrall-Jones, Jones, & Till, 2016b; McFarland, Dawes, Elder, & Lockie, 2016; Roe et al., 2017; Sawczuk et al., 2017; Wong et al., 2017), possibly due to greater availability and lower costs (Haugen & Buchheit, 2016).

The validity of single-beam timing lights to capture split and total times has been well investigated. Consistently, several researches question the accuracy at short distances (e.g., 5 m, 10 m, 20 m), whereas longer distances (e.g., 30 m, 40 m) can be measured with sufficient precision (Altmann et al., 2015; Altmann et al., 2017; Haugen et al., 2014c). However, little is known about single-beam systems' validity in capturing interval sprinting times and corresponding velocities, and these studies used differing approaches (Roe et al., 2017) and objectives (Bond et al., 2017a; Haugen et al., 2014c). In particular, the effect of different timing light heights measurement accuracy has not been investigated to date.

Therefore, the purpose of the present study was to analyze the accuracy of single-beam timing lights at two different heights in determining sprint velocities on the basis of high-speed cameras. Based on the results of this study recommendations could be given for coaches and researchers whether these systems can be employed for determining velocities during linear sprints. We hypothesized that both timing light heights would be able to capture sprint velocities with sufficient accuracy.

6.9 Materials and Methods

6.9.1 Study Design

For the purpose of this study, selected raw data of a previously published study (Altmann et al., 2017) were used. While the latter study focused on split (5 m and 10 m) and total times during 30-m sprints, the present research addressed the velocities reached in the last sprinting interval (10–30 m, representing a flying 20-m sprint), which have not been investigated to date.

In this cross-sectional experimental laboratory study, 15 male sports students performed flying 20-m sprints with a 10-m acceleration phase of maximum effort. The velocities were simultaneously determined by two sets of identical single-beam timing lights at a height of 64 cm (TL_{64}) and 100 cm (TL_{100}), respectively. High-speed cameras served as a reference.

6.9.2 Subjects

Fifteen healthy and physically active male subjects (age, 24.3 ± 1.8 years; age range, 20–27 years; height, 178.5 ± 7.4 cm; body mass, 74.6 ± 8.7 kg) with team-sport background participated in this study. The study was approved from full ethics review by the institutional review board and was conducted in accordance with the Declaration of Helsinki (World Medical Association (WMA), 2013). Prior to participation, all subjects gave their written informed consent.

6.9.3 Procedures

A detailed description of the methods can be found in Altmann et al. (2017). As only selected parameters of the mentioned study were used, merely the acquisition of the data analyzed for the present study is described in the following.

Two sets of single-beam timing lights (TAG Heuer, La-Chaux-de-Fonds, Switzerland) were placed at a distance of 10 m and 30 m from a start line. The first set (TL_{64}) was placed at a height of 64 cm, matching approx. participants’ knee height. With regard to the second set (TL_{100}), the timing lights were mounted at 100 cm, matching approx. hip height. These heights were chosen because knee (Cronin & Templeton, 2008; Shalfawi et al., 2012) and hip height (Sawczuk et al., 2017; Sawczuk et al., 2017; Yeadon et al., 1999) are commonly employed in literature, allowing for the findings of the present study to be transferred to other research in terms of measurement set-up. Behind each timing light, high-speed cameras (Weinberger Deutschland GmbH, Erlangen, Germany; 100 frames per second) were positioned to track a reflective marker on subjects’ right hip representing the body close to the height of the center of mass to provide a reference value of sprinting times. Following a standardized warm-up protocol and a familiarization trial, athletes performed three flying 20-m sprints with a 10-m acceleration phase and 2 min recovery between trials. To avoid an early deceleration, participants had to sprint as fast as possible past a cone placed 1.50 m behind the finish timing lights. The tests took place indoors on a PVC running surface.

6.9.4 Data Analysis

The time intervals between the timing lights positioned at 10 m and 30 m were automatically generated via the timing light software. By determining the measurement accuracy of the timing lights through the video sequences, the times of the reference system (high-speed cameras) were calculated (Altmann et al., 2017). Subsequently, the times captured by all systems were transformed into velocities (m/s). The mean values of all flying 20-m trials for all systems were used for analysis (Al Haddad et al., 2015).

6.9.5 Statistical Analysis

The data were analyzed using SPSS statistical software version 24.0 (SPSS, Inc., Chicago, IL). Mean values and standard deviations (SD) of all flying 20-m trials for all systems were calculated for the whole sample. A one-way repeated measures analysis of variance (ANOVA) was run to detect differences in sprint velocities between TL_{64}, TL_{100}, and the reference system. Bland & Altman's 95% limits of agreement (LOA), ICC, and Pearson correlation coefficients were used as additional measures of validity (Atkinson & Nevill, 1998; Bland & & Altman, 1999). Relative between-trial reliability was checked using ANOVA, and intraclass correlation coefficients (ICC; absolute agreement, single measures). Absolute reliability was assessed through root mean square errors (RMSE). For the applied statistical procedures normal distribution as an assumption was given. The significance level for all statistical tests was set a priori to 0.05.

To determine the usefulness, which describes the sensitivity of a test to measure meaningful changes in performance, for all systems the typical error (TE) and the smallest worthwhile change (SWC) were computed. While the TE is expressed as a coefficient of variation (CV) and raw data TE over three trials, the SWC corresponds to the between-subject SD of the mean over these three trials multiplied by 0.2. The calculation of the SWC is based on Cohen's effect size principle, where 0.2 is a typical small effect. The usefulness of the test was then assessed by comparing the TE with the SWC. A TE smaller than the SWC was rated as "good", a TE similar to the SWC as "OK" and a TE larger than the SWC as "marginal" (Hopkins, 2004).

6.10 Results

Descriptive statistics of sprint velocities and reliability measures (ANOVA, CV, ICC, and RMSE) for each system are presented in Table 6.4.

Table 6.4 Mean values ± SD of three trials of flying 20-m sprints and corresponding ANOVA, ICC, RMSE, CV, TE, SWC, and Test rating.

Parameter	Reference	TL_{64}	TL_{100}
Velocity flying 20-m sprint ± SD [m/s]	7.994 ± 0.249	7.964 ± 0.262	7.940 ± 0.255
ANOVA [*p*-value]	0.931	0.742	0.710
ICC [*r*]	0.935	0.894	0.887
RMSE [m/s]	<0.001	0.107	0.124
CV [%]	0.552	0.772	0.753
TE [m/s]	0.044	0.061	0.060
SWC [m/s]	0.050	0.052	0.051
Test rating	OK	OK	OK

Reference – High-speed video analysis; TL_{64} – 64 cm; TL_{100} – 100 cm; SD – Standard deviation; ANOVA – Analysis of variance; ICC – Intraclass correlation coefficient; RMSE – Root mean square error; CV – Coefficient of variation; TE – Typical error of measurement; SWC – Smallest worthwhile change

Comparisons between the systems (ANOVA) and validity measures (LOA, ICC, and Pearson's r) can be found in Table 6.5.

Table 6.5 ANOVA between all systems and pairwise comparisons (Bonferroni corrected *p*-values), LOA, ICC and Pearson's r for mean values of three trials of flying 20-m sprints.

Parameter	Overall	TL_{64} vs. Reference	TL_{100} vs. Reference	TL_{64} vs. TL_{100}
ANOVA [*p*]	0.001	0.076	0.001	0.157
LOA (95%) [m/s]	–	-0.060 – 0.120	-0.013 – 0.121	–
ICC [*r*]	0.977	0.978	0.969	0.982
Pearson's *r*	–	0.985	0.991	0.986

Reference – High-speed video analysis; TL_{64} – 64 cm; TL_{100} – 100 cm; ANOVA – Analysis of variance; LOA (95%) – Bland & Altman's 95% limits of agreement; ICC – Intraclass correlation coefficient

6.11 Discussion

The aim of the present study was to investigate the accuracy of single-beam timing lights at different heights for determining velocities during a flying 20-m sprint. ANOVA revealed velocities captured by TL_{100} to be significantly slower ($p<0.001$) than by the reference system (high-speed cameras) and a trend ($p=0.076$) for TL_{64} to measure slower velocities than the reference, while there was no difference between the two sets of timing lights (Table 6.5). However, as the difference between the systems was only approx. 0.4% (relative) and 0.03 m/s (absolute), the differing results by ANOVA have limited practical relevance.

In contrast, ICC and Pearson's r values were almost perfect for both timing light heights with regard to the reference, pointing out a high accuracy of measurement (Table 6.5). These results are supported by low LOA (95%) indicating low systematic and unsystematic errors. Although LOA of TL_{100} (-0.013–0.121 m/s) were somewhat smaller than LOA of TL_{64} (-0.060–0.120 m/s), both heights could detect performance improvements associated with specific sprint training interventions (Rumpf et al., 2016). Compared to previous findings (Altmann et al., 2017; Cronin & Templeton, 2008), the similarity of both heights is a novelty and seems to be counterintuitive at first sight. The similarity of TL_{64} and TL_{100} is likely due to the fact that the running velocities in this study were not dependent from a timing light's accuracy at the start of the acceleration phase, which is associated with the largest measurement error and notable differences between different heights (Altmann et al., 2017).

The high accuracy of both timing light heights in relation to the reference system in the present study can be explained in two ways. Firstly, there was a relatively large separation (20 m) between the timing lights. A large separation minimizes the measurement errors in relation to the interval times and, therefore, improves relative accuracy (Yeadon et al., 1999). Secondly, the larger the running distance, the lower the impact of measurement errors due to swinging arms or legs. In this context, studies by Altmann et al. (2015; 2017) demonstrated measurement errors to continuously decrease from the start to 5 m, 10 m, and 30 m timing lights. Combined with a more upright body position at greater distances (Bond et al., 2017a; Haugen et al., 2014c), timing lights at both heights (64 cm and 100 cm) were able to determine velocities during the flying 20-m sprint with a 10 m acceleration phase accurately.

In a previous study, Haugen et al. (2014c) found that there is no time difference between single and dual beam timing systems in the interval of 20–40 m during a 40-m sprint. Moreover, Bond et al. (2017a) reported a non-significant time difference of 0.01 s for an interval of 30–60 feet (9.14–18.29 m) between single-beam timing lights (height: 91 cm) and a high-speed video recording. In line with the present research, these studies demonstrate the accuracy of measuring sprint intervals of distances between approximately 10–40 m with the help of single-beam timing lights.

A high accuracy of single-beam timing lights for assessing maximal running velocities during a 40-m sprint in elite rugby players was previously shown by Roe et al. (2017). The exact timing light height was not reported, however. The significance of this result seems further questionable since authors used a radar system as a reference method. Actually, in several other studies radar systems were validated via timing lights. Interestingly, single-beam timing lights have been used for validating other technologies such as global positioning systems (GPS) (Castellano, Casamichana, Calleja-González, San Román, & Ostojic, 2011b; Portas, Rush, Barnes, & Batterham, 2007; Waldron, Worsfold, Twist, & Lamb, 2011) as well as radar guns and laser systems (Berthoin et al., 2001; Ferro et al., 2012; Morin et al., 2006; Samozino et al., 2016) in several recent studies, despite the validity of timing lights itself for capturing running velocities was unknown. However, with the here presented results, at least considering high velocities (e.g., 8 m/s), it seems justified to employ single-beam timing lights as a reference system.

The between-trial reliability of running velocities over three trials was also considered in this study. Accordingly, both the two sets of timing lights and the reference system showed a high relative (ANOVA, ICC) and absolute (RMSE) reliability. However, as expected, the reference system showed somewhat better values in all reliability measures, with TL_{64} and TL_{100} indicating similar reliability (Table 6.4).

In the present investigation, the usefulness of all three systems was rated as “OK” as the TE (noise) was similar to the SWC (signal). Therefore, all systems might detect performance changes following a training period. The relatively small between-subject SD compared to other studies assessing high or maximum velocities (Djaoui et al., 2017; Roe et al., 2017) suggests a high homogeneity of the athletes in the current study. This, in turn, leads to a low SWC and a usefulness rating of “OK”. A more heterogeneous group with a greater SD and similar TE would probably result in a higher test rating (“good”) (Düking, Born, & Sperlich, 2016; Lockie, Schultz, Callaghan, Jeffriess, & Berry, 2013).

As the sample of this study consisted of young males with a team-sport background, the transferability of the results to other populations remains to be investigated.

6.12 Conclusions

In conclusion, this research adds further knowledge into the accuracy of single-beam timing lights during sprint testing. While the accuracy over short and longer distances (5–30 m) has already been investigated (Altmann et al., 2015; Altmann et al., 2017), this study addressed the velocities during flying 20-m sprints with a 10-m acceleration phase using high-speed video cameras as a reference.

Accordingly, single-beam timing lights at both heights (64 cm and 100 cm) can be recommended to accurately and reliably determine running speeds during flying 20-m sprints with an acceleration phase of 10 m. Furthermore, both set-ups provide sensitive measures to track changes in athletic performance following a training period. This is in particular of interest for both coaches (e.g., monitoring sprint velocity at a certain time of a season) and researchers (e.g., evaluating the effectiveness of a specific training program).

7 Type of Timing Lights (Paper V)

Extended version of the original research article

Altmann, S., Ringhof, S., Becker, B., Woll, A., & Neumann, R. (2018). Error Correction Processing in Timing Lights for Measuring Sprint Performance: Does It Work? *International Journal of Sports Physiology and Performance, 13*(10), 1400–1402.

7.1 Abstract

Purpose: To investigate if error correction processing (ECP) algorithms in timing lights are able to eliminate or to reduce measurement errors (ME) and false signals due to swinging arms or legs.

Methods: First, a dummy was used to check if ECP generally works. Second, 15 male sports students performed sprints over 5 m and 10 m. Timing lights with ECP and a high-speed camera as a gold standard were used to simultaneously capture the athlete when passing the timing lights at start, 5 m or 10 m, respectively. ME of the timing lights were calculated for hip and upper body.

Results: The dummy condition revealed that in optimum controlled conditions, ECP eliminates ME. In real sprint conditions, ME was highest for timing lights at start and when using the hip as a reference. Overall, out of 120 trials, only four false signals were not detected by ECP. They all occurred at the start timing light, with highest ME being 0.263 s (hip) and 0.134 s (upper body). Regarding 5 m and 10 m, all false signals were eliminated.

Conclusions: As proven through video analyses, ECP eliminated almost all false signals. Greatest ME for the start timing light were associated with a distinct forward leaning of the athletes. Therefore, clear instructions concerning starting posture should be given to further improve measurement accuracy of the start timing light. This approach could also enhance comparisons between athletes. Nevertheless, based on our results, timing lights employing ECP can be recommended for measuring short sprints.

Keywords: Measurement Error, Photocells, Timing Gates, Validity, High-Speed Video Analysis, Smartspeed Pro

7.2 Introduction

Sprinting is an elementary component for success in many sports, such as soccer (Faude et al., 2012). Therefore, sprint testing plays a key role in the physical assessment of team sport athletes.

A recent review by Haugen & Buchheit (2016) examined different timing technologies, among other methodological issues, with regards to their validity to measure sprint performance. While fully-automatic systems and high-speed video analysis are considered as gold standards due to their accuracy (Haugen & Buchheit, 2016), these timing technologies are cost and time intensive. Through their superiority towards manual timing (Hetzler et al., 2008) and acceptable costs, timing lights got into the focus of both practitioners and researchers, and meanwhile are frequently employed in professional team sports.

Timing lights may consist of a single-beam or multiple beams. In terms of single-beam timing lights, the system can prematurely be triggered by an athlete's upper or lower limbs. This causes measurement errors (ME), as researchers and coaches usually seek to capture the athlete's torso during sprint testing (Altmann et al., 2015). Studies by Altmann et al. (2015; 2017) revealed ME of single-beam systems mounted at hip height to be 0.18 s at the start timing light and to decrease by longer distances (e.g., 5 m, 10 m, 30 m). The authors concluded, that a valid measurement of splits at 5 m and 10 m via single-beam systems seem to be questionable, while 30-m times have an acceptable validity.

To improve measurement accuracy, systems employing error correction processing algorithms (ECP) have been developed. These systems process all triggers as an athlete passes through the timing lights. Based on the assumption, that the torso causes a longer break than a swinging arm or leg, ECP always interprets the beginning of the longest break as the correct signal (Earp & Newton, 2012; Haugen & Buchheit, 2016).

To date, there is limited research quantifying ME when using ECP. Therefore, the purpose of the present study was to investigate if ECP is able to eliminate or to reduce ME on the basis of high-speed video analysis, both in a controlled and in a real sprint condition. The results of this study could help practitioners to decide if ECP systems are appropriate for sprint performance monitoring.

7.3 Methods

7.3.1 Design

The measurement accuracy and the effectiveness of single-beam timing lights employing ECP in eliminating false signals were examined in cross-sectional design employing two conditions: a controlled condition using a dummy and a real sprint condition with sports students serving as subjects.

In both conditions, timing lights with ECP sampling at 1.000 Hz (Smartspeed Pro, Fusion Sport, Coopers Plains, Australia) and a high-speed camera sampling at 200 Hz (SpeedCam Macro Vis, Weinberger Deutschland GmbH, Erlangen, Germany) were used to simultaneously capture the dummy or the athletes' torso, respectively, when passing the timing lights. The high-speed camera was positioned 3.40 m behind the timing light at a height of 95 cm, so that the timing light beam and the dummy or athlete, respectively, were within the camera's field of view (Figure 7.1). The settings of the high-speed camera were adapted to recommendations according to Pueo[7].

The high-speed camera served as a reference and was used to determine ME of the timing lights. ME was determined by computing the time difference between the signal taken by the timing lights and the actual passing of the middle timber beam and the torso, respectively, detected by the video image.

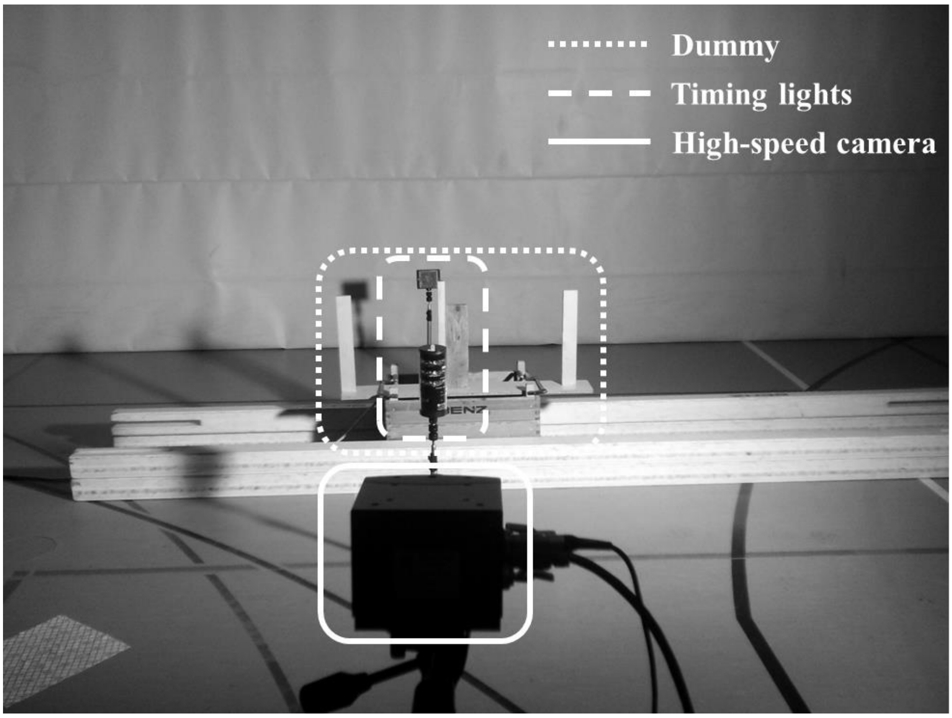


Figure 7.1 High-speed camera and timing light set-up for the controlled condition.

7.3.2 Subjects

Fifteen healthy and physically active male subjects (age, 24.9 ± 1.8 years; height, 182.1 ± 6.8 cm; mass, 76.6 ± 7.9 kg) were recruited for this study. The subjects were of different team-sport backgrounds (e.g., soccer, basketball, handball, volleyball) and were not injured during the investigation. Prior to participation, all subjects gave their written informed consent. The study was exempt from full ethics review by the institutional review board and conducted in accordance with the Declaration of Helsinki (World Medical Association (WMA), 2013).

7.3.3 Methodology

The self-built dummy in the controlled condition consisted of three timber beams (Figure 7.2). The outer beams had a width of 6.5 cm (representing a leading or trailing arm or leg) and the inner beam a width of 12.0 cm (representing the torso), therefore provoking different trigger durations. Ten trials were conducted, with the dummy moving through the timing lights at speeds between 6 and 13 km/h. The timing lights were positioned at a height of 30 cm.

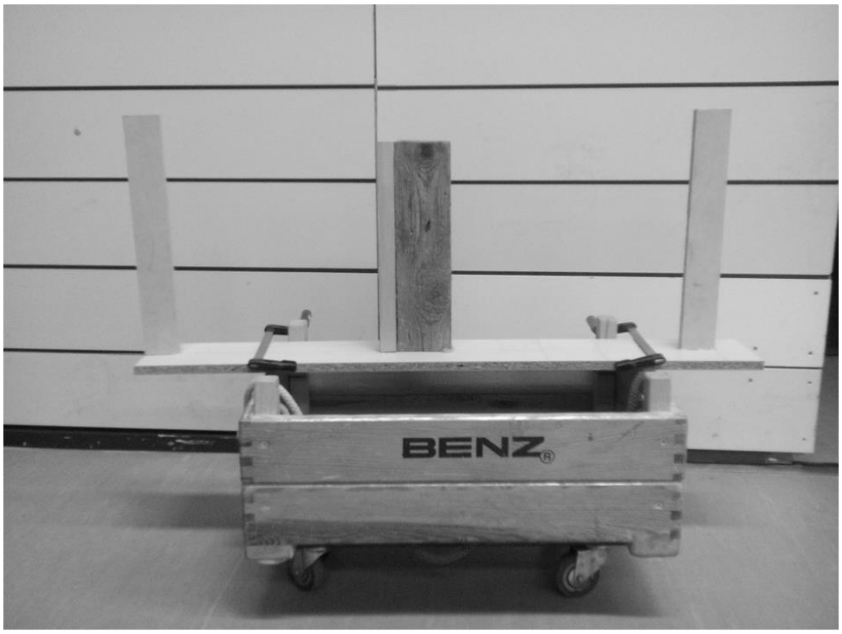


Figure 7.2 The self-built dummy used in the controlled condition.

In terms of the real condition, the athletes performed four sprint starts as well as two all-out sprints over 5 m and 10 m, leading to eight recordings for each subject and 120 trials in total. Only the respective timing light (start, 5 m, 10 m), was filmed by the high-speed camera. In the real condition the timing lights were placed at 95 cm, representing the body close to the height of the center of mass (Altmann et al., 2017; Haugen & Buchheit, 2016). Heights matching approximately hip height have been used in several previous studies (Altmann et al., 2015; Altmann et al., 2017; Bond et al., 2017a; Haugen & Buchheit, 2016).

Prior to the measurements, the athletes completed a standardized 15-minute warm-up protocol including jogging, short accelerations and movement preparation exercises followed by one familiarization trial for each distance. The sprints were performed in the following order: start, 5 m, and 10 m. To ensure full recovery, 2 min rest were provided between trials of the same distance and 3 min rest between the different distances.

Subjects were instructed to sprint as fast as possible over the given distance and to avoid a finishing dip or an early deceleration with regards to the 5 m and 10 m sprints. All participants received a standardized briefing concerning the starting procedures. The starting position was a split start (Figure 7.3). Athletes were allowed to choose the leading foot but were instructed to use the same starting position for all trials. Rocking movements or leaning back prior to sprinting were not allowed. A starting signal was not given. The starting distance from the first timing lights was set at 30 cm (Altmann et al., 2015; Haugen et al., 2015b). The same model of a running shoe (Puma Cell) was provided for all subjects. All tests took place indoors on a PVC running surface.

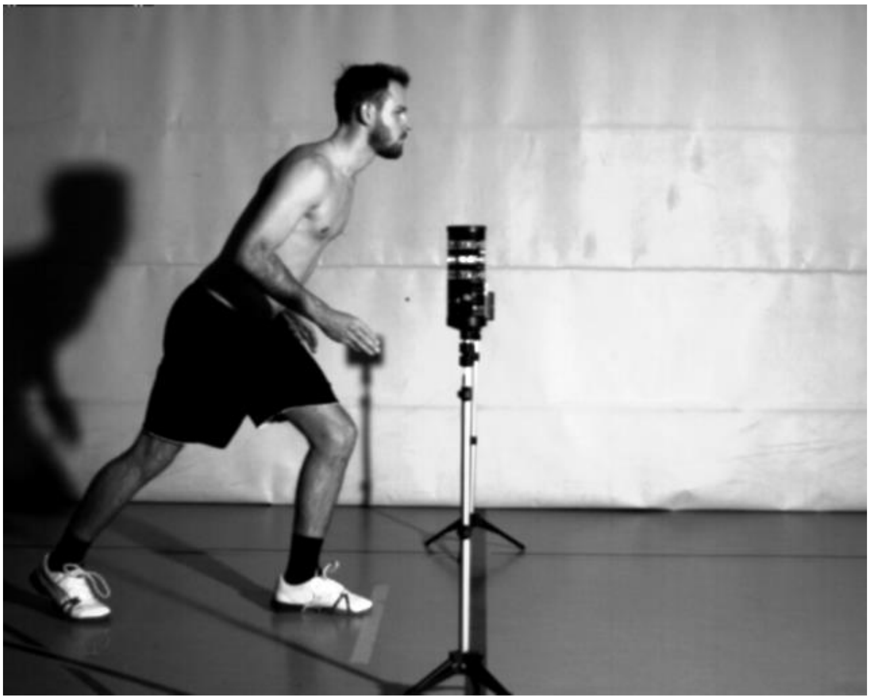


Figure 7.3 Starting position in the real condition.

In both conditions, two main triggers were provoked: the first was achieved manually by pushing a beam with a width of 5.0 cm through the timing lights. This approach ensured, that there was no ME with regards to the first trigger. The second was attained by the passing of the dummy or the athlete, respectively. Consequently, the ME achieved by the recordings of the high-speed camera entirely corresponded to the second triggers.

7.3.4 Data Analysis

The timing started automatically when the timing lights were manually triggered by the abovementioned beam and ended when the dummy (controlled condition) or the athlete (real condition) moved through the timing lights. Following the manufacturer's specifications, the ECP algorithm would always select the beginning of the longest break as the end of each trial.

The video sequences covered by the high-speed video camera were processed using Cam Control at 200 Hz. Reference video times for the dummy (controlled condition) were defined as the time frame between the first manual trigger by the beam and the passing of the middle timber beam of the dummy. Regarding the real condition, reference video times were calculated in two ways: the time interval between the first manual trigger by the beam and a) the passing of the athletes' hip, and b) the passing of the athletes' upper body (from hip to chest).

ME was determined by computing the difference between the time taken by the timing lights and

the video reference, respectively:

$$ME_{\text{Timing Light}} = \text{Timing Light Time}_{(\text{Start, 5 m or 10 m})} - \text{Reference Time}_{(\text{Start, 5 m or 10 m})}$$

All triggers of the timing lights were marked by a light to go out for the duration of the break in the video image. Therefore, it was possible to calculate the break durations and to assign the times recorded by the timing lights to specific triggers (e.g., torso, swinging arm or leg). "False signals" where defined as other parts of the dummy and the athlete than the middle timber beam or the torso, respectively, to trigger the timing lights. This approach allowed to both calculate how many false signals were not eliminated by ECP, and to detect common ME patterns.

Additionally, each video sequence was analysed for the occurrence of the first trigger, which would have been recorded by single-beam systems without ECP. Knowing the trigger taken by ECP, the reduction of ME ($ME_{\text{Reduction}}$) was calculated.

7.3.5 Statistical Analysis

The data were analysed using SPSS statistical software version 22.0 (SPSS, Inc., Chicago, IL). All trials for each condition (controlled and real) were included in the analysis. With regard to ME, maximum values, mean values, standard deviations (SD), as well as 95% confidence intervals (CI) were calculated for the whole sample. Additionally, one-sample t-tests were conducted to determine whether ME significantly differed from 0. As an absolute measure of ME, reliability between athletes was computed by root mean square errors (RMSE) (Bland & & Altman, 1999). Between-trial reliability for each athlete was assessed through SD of ME. Finally, Pearson correlations were run to analyse whether there were relationships between body heights of the athletes and ME.

Normal distribution as an assumption for the here used statistical procedures was given. The significance level for all statistical tests was set a priori to 0.05.

7.4 Results

All data for the controlled condition as well as the real condition can be found in Table 7.1. In the controlled condition, all false signals were eliminated, leading to ME close to 0. Beyond, results revealed that ME were smaller for the upper body reference than the hip reference in the real condition. Furthermore, ME at the start timing light were greater than ME at the 5 m and 10 m timing lights. In 39 out of 60 trials (start), 12 out of 30 trials (5 m), and 7 out of 30 trials (10 m) the first signal was different from the signal taken by ECP, leading to a $ME_{Reduction}$ of 0.102 ± 0.092 s (start), 0.019 ± 0.022 s, and 0.009 ± 0.019 s (10 m) due to ECP.

Regarding the real condition, there were multiple triggers and consequently false signals in most trials. Overall, 80 (start), 16 (5 m), and 12 (10 m) false signals were recorded. False signals at the start timing light (60 trials) including associated error patterns, frequency, amount of false signals not detected, and magnitude of ME can be seen in Table 7.2. Altogether, in the real condition, four false signals were not detected by ECP, whereas in the controlled condition all false signals were eliminated.

Table 7.1 Mean ± SD, 95% CI, Maximum, T-Test, and RMSE for the Controlled Condition as well as the Real Condition (Hip and Upper Body as Reference; Start, 5 m, and 10 m).

Measurement Error	Controlled Condition	Real Condition Hip Start	Real Condition Hip 5 m	Real Condition Hip 10 m	Real Condition Upper Body Start	Real Condition Upper Body 5 m	Real Condition Upper Body 10 m
Mean ± SD	0.001 ± 0.002 s	0.063 ± 0.043 s	-0.010 ± 0.007 s	-0.004 ± 0.006 s	0.007 ± 0.018 s	-0.001 ± 0.004 s	-0.002 ± 0.004 s
95% CI (lower – upper)	-0.000 – 0.003 s	0.039 – 0.087 s	-0.014 – -0.006 s	-0.007 – -0.001 s	-0.003 – 0.017 s	-0.004 – 0.001 s	-0.005 – 0.000 s
Maximum	0.003 s	0.263 s	0.027 s	0.028 s	0.134 s	0.014 s	0.018 s
T-Test (p-value)	0.096	<0.001*	<0.001*	0.019*	0.165	0.284	0.075
RMSE	0.004 s	0.084 s	0.014 s	0.012 s	0.035 s	0.008 s	0.008 s

SD – Standard Deviation; 95% CI – 95% Confidence Interval; Maximum – Maximum Value of all trials; RMSE – Root Mean Square Error; * – statistically significant at a 0.05-level

Table 7.2 False signals at the start timing light (60 trials) caused by other parts of the body than the torso to break the beam, including associated error patterns, frequency, amount of false signals not detected, and magnitude of measurement error.

Error Pattern	**Frequency**	**Not detected**	**Magnitude of Measurement Error**	
			Hip	**Upper Body**
Head breaks the beam	2 times	2 times	~ 0.255 s	~ 0.112 s
Upper body breaks the beam before the hip does	52 times	52 times	~ 0.063 s	–*
Leading arm breaks the beam	70 times**	–	–	–
Permanent break from leading arm to torso	1 time	1 time	~ 0.147 s	~ 0.072 s
Trailing arm breaks the beam	7 times	1 time	~ -0.074 s	~ -0.134 s

* – only considered as a false signal, when using the hip as a reference; ** – including multiple breaks by a leading arm in single trials

Between-trial reliability as expressed through SD of ME (start, 5 m, 10 m) of each athlete was 0.021 s, 0.006 s, 0.003 s for the hip reference, and 0.014 s, 0.002 s, 0.002 s for the upper body reference, respectively.

Pearson's r between athletes' body height and ME (start, 5 m, 10 m) were -0.043 ($p = 0.880$), 0.038 ($p = 0.892$), -0.578 ($p = 0.024$) for the hip reference, and -0.376 ($p = 0.168$), 0.339 ($p = 0.217$), -0.725 ($p = 0.002$) for the upper body reference, respectively.

7.5 Discussion

The purpose of this study was to investigate if timing lights employing ECP algorithms are able to eliminate or to reduce ME on the basis of high-speed video analysis, both in a controlled and in a real sprint condition. As described before, all trials were used for analysis in order to comprehensively capture ME and describe associated error patterns.

With regard to the controlled condition, ECP eliminated false signals (outer timber beams) in each single case. The outer beams of the dummy simulated a leading or trailing arm or leg, respectively. The inner beam, which represented the torso, was almost twice as wide and provoked a longer break duration. Therefore, this break was identified by ECP as the correct signal. Consequently, the ME difference against 0 reached no statistical significance, as proven through the one-sample t-test. The very small ME of 0.001 ± 0.002 s can likely be attributed to the different sampling rates between timing lights (1,000 Hz) and the high-speed camera (200 Hz).

Relating to the real condition, two different reference points were used (hip and upper body). ME was higher in general for the hip as compared to the upper body. Consequently, the t-test revealed that ME for the hip reference differed significantly from 0 at all distances (start, 5 m, and 10 m), while ME for the upper body did not. Supporting findings in the literature, for both reference points highest ME was detected at the start timing light with ME decreasing by greater distances (e.g., 5 m and 10 m (Altmann et al., 2017; Bond et al., 2017a; Haugen et al., 2012a)). This can be explained by higher running speeds and a more upright body position with increasing running distances (Bond et al., 2017a).

As illustrated in Figure 7.3, athletes adopted a forward lean in their starting position. Therefore, the start timing light registered a long break, beginning with the trigger of the upper body and ending when the athletes' dorsum left the light beam. Consequently, ME regarding the upper body reference was close to 0, as long as there were no false signals not detected by ECP, which will be discussed later. Conversely, ME for the hip reference was 0.063 ± 0.043 s. Due to leaning forwards, the hip moved through the timing later than the upper body, causing higher ME. Moreover, the mentioned forward lean differed between athletes, leading to an RMSE of 0.084 s for the hip reference.

False signals were defined as other parts of the body than the torso to break the beam and occurred in almost all trials. Concerning the start timing light (60 trials), four false signals were not detected by ECP (Table 7.2). In two cases, the same athlete had a very distinct forward lean, resulting in the head to break the beam. The associated ME was 0.255 s and 0.112 s for the hip and the upper body reference, respectively. In addition, one trial occurred where there was one permanent break from a leading arm to the torso (ME of 0.147 s and 0.072 s). The last false signal not detected by ECP was a trailing arm, which caused a longer trigger than the torso. In this scenario, ME was smaller for the hip reference (-0.074 s) than for the upper body reference (-0.134 s). However, some of the false signals like the head breaking the beam were somewhat obvious. Hence, a coach might probably notice the error visually, declaring the trial as invalid.

In terms of the appropriateness of the longest break criterion, some researchers assume that in certain cases a leading thigh could provoke longer breaks than the torso (Haugen & Buchheit, 2016). In fact, while this scenario did not occur in the 120 trials of this study (60 x start, 30 x 5 m, 30 x 10 m), during pilot testing in one out of 60 trials at the start timing light, the break caused by a leading arm was longer than the torso's break (ME of 0.113 s and 0.033 s). Hence, the aforementioned concerns are not unjustified. Certainly, the occurrence seems to be extremely rare.

The finding, that ECP did not detect four false signals is in contrast with research of Earp & Newton (2012). They found ECP to eliminate all false signals. A limitation of the study mentioned is that the correct signal was not captured by motion or video analysis. Instead, they defined the correct signal as the longest break. As ECP always took the longest trigger, authors concluded that the algorithm eliminated all false signals. In the present study, the multiple signals could be associated to different parts of the body triggering the timing lights. Following the results, the longest break was the correct signal in most, but not all cases. This finding is new to the literature.

Inspection of the video sequences revealed, that the signal taken by ECP was different from the first trigger, which would have been recorded by single-beam systems without ECP, in 23% to 65% of trials, depending on the distance. $ME_{Reduction}$ was very high at the start and got lower with increasing distance, highlighting the superiority of ECP towards conventional single-beam systems. These results correspond to and can be integrated into findings in the literature:

Compared to a previous study (Altmann et al., 2015), in which ME for single-beam timing lights without ECP placed at a height of 100 cm was 0.180 s at the start, the present results with ECP indicate a dramatic reduction of ME. In another study (Altmann et al., 2017) using the same timing light settings, authors found ME of 0.057 s and 0.025 s at 5 m and 10 m, respectively. Again, the ME in the present study are markedly lower, independent from the reference point chosen. In contrast, research by Bond et al. (2017a) using timing lights employing ECP at 0.91 m height revealed ME of 0.10 s at the start and 0.02 s at 9.14 m. However, results are not directly comparable as investigators used sacral-based video timing as a reference.

As mentioned before, greatest ME at the start timing light were due to extensive forward leaning. In order to minimize ME when using the hip reference, athletes should adopt a more upright body position. While this approach might further improve measurement accuracy and reliability, there remain concerns about the closeness to reality. From a biomechanical point of view, the center of mass must be positioned anterior to the base of support to initiate forward movement (Johnson et al., 2010). Hence, most athletes intuitively adopt this forward lean with different degrees of markedness. Due to the variability in posture between athletes, hip-based comparisons might be treated with caution on the basis of this measurement set-up. Otherwise, forward lean within a given athlete seems to be reliable and therefore allowing for comparisons over several trials of that athlete (Bond et al., 2017a). This was also supported by low SD of ME between trials of a given athlete in the present study.

Bond et al. (Bond et al., 2017a) reported positive correlations between body height and ME. In the present study, significant correlations between athletes' body height and ME were only found at 10 m (r = -0.578 and r = -0.376 for the hip reference and upper body reference, respectively). However, as most of ME recorded at this distance were below 0.01 s, this finding has no practical implication.

Although athletes' height did not seem to influence results, other populations (e.g., children and youths) remain to be investigated. Until then, no conclusions about generality can be drawn.

7.6 Practical Applications

Eliminating false signals in almost all sprint trials, single-beam timing lights employing ECP can be recommended for coaches and researches to measure short sprints. As ME decreases with increasing running distance, in particular interval times (e.g., 5–10 m) (Haugen et al., 2014c) or maximum sprinting velocity (Roe et al., 2017) could be measured with excellent accuracy. However, to confirm this assumption, further studies employing the here used timing system are advisable.

Forward lean of the starting position varied between athletes. Therefore, when wishing to measure a point near the center of mass (e.g., hip), comparisons between athletes should be treated with caution. However, since posture within a given athlete was reliable, it is justified to compare several trials of this athlete. If coaches want to measure the movement of the hip and consequently allowing for comparisons between athletes, a more upright body position should be adopted at the start. Indeed, possible biomechanical disadvantages due to this posture must be taken into consideration.

7.7 Conclusions

The present study shows that single-beam timing lights employing ECP worked in both, the controlled and the real condition, eliminating almost all false signals. ECP dramatically improved measurement accuracy at the start, 5 m, and 10 m compared to conventional single-beam systems (Altmann et al., 2015; Altmann et al., 2017). Therefore, systems such as Smartspeed Pro can be recommended for measuring short sprints. In line with previous research, the highest potential for imprecise measurements is in the start (Altmann et al., 2015; Altmann et al., 2017; Bond et al., 2017a; Haugen et al., 2012a). Therefore, the best starting procedure for both measurement accuracy and biomechanical variables have yet to be examined. This study supports the relevance of precisely reporting measurement set-up for monitoring sprint performance.

8 General Discussion

Speed is considered an integral aspect of overall soccer performance. Therefore, speed testing has become a standard component of performance assessment within this sport. Given the complexity of speed in soccer and the importance of valid and reliable tests as well as associated methodological aspects, the purpose of the present thesis was twofold:

I. To comprehensively review the available literature on speed tests used in soccer with special reference to the tests' validity and reliability.

II. To investigate the effects of starting distance, timing light height, and timing light type with respect to speed testing results itself and their validity and reliability.

These two aims were addressed by a systematic review (Paper I) and four original investigations (Paper II to V). This chapter will summarize the main findings and, based on existing literature, discuss them both in a specific and wider context. Furthermore, the limitations of the research included in this thesis will be addressed and recommendations for future research will be given. Finally, practical applications for both researchers and practitioners involved in speed testing will be provided.

8.1 Main Findings

8.1.1 Review (Paper I) – Applications to Soccer

Being an important prerequisite for overall performance, speed in soccer can be considered as multifaceted, including both physical and perceptual-cognitive components (Faude et al., 2012; Jeffreys et al., 2018; Paul et al., 2016). As a result, a plethora of different speed tests have been developed and introduced into soccer (Haugen et al., 2014a; Paul & Nassis, 2015a). According to the various demands related to speed during soccer matches, these tests can be categorized into linear sprinting, change-of-direction sprinting, repeated sprinting, agility, and combinations of these categories. In this context, being valid and reliable is mandatory for such tests to be implemented in performance assessments (Currell & Jeukendrup, 2008). Therefore, the systematic review according to the PRISMA statement (Moher et al., 2009) included in this thesis aimed to give a comprehensive overview of speed tests used in soccer, thereby focusing on the tests' validity and reliability.

The main findings of the review can be summarized as:

- There is no single test that is able to examine all aspects of speed. Instead, a holistic approach should incorporate specific tests that address the speed skills relevant to soccer.
- In terms of linear sprinting, repeated sprinting, change-of-direction sprinting, and combinations of these skills, there exist several valid and reliable tests. There is a lack of an

accepted gold-standard test in most of the categories. Measures of fatigue such as percent decrement scores should be treated with caution.

- There is a paucity of research investigating the criterion validity of speed tests in soccer. Furthermore, a valid and reliable soccer-specific agility test does not exist for adult players.

Besides these findings, which are discussed in detail in Paper I, there are some further aspects that should be considered when dealing with speed testing in soccer. With regards to validity, only the construct validity (the ability of a test to discriminate between performance levels) and the criterion validity (the relationship between test results and match parameters) were investigated in the systematic review. Conversely, the ecological validity of speed tests was not addressed in particular. To account for ecological validity, the tests should reflect the specific demands of match-play (Beavan, 2019; Ericsson & Smith, 1991). However, based on the speed demands during match-play discussed in *Chapter 2.2*, the extent to which the tests in the abovementioned categories reflect these demands differ markedly. Consequently, the ecological validity of the tests in each category is discussed in the following.

Linear-sprint tests

By using distances of up to 30 or 40 m, linear-sprint tests reflect the match demands in most cases (Di Salvo et al., 2010; Haugen et al., 2014a). Thereby, the total test distance is commonly split into several phases (Haugen et al., 2013a; Rumpf et al., 2016; Turner et al., 2011): acceleration (5, 10 or 20 m), maximal speed (30 or 40 m), and maintenance of maximal speed (> 40 m). However, the latter distance occurs rarely during matches and, therefore, such distances are tested scarcely (Iaia et al., 2015; Sonderegger et al., 2016). Altogether, it can be stated that a high ecological validity is evident for most of the linear-sprint tests included in the systematic review. In order to even improve the closeness to typical match actions, one could replace the commonly applied standing start with a rolling start, as players are mostly already in motion when initiating a sprint (Rehhagel, 2011; Varley & Aughey, 2013). However, the necessity for controlling the rolling start velocity between players and reduced reliability are drawbacks of this approach (Sonderegger et al., 2016). Consequently, in the vast majority of the identified studies, a standing start was applied.

Repeated-sprint tests

Following the traditional assumption that repeated sprints with only short recovery phases represent a key performance measure in soccer (Girard et al., 2011), a number of repeated-sprint tests has been introduced over the years (Taylor et al., 2016). However, more recent investigations demonstrated that bouts of repeated sprints occur rarely during matches, especially during those of male players (Datson et al., 2018; Schimpchen et al., 2016; Varley et al., 2014). In addition, such bouts usually comprise only 3 to 4 sprints (Carling et al., 2012; Gabbett & Mulvey, 2008; Schimpchen et al., 2016), rather than 6 to 10 sprints frequently applied in repeated-sprint tests (e.g., Dellal & Wong (2013); Ingebrigtsen et al. (2012); Wong et al. (2012)). From the above-described, it seems obvious that there is a discrepancy between current test designs and usual match demands.

Nevertheless, it was argued that repeated-sprint tests reflect the most demanding phases of a match. Thus, existing tests might provide information about how well players are prepared for „worst-case scenarios“ (Carling et al., 2012; Gabbett, 2010).

Change-of-direction sprint tests

There is scarce research addressing changes of directions during match-play in general (Bloomfield et al., 2007; Nedelec et al., 2014; Robinson et al., 2011; Taylor et al., 2017). Only two studies focused on changes of direction during sprinting (Rehhagel, 2011) and high-intensity running (Ade et al., 2016), respectively. Albeit, the studies available demonstrate that changes of direction occur frequently during soccer matches and approximately half of all sprints and high-intensity runs incorporate at least one directional change (Ade et al., 2016), usually with a wide angle (up to 90°) (Bloomfield et al., 2007; Nedelec et al., 2014; Robinson et al., 2011). It should be noted that in another study of Bloomfield et al. (2008), the sequence *sprinting – changing direction – sprinting* occurred less frequent than *jogging/running/shuffling – changing direction – sprinting*. Unfortunately, the exact definition of sprinting was not provided in this study. Nevertheless, with respect to change-of-direction sprint testing, it seems reasonable that directional changes should follow on short linear acceleration phases (e.g., 5 m), where higher sprinting velocities are not yet achieved. In contrast, many change-of-direction sprint tests used in soccer, e.g., the 505 test and the T Test (Emmonds et al., 2017; Miller et al., 2011; Rey et al., 2017), do not mimic the above-described demands, indicating a lack of ecological validity. More specifically, the number of directional changes are considerably higher (T Test) and the respective angles are sharper than commonly during match-play (both 505 test and T Test). This circumstance might be explained by the fact that many tests have been developed for other sports such as American Football and have later been adapted to soccer without modification. However, as the determining factors of distinct change-of-direction tests differ according to their characteristics (Chaouachi et al., 2012; Kadlubowski et al., 2019; Sporis et al., 2010), such tests might not always investigate aspects that are relevant to soccer.

Agility tests

Sprints and changes of direction during soccer matches are not always preplanned but occur in response to a stimulus (Paul et al., 2016; Young et al., 2015). Examples are evading an opponent, intercepting or reaching a pass, and creating or closing space between oneself and an opponent (Ade et al., 2016). Summarized under the term agility, in such situations players are required to anticipate in order to make fast and accurate decisions. Taking a look at the physical aspects of agility, in line with change-of-direction sprint tests, it becomes apparent that many existing tests incorporate more and sharper directional changes compared to common match situations (McGawley & Andersson, 2013; Pojskic et al., 2018). Relating to perceptual-cognitive aspects, the non-specific generic stimuli (e.g., arrows or flashing lights) applied in some studies (McGawley & Andersson, 2013; Pojskic et al., 2018) do not mimic typical situations during matches and do not allow the players to deploy there anticipation and decision-making skills (Young & Farrow, 2013). Only one study was identified that incorporated soccer-specific movements of a tester as stimuli (Bullock et al., 2012). However, the respective agility test was part of a complex test including a number of other tasks such as linear sprinting and passing. Therefore, at this point of time, there does not exist an isolated agility test in soccer that accounts for ecological validity in terms of movement patterns and type of stimulus.

Combinations

Tests categorized as combinations incorporate characteristics of two or more of the abovementioned categories. Most of these tests combine elements of repeated-sprint tests and change-of-direction sprint tests (Abrantes et al., 2004; Brahim et al., 2016; Impellizzeri et al., 2008; Rampinini et al., 2007a; Rampinini et al., 2009), while few tests also comprise features of agility tests (Di Mascio et al., 2015; Wragg et al., 2000). As a consequence, these tests commonly suffer from the same discrepancies (e.g., number and angles of directional changes, number of repetitions, type of stimuli) compared to match demands as tests of the other categories. The only test in this category, for which a design based on match analysis has been explicitly stated, is the reactive repeated-sprint test (Di Mascio et al., 2015). Unfortunately, this only refers to physical aspects (e.g., total distance, directional changes), while the stimulus used to indicate the directional changes remains generic (flashing light).

To sum up, high ecological validity can be attested only for linear-sprint tests. In contrast, many of the change-of-direction sprint, repeated-sprint, agility tests, and combinations lack game specificity at least to some extent. Indeed, one could argue that agility tests, for example, possess a higher ecological validity as linear-sprint tests per se (irrespective of the exact test design), as they not only assess physical but also perceptual-cognitive aspects of speed. However, the aim of this subchapter was not to compare the ecological validity between the test categories but rather the comparison of the tests with their specific designs within these categories.

As stated earlier in this thesis, it is recommended to develop soccer-specific speed tests on the basis of match analysis (Bradley et al., 2018; Jeffreys et al., 2018). However, the more game-realistic the test, the more influencing factors exist that make test standardization more complicated. As a consequence, it is known that the test complexity can directly impact the test reliability (Pojskic et al., 2018). Therefore, when designing or applying a test, closeness to the match (ecological validity) and test standardization must be weighed against each other.

8.1.2 Original Research (Paper II to V) – Methodological Aspects

A number of methodological aspects need to be considered when integrating speed tests into performance assessments (Haugen & Buchheit, 2016). Given that the performance differences between elite athletes are usually small, and that changes in speed performance during a period of several years represent only a few percents at this level (Haugen et al., 2015a; Haugen, 2017), the procedures and equipment used during speed tests must permit valid and reliable measurements. More specifically, when the performance of different athletes should be compared with each other, both an adequate validity and reliability are mandatory. Conversely, when performance changes should be tracked within this population (e.g., before and after a training intervention), the main focus should be on reliability (for detailed information on this topic, see *Chapter 8.3.2*).

Taking a look at the timing technology used, timing lights have been reported to be the most common (Rumpf et al., 2011). This finding is supported by the systematic review included in this thesis (Paper I). Specifically, in approximately 95% of the studies that were taken into account, timing lights were applied. Despite the frequent use of timing lights, questions remain to whether different methodological aspects such as starting distance and timing light height affect sprint times and the validity and reliability of measurement over various distances. Moreover, it is unclear whether ECP is able to eliminate false signals which are common when utilizing conventional single-beam timing lights. Therefore, the four original research articles in the present thesis aimed to investigate the effects of starting distance, timing light height, and timing light type with respect to speed testing results itself and their validity and reliability.

The general methodology in all original studies was similar. Timing lights were used to analyze the effects of starting distance, timing light height and timing light type on the speed testing results and their reliability. In addition, high-speed video recordings were utilized as a reference method to validate the results gained by the timing lights. As all original research articles focused on methodological aspects of speed testing using timing lights and applied a similar general methodology, the findings from these articles can be synthesized.

While all four articles highlight the influence of methodological aspects during speed testing, their main findings can be summarized in the following statements:

- Different starting distances affect sprint times but not measurement errors over a 5-m distance
- Single-beam timing lights cannot be recommended over 5-m and 10-m distances
- Single-beam timing lights can be recommended over a 30-m distance and during flying sprints
- Sprint times of 5-m, 10-m, and 30-m distances gained by different timing light heights are not comparable
- Single-beam timing lights using ECP reduce false signals and can be recommended over 5-m and 10-m distances

In the following, these statements will be briefly discussed.

Different starting distances affect sprint times but not measurement errors over a 5-m distance

Paper II revealed that the sprint times over 5 m recorded by applying a starting distance to the initial timing light of 0.5 m were on average 0.04 s faster than a 0.3 m starting distance. Based on a higher acceleration when passing the initial timing light, starting 1.0 m in front even yield 0.10 s faster times. From these results, it seems obvious that results gained by the use of different starting distances are not interchangeable. This finding has implications for both the comparison of different studies as well as to multiple measurements of one team or one athlete, respectively. More recent research with a comparable study design supports this finding (Haugen et al., 2015b). Moreover, in that study, the authors introduced correction factors aiming to allow for comparisons of different starting distances. However, based on the relatively low common variance (5–56%) shared between 5-m times gained by different starting distances, Paper II does not support the use of correction factors.

A second important finding of Paper II was that the measurement errors at the starting timing lights comprised approximately 16% of the 5-m sprint times and differed only slightly between starting distances. This finding indicates that no starting distance is superior to another in terms of validity (expressed, among other measures, through the magnitude of measurement errors). Consequently, the decision of which starting distance to employ could be based on reliability of sprint times as it was previously done in the case of different starting positions (Duthie et al., 2006). Findings of Paper II indicated that a starting distance of 0.3 m was more reliable (ICC = 0.84) than distances of 0.5 m (ICC = 0.65) and 1.0 m (ICC = 0.64). Consequently, when aiming to track changes in performance during 5-m sprints, starting 0.3 m in front of the first timing light can be recommended with the set-up applied in that study (single-beam systems mounted at a height of 1.00 m).

Single-beam timing lights cannot be recommended over 5-m and 10-m distances

Among other questions, Paper II and Paper III addressed the validity of sprint times over 5 m and 10 m using single-beam timing lights. Regardless of the timing light height used (0.25 m, 0.64 m, and 1.00 m), low validity was evident. This finding was indicated by high mean differences between timing lights and high-speed video recordings (4.5–16.5% of the time recorded) and low to moderate ICC values (0.01–0.40). In line with this, high 95% LOA (-0.27–0.09 s and 0.04–0.19s for 5 m; -0.28–0.08 s and 0.04–0.13 s for 10 m) highlight the existence of both systematic and unsystematic bias due to measurement errors. Practically speaking, a rather slow athlete with a low measurement error might obtain a better result via timing lights than a faster athlete with a high measurement error. This makes it extremely difficult to compare the performance of different athletes.

The presence of considerable mean differences between sprint times recorded by single-beam timing lights and a reference system (e.g., motion capture, high-speed video) has also been reported in the literature. More specifically, Whitting et al. (2013) reported a difference of 11% between 6-m sidestep times achieved by single-beam timing lights and a motion-capture system, and (Bond et al., 2017a) found a time difference of 7.8% between single-beam timing lights and high-speed video analysis in a 9.14-m sprint. As already stated, the reason for these differences is that single-beam timing lights can be triggered prematurely by swinging arms or legs (i.e., false signals), which lead to measurement errors and the time differences described above.

To sum up, based on the acceptable reliability, the set-up described in Paper II (single-beam timing lights, starting distance 0.3 m, height 1.00 m) can be advised only for tracking changes in performance during 5-m sprints (see above). Conversely, because of the low validity, which was present irrespective of the set-up applied in Paper II and Paper III, single-beam timing lights are not recommended for timing sprints over 5 m and 10 m, when aiming to compare the performance between athletes.

Single-beam timing lights can be recommended over a 30-m distance and during flying sprints

In addition to the 5-m and 10-m sprint times, the study in Paper III also investigated the validity of 30-m sprint times using single-beam timing lights. In contrast to the shorter distances (5 m and 10 m), higher validity of the single-beam system was evident in relation to the high-speed video recordings. While there was still a systematic bias, this bias was of a rather small magnitude (1.5–2.4%) in relation to the total sprint time. Furthermore, large to nearly perfect Pearson's r and ICC values (r = 0.85–0.91; ICC = 0.66–0.87) as well as relatively low 95% LOA (-0.28–0.07 s; 0.01–0.12 s) in relation to the high-speed video recordings indicate rather small unsystematic bias due to measurement errors fort both systems. This was especially true for the timing light system 2 (mounted at 0.25 m at the start and at 1.00 m at all following timing lights). While the reliability of 30-m sprint times was not investigated in Paper III, high levels of reliability (ICC = 0.97) have been reported for this distance in the literature when applying single-beam timing lights and a starting distance of 0.3 m (Rebelo et al., 2013).

Paper IV used the same raw data as Paper III, thereby analyzing the 10–30 m interval (as referred to a flying 20-m sprint) in depth. The results suggest a high validity regarding the velocity obtained in the flying 20-m sprint in relation to the analysis of the high-speed video recordings. This finding was highlighted by low systematic bias (> 0.1%), nearly perfect Pearson's r and ICC values (r = 0.99; ICC = 0.97–0.98) as well as low 95% LOA (-0.06–0.12 s; -0.01–0.12 m/s) for both systems. In addition to the high validity, high reliability regarding the velocity obtained during the three trials, which the athletes performed during the study, was present (ICC = 0.89).

In line with this finding, research by Bond et al. (2017a) and Haugen et al. (2014b) yielded similar results. That is, the sprint times gained by single-beam timing lights differed only by 0.8% from high-speed video recordings during the second half of a 18.29-m sprint (Bond et al., 2017a) and were equal to the times gained by dual-beam timing lights during the second half of a 40-m sprint (Haugen et al., 2014c), respectively.

The high validity of 30-m or flying 20-m sprint times in comparison to short distances (e.g., 5 m and 10 m) can be explained by different body postures and running velocities when passing the respective timing lights. While athletes commonly adopt a pronounced forward lean at the start, the body becomes more upright with increasing running distance (Bond et al., 2017a; Cronin & Templeton, 2008; Haugen et al., 2014c). This leads to smaller time differences between the triggering of the timing lights when triggered by the torso and the signal captured by the high-speed camera (commonly at the hip). Moreover, because of higher running velocities, false signals caused by swinging arms or legs yield smaller measurement errors with increasing running distance at a given horizontal distance (e.g., 0.2 m) between an arm or leg and the torso (see Paper III).

Consequently, based on the existing research and the results obtained in Paper III and Paper IV, single-beam timing lights can be recommended as timing systems over a 30-m distance and for flying 20-m sprints. Due to the high validity and reliability, these distances can be used for both comparing performance between athletes and tracking performance changes.

Sprint times of 5-m, 10-m, and 30-m distances gained by different timing light heights are not comparable

Another aim of the study presented in Paper III was to investigate whether timing light height affects sprint times over distances of 5 m, 10 m, and 30 m. For this purpose, two systems were installed (system 1: all timing lights at a height of 0.64 m; system 2: starting timing light at 0.25 m, all following timing lights at 1.00 m) to simultaneously capture sprint times over the aforementioned distances. The results showed that the times gained by the two systems differ from each other, with system 2 measuring shorter times for each distance compared to system 1 (5 m: 0.20 s, 17.8%; 10 m: 0.18 s, 9.7%; 30 m: 0.17 s, 3.9%). The finding that different timing light heights yield different sprint times can be confirmed when integrating the results of Paper II, where a timing light height of 1.00 m was used both at the start and at 5 m. With respect to the 0.3-m starting distance, which was also applied in Paper III, the mean time of the athletes for 5 m was 1.09 s. This corresponds to a 0.05 s (4.3%) shorter time compared to system 1 and a 0.15 s (14.3%) longer time compared to system 2 as applied in Paper III. Although the sample was not exactly the same in these two studies, the sample characteristics were very similar (male team-sport athletes at an amateur level, similar age and anthropometric characteristics). Therefore, comparisons between the two studies seem to be justified. Further support for the assumption that timing light height affects sprint times is given by the studies of Cronin & Templeton (2008) and Bond et al. (2017a). The first study (Cronin & Templeton, 2008) found timing lights mounted at hip height to record 0.07 s shorter 10-m and 20-m sprint times than timing lights at shoulder height when using dual-beam systems. The second study (Bond et al., 2017a) applied single-beam timing lights employing ECP and reported 0.05 s and 0.08 s shorter times over a 9.14-m distance when mounting timing lights at 0.61 m compared to 0.91 m and 1.21 m, respectively.

With regards to Paper III, only trivial to moderate ICC values between system 1 and system 2 were evident (5 m: -0.03; 10 m: 0.13; 30 m: 0.49). This indicates the existence of not only systematic (expressed through high mean differences, see above) but also of unsystematic bias between results gained by different timing light heights. These biases can be explained by different parts of the body triggering the timing lights, which was also confirmed by analysis of the high-speed video recordings. For example, at the start, the timing lights are triggered by the back foot (timing light height: 0.25 m), the knee (timing light height: 0.64 m), and the torso (timing light height: 1.00 m), respectively. As a result, sprint times are shorter for a height of 0.25 m compared to 0.64 m and 1.00 m. In addition, the specific starting and running technique differs between athletes (e.g., forward lean of the upper body, movements of the arms), which further influences the point of time and by which part of the body the timing lights are triggered (Bond et al., 2017a). This factor mainly accounts for the unsystematic bias found in Paper III and makes comparisons between different timing light heights impossible. Therefore, as with different starting distances, the use of correction factors to allow for comparisons is not advised.

Single-beam timing lights using ECP reduce false signals and can be recommended over 5-m and 10-m distances

One of the main findings of Paper II and Paper III was that conventional single-beam timing lights do not provide a satisfactory validity of sprint times over short distances (5 m and 10 m), even when modifying the starting distance and the timing light height. Based on this finding, Paper V investigated if single-beam timing lights employing ECP are able to eliminate false signals and to provide valid and reliable results during short sprints. For this purpose, a controlled condition (dummy) and a real condition (athletes performing 5-m and 10-m sprints) were investigated using single-beam timing lights with ECP and a high-speed camera that served as a reference.

Results revealed that single-beam timing lights employing ECP eliminated all false signals in the controlled condition. Therefore, it can be concluded that ECP generally works. During the real condition, multiple triggers (false signals), predominantly due to swinging arms, occurred in most of the trials. However, ECP was able to detect and eliminate almost all of these false signals – in sum, 104 out of 108 were detected.

Indeed, the problem caused by the forward lean of the athletes at the start timing lights (see also Paper II and Paper III) could not be solved through ECP, as the upper body provokes only one long signal when passing the timing lights. The consequent time difference (or measurement error) between the triggering of the timing light and the passing of the athletes‘ hip was negligible at the 5-m and 10-m timing lights. In contrast, at the start, the measurement error was considerably higher (0.06 ± 0.04 s). In addition, the relatively high SD (0.04 s) in relation to the mean measurement error (0.06 s) indicates that the forward lean differed between athletes at the start. Based on this, between-athletes comparisons should be treated with caution. Nevertheless, a measurement error at the start of 0.06 s reflects a dramatic reduction of about 0.10 s compared to the signal conventional single-beam timing lights would have taken. This value could be further reduced by instructing the athletes to adopt a more upright starting position. By this means, both the measurement error itself and its between-athlete variability would probably decrease. However, possible biomechanical disadvantages of an upright upper body at the start should be taken into account when adopting this approach (Johnson et al., 2010).

Conversely, when accepting the upper body as a reference point, as it is stated in the competition rules of the International Association of Athletics Federations (IAAF, 2017), the measurement error was

< 0.01 s at all timing lights, thereby allowing for a valid measurement of short sprints via the system used in this study. As the forward lean within a given athlete was relatively consistent independent from the reference point chosen (expressed through the SD of the measurement error within athletes which was 0.01–0.02 s at the start and < 0.01 s at 5 m and 10 m, respectively), tracking performance changes of a given athlete seem possible using single-beam timing lights with ECP.

The study presented in Paper V adds to the current body of knowledge regarding timing lights with ECP in two ways. Firstly, not only the frequency of false signals was quantified (Earp & Newton, 2012), but also the magnitude of each false signal (expressed through measurement errors) with its associated error pattern. Secondly, it was not only confirmed that ECP always took the longest break (Earp & Newton, 2012), but it was also examined if the longest break was the correct one in each scenario. Out of the 108 cases where false signals occurred, the longest break was not the correct one in only 4 cases (e.g., the head breaks the beam and causes a longer signal than the torso; one permanent break from a leading arm to the torso, the trailing hand breaks the beam and causes a longer signal than the torso; see also *Chapter 2.3.1*, Figure 2.4 b and c). Therefore, the assumption of some researchers that the longest break criterion should be used with caution (Bond et al., 2017b; Haugen & Buchheit, 2016) can be disconfirmed for the vast majority of scenarios. Moreover, some of the abovementioned scenarios (e.g., the head breaks the beam), may already be identified by experienced coaches and researchers through visual inspection and, consequently, be declared as invalid.

To sum up, bearing the implications of leaning forwards (especially at the start) in mind, single-beam timing lights employing ECP can be recommended over 5-m and 10-m distances by eliminating almost all false signals.

This subchapter discussed the main findings of the studies included in this thesis. However, these findings should be interpreted in light of the studies' limitations. These limitations – along with suggestions for potential future research questions – will be addressed in the following subchapter.

8.2 Limitations and Future Research

In the following, the limitations of the studies included in this thesis and recommendations for future research will be discussed.

8.2.1 Review (Paper I) – Applications to Soccer

Regarding the systematic review (Paper I) dealing with speed testing in soccer, some important limitations and recommendations for future research have been already addressed in the paper itself. However, there are some additional aspects that should be considered and such that have yet been referred to, but deserve a more in-depth discussion.

An important limitation of the systematic review is that it does not account for position-specificity. As indicated in *Chapter 2.2* of this thesis, the speed demands during matches vary by playing position (e.g., central vs. wide positions) (Ade et al., 2016; Bush et al., 2015a). Therefore, the investigation of position-specific tests seems plausible. However, there is only scarce research available that addresses this topic (Slimani & Nikolaidis, 2017). In addition, the introduction of position-specific tests could also be questioned, as players not seldom are able to play in several positions. From a practical point of view, a researcher or coach would have to decide which positional test to choose, or even would have to conduct several tests with such players. Moreover, positional demands have shown to be affected by team tactics which can markedly differ between teams (Bradley et al., 2011; Bush et al., 2015b). In turn, this could alter the optimal test design for a specific position. As a consequence, the development and implementation of position-specific tests are associated with a number of difficulties.

Based on the findings obtained in the original studies of this thesis, an additional item considering the reporting of methodological aspects was added to the quality assessment checklist in the systematic review. Moreover, in order to account for an appropriate timing technology being used in the studies included in the review, studies applying stopwatches were excluded (Haugen & Buchheit, 2016). However, it was not particularly investigated if the influence of methodological aspects (e.g., timing technology (timing lights, radar, high-speed video, GPS), starting position, starting distance, surface) is reflected by the findings of the respective studies included in the review. Such an approach might be promising, e.g., in order to analyze if the studies using conventional single-beam timing lights generally report lower reliability and validity compared to studies where dual-beam systems or single-beam systems employing ECP have been applied.

Considering the construct validity of the tests, it would be of great interest which the „most valid“ test is for each category. At first sight, this question could be answered by comparing the effect sizes between playing levels obtained in the respective studies. However, this approach might be biased as the playing levels that were compared with each other differed between investigations: While one study compared professional and recreational players (Russell et al., 2010), another study might compare starters and non-starters of the same professional team (Risso et al., 2017). While not statistically proven, it seems that the effect sizes increase with the „gap“ between the playing levels examined. As a consequence, comparability between studies is limited and, therefore, it was not possible to determine the „most valid“ tests, which could have been a highly applied finding of the review.

In order to appropriately address this issue, future studies investigating a number of tests in a specific category (e.g., change-of-direction sprint tests: 505 test, T Test, and zig-zag test) as well as a range of playing levels (e.g., recreational vs. amateur vs. semi-professional vs. professional) are recommended. Especially the comparison between first league and national team players as well as starters and non-starters from the same professional team seems promising, as these playing levels are commonly the setting where speed tests are regularly applied (Haugen & Seiler, 2015).

To reinforce two aspects already mentioned in the systematic review, the development of soccer-specific agility and repeated-acceleration tests is strongly advised. Regarding agility, there exist promising results in terms of validity and reliability from other team sports such as Australian football, basketball or rugby league (Paul et al., 2016). Moreover, the growing importance of agility in soccer is underlined by Wallace & Norton (2014) who stated that the modern game style led to increased anticipatory and decision-making demands during matches. To account for ecological validity, such tests should be designed on the basis of match analysis (e.g., total distance, number and angles of directional changes, type of stimuli). As earlier stated, sequences of repeated sprints occur rather infrequent during games (Schimpchen et al., 2016; Taylor et al., 2016). In contrast, a much higher frequency of repeated-acceleration sequences has been observed (Barron et al., 2016; Serpiello et al., 2018). However, the existing research on this topic solely relies on study examining youth players. Therefore, studies investigating repeated-acceleration sequences in adult players are warranted. In turn, the results could serve for the development of repeated-acceleration tests.

8.2.2 Original Research (Paper II to V) – Methodological Aspects

A main limitation of all original studies (Paper II–V) is the small sample size and that only one group of participants (adult male athletes with team-sport background) were investigated. This limits the generalizability of the findings from these studies and future investigations focusing on other samples (e.g., different types of sports, women, children) are warranted. Conversely, examining similar groups of athletes can also considered a strength as the results from these studies can be compared to each other. In addition, the sample of team-sport athletes reflects the characteristics of soccer players to a relatively high extent, thereby allowing to link the findings of the systematic review and the original research in this thesis.

Regarding Paper II, only the starting timing light was recorded by a high-speed camera, thereby not permitting to make statements about the following timing light(s). This limitation was solved by Paper III in which the timing lights at the start, 5 m, 10 m, and 30 m were examined by high-speed cameras. In terms of the psychometric properties investigated, only validity was determined in Paper III, while reliability was not analyzed. However, reliability data for similar samples and measurement set-ups can be acquired from existing research (Rebelo et al., 2013).

The single-beam timing lights employing ECP investigated in Paper V were able to eliminate most of false signals which would have been taking by conventional single-beam systems. Indeed, measurement errors at the start due to the forward lean of the athletes were still evident, especially when using the hip as a reference point. It seems that the forward lean at the start influences the results and the validity over short distances to a relatively great extent. Certainly, the effect of a modified or standardized forward lean has yet to be examined. Moreover, from the promising results compared to conventional single-beam timing lights, it can be speculated that longer distances (e.g., 30 m) could be measured with high validity and reliability using systems with ECP. Again, this assumption should be subject to future research.

Apart from single-beam timing lights, dual-beam systems are also frequently employed in research and practice. While not investigated in the original research studies of this thesis, such systems have been evaluated and recommended for sprints over various distances by other researchers (Duthie et al., 2006; Haugen et al., 2014a; Haugen & Buchheit, 2016). However, the respective investigations have mainly focused on reliability. Therefore, examining the validity of sprint times gained by dual-beam timing lights in relation to a reference system such as a high-speed camera is advisable.

From a more general perspective, the decision which timing system to choose (e.g., timing lights, fully-automatic timing systems, motion capture, high-speed video recording, manual timing, radar and laser systems, GPS and LPS) for speed testing should be based on several aspects. These include validity, reliability, usability, time required for data collection and analysis as well as costs. Currently, there does not exist the „one“ system and procedure that fulfills all of these aspects entirely. Conversely, a system permitting the acquisition of valid and reliable results might have weaknesses regarding usability and vice versa. Therefore, a rigorous evaluation of existing timing technologies and associated methodological aspects is needed to determine which timing system fits best for a specific purpose (e.g., detailed analysis for scientific purposes vs. routine in-season testing).

This subchapter discussed the limitations of the studies included in this thesis and provided suggestions for future studies which are thought to advance the scientific knowledge in the field of speed testing in soccer and associated methodological aspects. In the following subchapter, practical applications based on the current knowledge and the five studies of this thesis will be addressed.

8.3 Practical Applications

While this thesis contributes to the existing literature on speed testing from a soccer-specific and methodological view, there still exist a number of research gaps. Nevertheless, the current knowledge yet allows for a number of practical applications for researchers and practitioners to be provided.

8.3.1 Review (Paper I) – Applications to Soccer

Based on the consideration presented in *Chapter 2.1.1* that speed involves several relatively independent skills, a comprehensive examination of speed should address these skills with specific tests. As already emphasized, speed in soccer can be categorized into linear sprinting, repeated sprinting, change-of-direction sprinting, agility and combinations of these skills.

Except for agility, a number of valid (in terms of construct and criterion validity) and reliable tests exist for each category. In addition, the high number of single tests identified by the systematic review indicates a lack of an accepted gold-standard test in most of the categories. Therefore, researchers and practitioners are advised to base their decision on which test(s) to choose on the comprehensive database provided. Indeed, specific recommendations for each category would represent a more immediate benefit for researchers and practitioners. In order to justify recommending a certain test, high levels of validity and reliability of this test should have been reported. Moreover, this must have been confirmed through a number of studies, preferably over a wide range of playing levels. Accordingly, the following specific recommendations can be proposed for each test category (see Table 8.1).

Table 8.1 Recommended speed tests in soccer for the categories linear sprint, repeated sprint, change-of-direction sprint, agility, and combinations.

Test category	Recommended tests	References
Linear sprint	5-m, 10-m, 20-m sprint (acceleration) 30-m, 40-m sprint (maximum speed)	e.g., Coelho et al. (2016); Ferro et al. (2014); Haugen et al. (2013a); Rebelo et al. (2013); Silva et al. (2013b)
Repeated sprint	6 x 20-m sprints with 20–25 s of active recovery	Aziz et al. (2008); Gabbett (2010); Wong et al. (2012)
	7 x 30-m sprints with 20–30 s of active or passive recovery	Chaouachi et al. (2010); Ingebrigtsen et al. (2012); Ruscello et al. (2013); Shalfawi et al. (2013b)
Change-of-direction sprint	T Test	e.g., Kutlu et al. (2012); Kutlu et al. (2017); Rebelo et al. (2013); Rey et al. (2017)
	(Modified) zig-zag test	e.g., Kutlu et al. (2012); Loturco et al. (2017); Mirkov et al. (2008)
Agility	No test with confirmed validity and reliability available	–
Combinations	(Modified) Bangsbo sprint test	Abrantes et al. (2004); Brahim et al. (2016); Kaplan (2010); Wragg et al. (2000)
	Repeated shuttle sprint test	Impellizzeri et al. (2008); Rampinini et al. (2007a); Rampinini et al. (2009)

Indeed, there are several aspects that should be considered when applying the tests recommended in Table 8.1. It should be acknowledged that the tests in the respective categories do not necessarily represent the most appropriate ones in terms of construct validity as this is not possible to determine using the studies currently available (see *Chapter 8.2.1*). Moreover, as discussed in *Chapter 8.1.1*, some of the recommended tests lack ecological validity and might be replaced when more ecologically valid tests have been thoroughly evaluated. Another important aspect is that the relationships between different tests in the same category are limited as the determining factors of the test performance differ in relation to the characteristics of the tests. Therefore, results between different tests in the same category are not necessarily comparable (Kadlubowski et al., 2019). A last point to consider with reference to repeated-sprint tests and combinations is that the validity and reliability have only been confirmed for the total time and the average time during such tests. Conversely, measures of fatigue such as percent decrement scores should be treated with caution as they possess markedly lower levels of validity and reliability. Keeping these issues in mind, Table 8.1 can serve as a more specific basis for selecting speed tests in adult soccer players.

8.3.2 Original Research (Paper II to V) – Methodological Aspects

The findings of the four original research studies in conjunction with existing literature provide a number of practical applications.

All four studies highlight the influence of methodological aspects (starting distance, timing light height, and timing light type) on the speed testing results and their validity and reliability. From these findings, it seems obvious, that the use of universal normative values (e.g., a 10-m time of 2.23 s for a 25-year old male soccer player to be above the 90th percentile in his age group) (Nikolaidis et al., 2016) should be treated with caution and always be considered with regards to the respective method applied (timing technology, specific measurement set-up, etc.). This aspect can also be extended to a wider audience. For instance, in 2013, the former Borussia Dortmund striker Pierre-Emerick Aubameyang announced that his best time for a 30-m sprint was 3.70 s (Bundesliga, 2017). This statement was taken up by the media to compare this time to Usain Bolt's 100-m world record in 2009. In fact, during his world-record sprint, Bolt needed 3.78 s for the first 30 m, which is 0.08 s slower than Aubameyang's time. Consequently, the question arose, is Aubameyang really faster than Bolt? Obviously, such discussions are unrewarding, as the respective methods to obtain the sprint times likely differed to great extends, making comparisons impossible. To sum up, when comparing different athletes or tracking performance changes of these athletes, the same (valid and reliable) measurement method and set-up should be used constantly. In addition, to allow for a meaningful interpretation of the results not only by the investigators but also by persons not involved in the data collection process, the measurement method and set-up applied should be reported in detail.

The role of validity and reliability during testing has already been briefly addressed. However, in order to handle the following practical recommendations and the underlying reasoning adequately, a common understanding of validity and reliability in the context of this thesis is necessary: Desirably, a test using a specific measurement method and set-up should permit valid and reliable results to be obtained. Taking the example of a linear-sprint test, which is used in the original studies of this thesis, it can be assumed that the test measures what it intends to measure (that is, the skill linear sprinting) only by logical considerations (face validity). Given that, the type of validity that is of interest in terms of a linear-sprint test is reflected by comparing the results obtained to those gained by a reference method (e.g., high-speed video analysis). In contrast, the reliability reflects if the results are reproducible over several trials or points of time within a specific population. Consequently, when wishing to compare the results between athletes (e.g., athlete A vs. athlete B), both validity and reliability are needed. If performance changes want to be tracked within this population (e.g., before and after a training intervention), reliability but not validity is mandatory. It should be mentioned that this reasoning can only be adopted based on the specific consideration of validity as described above.

Given this reasoning, the following specific recommendations can be made when using timing lights in the context of speed testing.

- Different starting distances to the first timing light should not be used interchangeably. A starting distance of 0.3 m is recommended in order to track performance changes of athletes (high reliability).
- Single-beam timing lights are not advised over 5-m and 10-m distances when aiming to compare performance between athletes (low validity).
- Single-beam timing lights can be recommended as timing systems over a 30-m distance and for flying 20-m sprints for both comparing performance between athletes and tracking performance changes (high validity and reliability).
- Bearing in mind the implications of leaning forwards (especially at the start), single-beam timing lights employing ECP can be recommended over 5-m and 10-m distances. This applies to both the comparison between athletes (high validity when accepting the upper body as an adequate reference point) and for tracking performance changes (high reliability).

A short summary of which type of timing lights to choose in relation to the distance in question and the specific purpose is presented in Table 8.2.

Table 8.2 Recommendations for the use of single-beam timing lights with and without ECP over various distances for the two purposes *between-athletes comparisons* and *tracking performance changes*.

Type of timing lights	**Distance**		
	5 m and 10 m	**30 m**	**20-m flying**
Between-athletes comparisons			
Single-beam	No	Yes	Yes
Single-beam with ECP	Yes*	Yes**	Yes**
Tracking performance changes			
Single-beam	Yes***	Yes	Yes
Single-beam with ECP	Yes	Yes**	Yes**

* – When accepting the upper body as an adequate reference point
** – Based on the findings that a) validity and reliability get higher with increasing running distance using single-beam timing lights and b) validity and reliability is increased using single-beam timing lights with ECP even over 5 m and 10 m
*** – Only when using a starting distance of 0.3 m

Regarding the starting distance, it is recommended to start 0.3 m behind the first timing light. The timing light height seems to play a minor role in terms of validity when using systems without ECP. That is, low validity is evident over 5 m and 10 m, an increased validity over 30 m, and a high validity over 20-m flying sprints, relatively independent of the height used. Indeed, when a specific height has been chosen, this height should be maintained in order to allow comparisons between testing sessions. Obviously, tests should not only be standardized regarding timing light height but also in a general way (e.g., starting procedures, environment, surface). Based on its superiority against conventional single-beam timing lights in terms of detecting false signals, systems employing ECP should be used when available.

While the original studies in this thesis only addressed linear-sprint tests, the abovementioned methodological recommendations can be transferred to the other test categories included in the systematic review at least to some extent. More specifically, because of the similar test set-up, repeated-sprint tests might be treated practically equally. Conversely, the decelerations and accelerations occurring before and after the changes of directions during the change-of-direction sprint tests, agility tests, and combinations lead to different velocities and body postures when running through the timing lights. Therefore, from a methodological perspective, the validity and reliability of tests in these categories might vary according to the angles of directional changes and the linear-sprinting distance before passing the finish timing lights.

This subchapter provided a number of practical applications based both on the five studies of this thesis and the current body of knowledge that can be used by researchers and practitioners. The thesis closes with a conclusion in the following chapter.

9 Conclusion

The aims of this thesis were to

I) comprehensively review the available literature on speed tests used in soccer with special reference to the tests‘ validity and reliability

II) investigate the effects of methodological aspects including starting distance, timing light height, and timing light type with respect to speed testing results itself and their validity and reliability.

The systematic review highlighted that speed in soccer can be considered a complex construct which encompasses both physical and perceptual-cognitive aspects of speed. Speed tests used in soccer can be categorized into linear sprinting, repeated sprinting, change-of-direction sprinting, agility, and combinations of these skills. Given the specificity and the limited transfer between these speed skills, they can be considered as relatively independent from each other. Therefore, speed testing should be based on specific tests in order to address these skills. In terms of linear sprinting (e.g., 5-m, 10-m, 20-m, 30-m, 40-m sprint), repeated sprinting (e.g., 6 x 20-m sprints with 20–25 s of active recovery, 7 x 30-m sprints with 20–30 s of active or passive recovery), change-of-direction sprinting (e.g., T Test, (modified) zig-zag test), and combinations (e.g., (modified) Bangsbo sprint test, repeated shuttle sprint test), there exist a number of valid and reliable tests. However, as no gold-standard test for each skill seems to exist, researchers and practitioners may use the broad database provided in the systematic review for their test selection. While the total or average time represent valid and reliable parameters, the use of fatigue measures such as percent decrement scores should be treated with caution.

When having selected a specific speed test, attention should be paid to methodological aspects, such as the exact procedures and timing technology applied. In this context, the four original research papers included in this thesis and their integration into the existing literature emphasize the influence of methodological aspects on speed testing results itself as well as their validity and reliability based on linear sprints over various distances. In the case of using conventional single-beam timing lights as a timing technology, results gained by different starting distances from the initial timing light are not comparable. The same applies to the use of different timing light heights. Because of the high reliability, a starting distance of 0.3 m is advised. Irrespective of timing light height, single-beam systems do not provide valid results over short distances (e.g., 5 m and 10 m), which can be attributed to high measurement errors due to swinging extremities. Conversely, results become more valid with increasing distance (e.g., 30 m). In line with this, flying sprints can be measured with high validity and reliability using single-beam systems. Bearing the implications of leaning forwards in mind, single-beam timing lights employing ECP have been shown to eliminate measurement errors, thereby accounting for a high validity of measurement even over short distances (e.g., 5 m and 10 m). Consequently, single-beam timing lights employing ECP should be used when possible, especially over short distances. As a whole, the findings of the four original research papers included in this thesis are crucial for selecting the most appropriate procedures and timing technology in relation to the purpose of testing, e.g., comparing speed performance of athletes or detecting performance changes.

To conclude, this thesis adds some valuable findings to the current body of knowledge, thereby emphasizing that the selection of both the speed test itself as well as the exact procedures and timing technology should be done with caution. Furthermore, this thesis provides practical recommendations for researchers and practitioners dealing with highly relevant topics such as monitoring player performance and training interventions. In doing so, this thesis contributes to a better understanding of how to test speed with the example of soccer and associated methodological aspects – always keeping in mind that speed is only one important piece of the puzzle including several other physical, technical, and tactical aspects that contribute to overall soccer performance. As this field is far from being fully understood and soccer continuously evolves, a number of questions remain that should be addressed in future studies. Possible topics of such studies should relate to position-specificity and criterion validity of tests, the development and evaluation of agility and repeated-acceleration tests as well as to the optimal procedures and timing technologies applied.

Reference List

Abbott, W., Brickley, G., & Smeeton, N. J. (2018). Physical demands of playing position within English Premier League academy soccer. *Journal of Human Sport and Exercise, 13*(2), 285–295.

Abrantes, C., Maçãs, V., & Sampaio, J. (2004). Variation in football players' sprint test performance across different ages and levels of competition. *Journal of Sports Science and Medicine, 3*(YISI 1), 44–49.

Ade, J., Fitzpatrick, J., & Bradley, P. S. (2016). High-intensity efforts in elite soccer matches and associated movement patterns, technical skills and tactical actions. Information for position-specific training drills. *Journal of sports sciences, 34*(24), 2205–2214.

Akenhead, R., Hayes, P. R., Thompson, K. G., & French, D. (2013). Diminutions of acceleration and deceleration output during professional football match play. *Journal of science and medicine in sport, 16*(6), 556–561.

Al Haddad, H., Simpson, B. M., & Buchheit, M. (2015). Monitoring changes in jump and sprint performance: best or average values? *International journal of sports physiology and performance, 10*(7), 931–934.

Altmann, S., Hoffmann, M., Kurz, G., Neumann, R., Woll, A., & Haertel, S. (2015). Different Starting Distances Affect 5-m Sprint Times. *Journal of Strength and Conditioning Research, 29*(8), 2361–2366.

Altmann, S., Kuberczyk, M., Ringhof, S., Neumann, R., & Woll, A. (2018a). Relationships between performance test and match-related physical performance parameters. *German Journal of Exercise and Sport Research, 48*(2), 218–227.

Altmann, S., Ringhof, S., Becker, B., Woll, A., & Neumann, R. (2018b). Error-Correction Processing in Timing Lights for Measuring Sprint Performance: Does It Work? *International journal of sports physiology and performance*, 1–3.

Altmann, S., Spielmann, M., Engel, F. A., Neumann, R., Ringhof, S., Oriwol, D., & Haertel, S. (2017). Validity of Single-Beam Timing Lights at Different Heights. *Journal of Strength and Conditioning Research, 31*(7), 1994–1999.

Altmann, S., Ringhof, S., Neumann, R., Woll, A., & Rumpf, M. C. (2019). Validity and reliability of speed tests used in soccer: A systematic review. *PloS one, 14*(8), e0220982.

Altmann, S., Spielmann, M., Engel, F. A., Ringhof, S., Oriwol, D., Härtel, S., & Neumann, R. (2018c). Accuracy of single beam timing lights for determining velocities in a flying 20-m sprint: Does timing light height matter? *Journal of Human Sport and Exercise, 13*(3), 601–610.

Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., & Kasprzak, A. (2013). Analysis of sprinting activities of professional soccer players. *Journal of Strength and Conditioning Research, 27*(8), 2134–2140.

Araujo, M. C., Baumgart, C., Pieper, S., Hoppe, M. W., Hassan, I., & Freiwald, J. (2012). Comparison of sprint and agility performance between German and Brazilian young male elite soccer players. *3rd World Conference on Science and Soccer (WCSS), 14.-16.05. Ghent, Belgium. In: Abstract Book, p. 222.*

Asadi, A., Arazi, H., Young, W. B., & Sáez de Villarreal, E. (2016). The Effects of Plyometric Training on Change-of-Direction Ability: A Meta-Analysis. *International journal of sports physiology and performance, 11*(5), 563–573.

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports medicine (Auckland, N.Z.), 26*(4), 217–238.

Aughey, R. J. (2011). Applications of GPS Technologies to Field Sports. *International journal of sports physiology and performance, 6*(3), 295–310.

Aziz, A. R., Mukherjee, S., Chia, M. Y. H., & Teh, K. C. (2008). Validity of the running repeated sprint ability test among playing positions and level of competitiveness in trained soccer players. *International journal of sports medicine, 29*(10), 833–838.

Balsalobre-Fernández, C., Bishop, C., Beltrán-Garrido, J. V., Cecilia-Gallego, P., Cuenca-Amigó, A., Romero-Rodríguez, D., & Madruga-Parera, M. (2019). The validity and reliability of a novel app for the measurement of change of direction performance. *Journal of sports sciences, 37*(21), 2420–2424.

Balser, N., Lorey, B., Pilgramm, S., Naumann, T., Kindermann, S., Stark, R., et al. (2014). The influence of expertise on brain activation of the action observation network during anticipation of tennis and volleyball serves. *Frontiers in human neuroscience, 8*, 568.

Baptista, I., Johansen, D., Seabra, A., & Pettersen, S. A. (2018). Position specific player load during match-play in a professional football club. *PloS one, 13*(5), e0198115.

Barbero-Alvarez, J. C., Coutts, A., Granda, J., Barbero-Alvarez, V., & Castagna, C. (2010). The validity and reliability of a global positioning satellite system device to assess speed and repeated sprint ability (RSA) in athletes. *Journal of science and medicine in sport, 13*(2), 232–235.

Barberó-Álvarez, J. C., Boullosa, D., Nakamura, F. Y., Andrín, G., & Weston, M. (2013). Repeated Acceleration Ability (RAA): A New Concept with Reference to Top-Level Field and Assistant Soccer Referees. *Asian Journal of Sports Medicine, 5*(1), 63–66.

Barlett, R. (2007). *Introduction to sports biomechanics: Analysing human movement patterns.* Abingdon, UK: Routledge.

Barnes, C., Archer, D. T., Hogg, B., Bush, M., & Bradley, P. S. (2014). The evolution of physical and technical performance parameters in the English Premier League. *International journal of sports medicine, 35*(13), 1095–1100.

Barr, M., Beaver, T., Turczyn, D., & Cornish, S. (2017). The Validity and Reliability of 15 Hz Global Positioning System Units for Assessing the Activity Profiles of University Football Players. *Journal of Strength and Conditioning Research*.

Barrett, E., McCreesh, K., & Lewis, J. (2014). Reliability and validity of non-radiographic methods of thoracic kyphosis measurement: a systematic review. *Manual therapy, 19*(1), 10–17.

Barris, S., & Button, C. (2008). A Review of Vision-Based Motion Analysis in Sport. *Sports Medicine, 38*(12), 1025–1043.

Barron, D. J., Atkins, S., Edmundson, C., & Fewtrell, D. (2016). Repeated acceleration activity in competitive youth soccer. *Central European Journal of Sport Sciences and Medicine, 14*(2), 55–61.

Barros, R.M.L., Misuta, M. S., Menezes, R. P., Figueroa, P. J., Moura, F. A., Cunha, S. A., et al. (2007). Analysis of the Distances Covered by First Division Brazilian Soccer Players Obtained with an Automatic Tracking Method. *Journal of Sports Science & Medicine, 6*(2), 233–242.

Bastian, A. J. (2006). Learning to predict the future: the cerebellum adapts feedforward movement control. *Current Opinion in Neurobiology, 16*(6), 645–649.

Beavan, A. (2019). Extraordinary tools require extraordinary evidence. *Science and Medicine in Football, 3*(4), 263–264.

Bekris, E., Gissis, I., & Kounalakis, S. (2018). The dribbling agility test as a potential tool for evaluating the dribbling skill in young soccer players. *Research in sports medicine (Print), 26*(4), 425–435.

Bendiksen, M., Pettersen, S. A., Ingebrigtsen, J., Randers, M. B., Brito, J., Mohr, M., et al. (2013). Application of the Copenhagen Soccer Test in high-level women players - locomotor activities, physiological response and sprint performance. *Human movement science, 32*(6), 1430–1442.

Benvenuti, C., Minganti, C., Condello, G., Capranica, L., & Tessitore, A. (2010). Agility assessment in female futsal and soccer players. *Medicina (Kaunas, Lithuania), 46*(6), 415–420.

Bergh, U., Thorstensson, A., Sjödin, B., Hulten, B., Piehl, K., & Karlsson, J. (1978). Maximal oxygen uptake and muscle fiber types in trained and untrained humans. *Medicine and science in sports, 10*(3), 151-154.

Berthoin, S., Dupont, G., Mary, P., & Gerbeaux, M. (2001). Predicting sprint kinematic parameters from anaerobic field tests in physical education students. *Journal of Strength and Conditioning Research, 15*(1), 75–80.

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001a). Anticipatory effects on knee joint loading during running and cutting maneuvers. *Medicine and science in sports and exercise, 33*(7), 1176–1181.

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackerland, T. R. (2001b). External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sports and Exercise*, 1168–1175.

Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2012). Measurement error in estimates of sprint velocity from a laser displacement measurement device. *International journal of sports medicine, 33*(6), 439–444.

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-Sprint Ability — Part II. *Sports Medicine, 41*(9), 741–756.

Bishop, D. T., Wright, M. J., Jackson, R. C., & Abernethy, B. (2013). Neural Bases for Anticipation Skill in Soccer: An fMRI Study. *Journal of Sport and Exercise Psychology, 35*(1), 98–109.

Bland, J. M., & & Altman, D. G. (1999). Measuring agreement in method comparison studies. *Statistical methods in medical research, 8*(2), 135–160.

Bland, J. M., & Altman, D. G. (1996). Measurement error. *BMJ, 31*, 744.

Bloomfield, J., Polman, R., & ODonoghue, P. (2008). Deceleration and turning movements performed during FA Premier League soccer matches. *Science and football VI; the proceedings of the sixth world congress on science and football. Taylor & Francis, London*, 174–181.

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical Demands of Different Positions in FA Premier League Soccer. *Journal of Sports Science & Medicine, 6*(1), 63–70.

Bolger, R., Lyons, M., Harrison, A. J., & Kenny, I. C. (2015). Sprinting performance and resistance-based training interventions: a systematic review. *Journal of Strength and Conditioning Research, 29*(4), 1146–1156.

Bond, C. W., Willaert, E. M., & Noonan, B. C. (2017a). Comparison of Three Timing Systems: Reliability and Best Practice Recommendations in Timing Short-Duration Sprints. *Journal of Strength and Conditioning Research, 31*(4), 1062–1071.

Bond, C. W., Willaert, E. M., Rudningen, K. E., & Noonan, B. C. (2017b). Reliability of Three Timing Systems Used to Time Short on Ice-Skating Sprints in Ice Hockey Players. *Journal of Strength and Conditioning Research, 31*(12), 3279–3286.

Boone, J., Vaeyens, R., Steyaert, A., Vanden Bossche, L., & Bourgois, J. (2012). Physical fitness of elite Belgian soccer players by player position. *Journal of Strength and Conditioning Research, 26*(8), 2051–2057.

Bös, K. (1987). *Handbuch sportmotorischer Tests.* Göttingen: Hogrefe.

Bouchard, C. (2012). Genomic predictors of trainability. *Experimental physiology, 97*(3), 347–352.

Bouchard, C., Dionne, F. T., Simoneau, J. A., & Boulay, M. R. (1992). Genetics of aerobic and anaerobic performances. *Exercise and sport sciences reviews, 20*(1), 27–58.

Boussetta, N., Abedelmalek, S., Aloui, K., & Souissi, N. (2017). The effect of air pollution on diurnal variation of performance in anaerobic tests, cardiovascular and hematological parameters, and blood gases on soccer players following the Yo-Yo Intermittent Recovery Test Level-1. *Chronobiology international, 34*(7), 903–920.

Bradley, P. S., & Ade, J. D. (2018). Are Current Physical Match Performance Metrics in Elite Soccer Fit for Purpose or Is the Adoption of an Integrated Approach Needed? *International journal of sports physiology and performance, 13*(5), 656–664.

Bradley, P. S., Archer, D. T., Hogg, B., Schuth, G., Bush, M., Carling, C., & Barnes, C. (2016). Tier-specific evolution of match performance characteristics in the English Premier League: it's getting tougher at the top. *Journal of sports sciences, 34*(10), 980–987.

Bradley, P. S., Carling, C., Archer, D., Roberts, J., Dodds, A., Di Mascio, M., et al. (2011). The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. *Journal of sports sciences, 29*(8), 821–830.

Bradley, P. S., Di Mascio, M., Mohr, M., Fransson, D., Wells, C., Moreira, A., et al. (2018). Can modern trends in elite football match demands be translated into novel training and testing modes? *Aspetar Sports Med J*. (7), 46–52.

Bradley, P. S., Di Mascio, M., Peart, D., Olsen, P., & Sheldon, B. (2010). High-intensity activity profiles of elite soccer players at different performance levels. *Journal of Strength and Conditioning Research, 24*(9), 2343–2351.

Bradley, P. S., & Noakes, T. D. (2013). Match running performance fluctuations in elite soccer: indicative of fatigue, pacing or situational influences? *Journal of sports sciences, 31*(15), 1627–1638.

Bradley, P. S., Sheldon, W., Wooster, B., Olsen, P., Boanas, P., & Krustrup, P. (2009). High-intensity running in English FA Premier League soccer matches. *Journal of sports sciences, 27*(2), 159–168.

Brahim, M. B., Mohamed, A., & Shalfawi, S. A. (2016). The evaluation of soccer playersperformance on different repeated sprint testes: Training and testing implications. *Kinesiologia Slovenica, 22*(2), 49–63.

Brearley, S., & Bishop, C. (2019). Transfer of Training: How Specific should we be? *Strength and Conditioning Journal, 41*, 1–25.

Brechue, W. F., Mayhew, J. L., & Piper, F. C. (2005). Equipment and running surface alter sprint performance of college football players. *Journal of Strength and Conditioning Research, 19*(4), 821–825. Retrieved November 08, 2018.

Brink, M. S., & Lemmink, K. A.P.M. (2018). Performance analysis in elite football: all in the game? *Science and Medicine in Football, 2*(4), 253–254.

Brink, Y., & Louw, Q. A. (2012). Clinical instruments: reliability and validity critical appraisal. *Journal of evaluation in clinical practice, 18*(6), 1126–1132.

Brito, J., Nassis, G. P., Seabra, A. T., & Figueiredo, P. (2018). Top 50 most-cited articles in medicine and science in football. *BMJ open sport & exercise medicine, 4*(1), e000388.

Broadbent, D. P., Causer, J., Williams, A. M., & Ford, P. R. (2015). Perceptual-cognitive skill training and its transfer to expert performance in the field: future research directions. *European journal of sport science, 15*(4), 322–331.

Broos, S., Malisoux, L., Theisen, D., van Thienen, R., Ramaekers, M., Jamart, C., et al. (2016). Evidence for ACTN3 as a Speed Gene in Isolated Human Muscle Fibers. *PloS one, 11*(3), e0150594.

Brown, A. M., Kenwell, Z. R., Maraj, B. K., & Collins, D. F. (2008). "Go" signal intensity influences the sprint start. *Medicine and Science in Sports and Exercise, 40*(6), 1142–1148.

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: a review of resistance training studies. *Sports medicine (Auckland, N.Z.), 38*(12), 1045–1063.

Buchheit, M. (2017). Want to see my report, coach. Sport science reporting in the real world. Aspetar Sports Med. J. (6), 36–42.

Buchheit, M., Allen, A., Poon, T. K., Modonutti, M., Gregson, W., & Di Salvo, V. (2014). Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies. *Journal of sports sciences, 32*(20), 1844–1857.

Buchheit, M., Mendez-Villanueva, A., Delhomel, G., Brughelli, M., & Ahmaidi, S. (2010). Improving repeated sprint ability in young elite soccer players: repeated shuttle sprints vs. explosive strength training. *Journal of Strength and Conditioning Research, 24*(10), 2715–2722.

Buchheit, M., & Simpson, B. M. (2017). Player-Tracking Technology: Half-Full or Half-Empty Glass? *International journal of sports physiology and performance, 12*(Suppl 2), S235-S241.

Bullock, W., Panchuk, D., Broatch, J., Christian, R., & Stepto, N. K. (2012). An integrative test of agility, speed and skill in soccer: effects of exercise. *Journal of science and medicine in sport, 15*(5), 431–436.

Bundesliga (2017). *Wer ist schneller? Aubameyang sprintet gegen Usain Bolt. Retrieved from https://www.bundesliga.com/de/bundesliga/news/wer-ist-schneller-pierre-emerick-aubameyang-gegen-usain-bolt-im-sprintduell-noblmd13.jsp at April 22, 2019.*

Burton, A. W., & Miller, D. E. (1998). *Movement skill assessment:* Human Kinetics.

Burton, A. W., & Rodgerson, R. W. (2001). New Perspectives on the Assessment of Movement Skills and Motor Abilities. *Adapted Physical Activity Quarterly, 18*(4), 347–365.

Bush, M., Barnes, C., Archer, D. T., Hogg, B., & Bradley, P. S. (2015a). Evolution of match performance parameters for various playing positions in the English Premier League. *Human movement science, 39*, 1–11.

Bush, M. D., Archer, D. T., Hogg, R., & Bradley, P. S. (2015b). Factors influencing physical and technical variability in the English Premier League. *International journal of sports physiology and performance, 10*(7), 865–872.

Buttifant, D., Graham, K., & Cross, K. (2001). *55 agility and speed in soccer players are two different performance parameters* (4th ed.). *329:* Science and football IV.

Caldwell, B. P., & Peters, D. M. (2009). Seasonal variation in physiological fitness of a semiprofessional soccer team. *Journal of Strength and Conditioning Research, 23*(5), 1370–1377.

Carling, C. (2013). Interpreting Physical Performance in Professional Soccer Match-Play: Should We be More Pragmatic in Our Approach? *Sports Medicine, 43*(8), 655–663.

Carling, C., & Collins, D. (2014). Comment on "football-specific fitness testing: adding value or confirming the evidence?". *Journal of sports sciences, 32*(13), 1206–1208.

Carling, C., Reilly, T., & Williams, A. M. (Eds.) (2008a). *Performance Assessment for Field Sports.* London: Routledge.

Carling, C., Bloomfield, J., Nelsen, L., & Reilly, T. (2008b). The Role of Motion Analysis in Elite Soccer. *Sports Medicine, 38*(10), 839–862, from https://doi.org/10.2165/00007256-200838100-00004.

Carling, C., Bradley, P., McCall, A., & Dupont, G. (2016). Match-to-match variability in high-speed running activity in a professional soccer team. *Journal of sports sciences, 34*(24), 2215–2223.

Carling, C., Le Gall, F., & Dupont, G. (2012). Analysis of repeated high-intensity running performance in professional soccer. *Journal of sports sciences, 30*(4), 325–336.

Casey, A., Constantin-Teodosiu, D., Howell, S., Hultman, E., & Greenhaff, P. L. (1996). Metabolic response of type I and II muscle fibers during repeated bouts of maximal exercise in humans. *The American journal of physiology, 271*(1 Pt 1), E38-43.

Castagna, C., Manzi, V., Impellizzeri, F., Weston, M., & Barbero Alvarez, J. C. (2010). Relationship between endurance field tests and match performance in young soccer players. *Journal of Strength and Conditioning Research, 24*(12), 3227–3233.

Castellano, J., Alvarez-Pastor, D., & Bradley, P. S. (2014). Evaluation of Research Using Computerised Tracking Systems (Amisco® and Prozone®) to Analyse Physical Performance in Elite Soccer: A Systematic Review. *Sports Medicine, 44*(5), 701–712.

Castellano, J., Blanco-Villaseñor, A., & Alvarez, D. (2011a). Contextual Variables and Time-Motion Analysis in Soccer. *International journal of sports medicine, 32*(6), 415–421.

Castellano, J., Casamichana, D., Calleja-González, J., San Román, J., & Ostojic, S. M. (2011b). Reliability and Accuracy of 10 Hz GPS Devices for Short-Distance Exercise. *Journal of Sports Science & Medicine, 10*(1), 233–234.

Castillo-Rodríguez, A., Fernández-García, J. C., Chinchilla-Minguet, J. L., & Carnero, E. Á. (2012). Relationship between muscular strength and sprints with changes of direction. *Journal of Strength and Conditioning Research, 26*(3), 725–732.

Chaalali, A., Rouissi, M., Chtara, M., Owen, A., Bragazzi, N. L., Moalla, W., et al. (2016). Agility training in young elite soccer players: promising results compared to change of direction drills. *Biology of Sport, 33*(4), 345–351.

Chaouachi, A., Chtara, M., Hammami, R., Chtara, H., Turki, O., & Castagna, C. (2014). Multidirectional sprints and small-sided games training effect on agility and change of direction abilities in youth soccer. *Journal of Strength and Conditioning Research, 28*(11), 3121–3127.

Chaouachi, A., Manzi, V., Chaalali, A., Wong, D. P., Chamari, K., & Castagna, C. (2012). Determinants analysis of change-of-direction ability in elite soccer players. *Journal of Strength and Conditioning Research, 26*(10), 2667–2676.

Chaouachi, A., Manzi, V., Wong, D. P., Chaalali, A., & Laurencelle, L. (2010). Intermittent endurance and repeated sprint ability in soccer players. *Journal of Strength and Conditioning Research, 24*(10), 2663–2669.

Chelly, M. S., Chérif, N., Amar, M. B., Hermassi, S., Fathloun, M., Bouhlel, E., et al. (2010). Relationships of peak leg power, 1 maximal repetition half back squat, and leg muscle volume to 5-m sprint performance of junior soccer players. *Journal of Strength and Conditioning Research, 24*(1), 266–271.

Chimera, N. J., Swanik, K. A., Swanik, C. B., & Straub, S.J. (2004). Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes. *Journal of Athletic Training, 39*(1), 24–31.

Chiwaridzo, M., Oorschot, S., Dambi, J. M., Ferguson, G. D., Bonney, E., Mudawarima, T., et al. (2017). A systematic review investigating measurement properties of physiological tests in rugby. *BMC sports science, medicine & rehabilitation, 9*, 24.

Clark, R. A., Pua, Y. H., Bower, K. J., Bechard, L., Hough, E., Charlton, P. C., & Mentiplay, B. (2019). Validity of a low-cost laser with freely available software for improving measurement of walking and running speed. *Journal of science and medicine in sport, 22*(2), 212–216.

Coelho, D. B., Pimenta, E., Rosse, I. C., Veneroso, C., Becker, L. K., Carvalho, M. R., et al. (2016). The alpha-actinin-3 r577x polymorphism and physical performance in soccer players. *The Journal of sports medicine and physical fitness, 56*(3), 241–248.

Coh, M., Vodicar, J., Žvan, M., Šimenko, J., Stodolka, J., Rauter, S., & Mackala, K. (2018). Are Change-of-Direction Speed and Reactive Agility Independent Skills Even When Using the Same Movement Pattern? *Journal of Strength and Conditioning Research, 32*(7), 1929–1936.

Collins, B. W., Pearcey, G. E. P., Buckle, N. C. M., Power, K. E., & Button, D. C. (2018). Neuromuscular fatigue during repeated sprint exercise: underlying physiology and methodological considerations. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme, 43*(11), 1166–1175.

Cometti, G., Maffiuletti, N. A., Pousson, M., Chatard, J. C., & Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *International journal of sports medicine, 22*(1), 45–51.

Comfort, P., Jones, P. A., & McMahon, J. J. (2018). *Performance Assessment in Strength and Conditioning.* Milton: Routledge.

Comfort, P., Stewart, A., Bloom, L., & Clarkson, B. (2014). Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *Journal of Strength and Conditioning Research, 28*(1), 173–177.

Costill, D. L., Daniels, J., Evans, W., Fink, W., Krahenbuhl, G., & Saltin, B. (1976). Skeletal muscle enzymes and fiber composition in male and female track athletes. *Journal of applied physiology, 40*(2), 149–154.

Cotte, T., & Chatard, J. C. (2011). Isokinetic strength and sprint times in English premier league football players. *Biology of Sport, 28*(2), 89–94.

Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of science and medicine in sport, 13*(1), 133–135.

Cronin, J. B., Green, J. P., Levin, G. T., Brughelli, M. E., & Frost, D. M. (2007). Effect of starting stance on initial sprint performance. *Journal of Strength and Conditioning Research, 21*(3), 990.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength and Conditioning Research, 19*(2), 349–357.

Cronin, J. B., & Templeton, R. L. (2008). Timing light height affects sprint times. *Journal of Strength and Conditioning Research, 22*(1), 318–320.

Cross, M. R., Brughelli, M., Samozino, P., & Morin, J. B. (2017). Methods of Power-Force-Velocity Profiling During Sprint Running: A Narrative Review. *Sports Medicine, 47*(7), 1255–1269.

Currell, K., & Jeukendrup, A. E. (2008). Validity, reliability and sensitivity of measures of sporting performance. *Sports medicine (Auckland, N.Z.), 38*(4), 297–316.

Currell, K., St. Conway, & Jeukendrup, A. E. (2009). Carbohydrate ingestion improves performance of a new reliable test of soccer performance. *International journal of sport nutrition and exercise metabolism, 19*(1), 34–46.

D'Auria, S., Tanner, R., Sheppard, J., & Manning, J. (2006). Evaluation of various methodologies used to assess sprint performance. *In Proceedings of the Australian Institute of Sport Applied Physiology Conference. ACT.*

Dalen, T., Øverås, Ø., van den Tillaar, R., Welde, B., & Heimburg, E. D. von (2018). Influence of different soccer-specific maximal actions on physiological, perceptual and accelerometer measurement loads. *Open Access Journal of Sports Medicine, 9*, 107–114.

Damerow, M. (2006). *Die Betrachtung der Schnelligkeit im Kontext der konditionellen Fähigkeiten und die Notwendigkeit einer neuartigen Sichtweise-ein Modellansatz zur Strukturierung der Schnelligkeit.* Dissertation. Magdeburg.

Darrall-Jones, J. D., Jones, B., Roe, G., & Till, K. (2016a). Reliability and Usefulness of Linear Sprint Testing in Adolescent Rugby Union and League Players. *Journal of Strength and Conditioning Research, 30*(5), 1359–1364.

Darrall-Jones, J. D., Jones, B., & Till, K. (2016b). Anthropometric, Sprint, and High-Intensity Running Profiles of English Academy Rugby Union Players by Position. *Journal of Strength and Conditioning Research, 30*(5), 1348–1358.

Datson, N., Drust, B., Weston, M., & Gregson, W. (2018). Repeated high-speed running in elite female soccer players during international competition. *Science and Medicine in Football, 24*(4), 1–7.

Dawson, B. (2012). Repeated-Sprint Ability: Where Are We? *International journal of sports physiology and performance, 7*(3), 285–289.

Debaere, S., Jonkers, I., & Delecluse, C. (2013). The contribution of step characteristics to sprint running performance in high-level male and female athletes. *Journal of Strength and Conditioning Research, 27*(1), 116–124.

Delecluse, C. (1997). Influence of strength training on sprint running performance. Current findings and implications for training. *Sports medicine (Auckland, N.Z.), 24*(3), 147–156.

Dellal, A., & Wong, D. P. (2013). Repeated sprint and change-of-direction abilities in soccer players: effects of age group. *Journal of Strength and Conditioning Research, 27*(9), 2504–2508.

Dellal, A., Chamari, K., Wong, D. P., Ahmaidi, S., Keller, D., Barros, R., et al. (2011). Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. *European journal of sport science, 11*(1), 51–59.

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*(11), 423–431.

Di Mascio, M., Ade, J., & Bradley, P. S. (2015). The reliability, validity and sensitivity of a novel soccer-specific reactive repeated-sprint test (RRST). *European journal of applied physiology, 115*(12), 2531–2542.

Di Prampero, P. E., Fusi, S., Sepulcri, L., Morin, J. B., Belli, A., & Antonutto, G. (2005). Sprint running: a new energetic approach. *The Journal of experimental biology, 208*(Pt 14), 2809–2816.

Di Salvo, V., Baron, R., González-Haro, C., Gormasz, C., Pigozzi, F., & Bachl, N. (2010). Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. *Journal of sports sciences, 28*(14), 1489–1494.

Di Salvo, V., Baron, R., Tschan, H., Montero, F. C., Bachl, N., & Pigozzi, F. (2007). Performance characteristics according to playing position in elite soccer. *International journal of sports medicine, 28*(3), 222–227. Retrieved November 08, 2018.

Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high intensity activity in Premier League soccer. *International journal of sports medicine, 30*(3), 205–212.

Di Salvo, V., Pigozzi, F., González-Haro, C., Laughlin, M. S., & Witt, J. K. de (2013). Match performance comparison in top English soccer leagues. *International journal of sports medicine, 34*(6), 526–532.

Djaoui, L., Chamari, K., Owen, A. L., & Dellal, A. (2017). Maximal Sprinting Speed of Elite Soccer Players During Training and Matches. *Journal of Strength and Conditioning Research, 31*(6), 1509–1517.

Dolenec, A., & Čoh, M. (2009). Comparison of photocell and opojump measurements of maximum running velocity. *Kinesiologia Slovenica, 15*(2).

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The Effect of Angle and Velocity on Change of Direction Biomechanics: An Angle-Velocity Trade-Off. *Sports medicine (Auckland, N.Z.), 48*(10), 2235–2253.

DRAPER, J. A. (1985). The 505 test : a test for agility in horizontal plane. *Aust J Sci Med Sport, 17*(1), 15–18.

Düking, P., Born, D. P., & Sperlich, B. (2016). The SpeedCourt: Reliability, Usefulness, and Validity of a New Method to Determine Change-of-Direction Speed. *International journal of sports physiology and performance, 11*(1), 130–134.

Duthie, G. M., Pyne, D. B., Ross, A. A., Livingstone, S. G., & Hooper, S. L. (2006). The reliability of ten-meter sprint time using different starting techniques. *Journal of Strength and Conditioning Research, 20*(2), 246–251.

Dwyer, D. B., & Gabbett, T. J. (2012). Global positioning system data analysis: velocity ranges and a new definition of sprinting for field sport athletes. *Journal of Strength and Conditioning Research, 26*(3), 818–824.

Dyas, J. W., & Kerwin, D. G. (1995). A photocell based timing system for studying linear kinematics of running. In *Proceedings of the Sports Biomechanics Section of the British Association of Sport and Exercise Sciences* (pp. 29–32).

Earp, J. E., & Newton, R. U. (2012). Advances in electronic timing systems: considerations for selecting an appropriate timing system. *Journal of Strength and Conditioning Research, 26*(5), 1245–1248.

Ebben, W. P., Petushek, E. J., & Clewein, R. (2009). A Comparison of Manual and electronic Timing during 20 and 40 Yards Sprints. *Journal of Exercise Physiology online, 12*(5).

Emmonds, S., Nicholson, G., Beggs, C., Jones, B., & Bissas, A. (2017). Importance of physical qualities for speed and change of direction ability in elite female soccer players. *Journal of Strength and Conditioning Research*.

Ericsson, K. A., Nandagopal, K., & Roring, R. W. (2009). Toward a science of exceptional achievement: attaining superior performance through deliberate practice. *Annals of the New York Academy of Sciences, 1172*, 199–217.

Ericsson, K. A., & Smith, J. (1991). *Prospects and limits of the empirical study of expertise: an introduction. Toward Gen Theory Expertise.* New York: Cambridge University Press.

Eynon, N., Hanson, E. D., Lucia, A., Houweling, P. J., Garton, F., North, K. N., & Bishop, D. J. (2013). Genes for elite power and sprint performance: ACTN3 leads the way. *Sports medicine (Auckland, N.Z.), 43*(9), 803–817.

Farrow, D., Young, W., & Bruce, L. (2005). The development of a test of reactive agility for netball: a new methodology. *Journal of science and medicine in sport, 8*(1), 52–60.

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of sports sciences, 30*(7), 625–631.

Faude, O., Meyer, T., Buchmann, M., & Kindermann, W. (2007.). Influence of surface and jumping ability on sprint performance in soccer players. *Detsche Zeitschrift für Sportmedizin*. (58), 259.

Faude, O., Schlumberger, A., Fritsche T., Treff, G., & Meyer, T. (2010). Leistungsdiagnostische Testverfahren im Fußball–methodische Standards. *Deutsche Zeitschrift für Sportmedizin, 61*(6), 129–133.

Ferro, A., Floría, P., Villacieros, J., & Aguado-Gómez, R. (2012). Validez y fiabilidad del sensor láser del sistema BioLaserSport® para el análisis de la velocidad de la carrera: [Validity and reliability of the laser sensor of BioLaserSport® system for the analysis of the running velocity]. *Revista Internacional de Ciencias del Deporte*. (8), 357–370.

Ferro, A., Villacieros, J., Floría, P., & Graupera, J. L. (2014). Analysis of speed performance in soccer by a playing position and a sports level using a laser system. *Journal of human kinetics, 44*, 143–153.

FIFA (2015). *International Federation of Association Football (FIFA). FIFA Marketing Research. Retrieved from https://www.fifa.com/about-fifa/news/y=2010/m=12/news=fifa-marketing-research-1354721.html. Updated April 24, 2015.*

Fiorilli, G., Iuliano, E., Mitrotasios, M., Pistone, E. M., Aquino, G., Calcagno, G., & Di Cagno, A. (2017). Are Change of Direction Speed and Reactive Agility Useful for Determining the Optimal Field Position for Young Soccer Players? *Journal of Sports Science & Medicine, 16*(2), 247–253.

Frost, D. M., & Cronin, J. B. (2011). Stepping back to improve sprint performance: a kinetic analysis of the first step forwards. *Journal of Strength and Conditioning Research, 25*(10), 2721–2728.

Frost, D. M., Cronin, J. B., & Levin, G. (2008). Stepping backward can improve sprint performance over short distances. *Journal of Strength and Conditioning Research, 22*(3), 918–922.

Fuerst, P., Gollhofer, A., & Gehring, D. (2017). Preparation time influences ankle and knee joint control during dynamic change of direction movements. *Journal of sports sciences, 35*(8), 762–768.

Fusion-Sport (2010). Timing Accuracy Research Update.

Gabbett, T., & Benton, D. (2009). Reactive agility of rugby league players. *Journal of science and medicine in sport, 12*(1), 212–214.

Gabbett, T. J. (2010). The development of a test of repeated-sprint ability for elite women's soccer players. *Journal of Strength and Conditioning Research, 24*(5), 1191–1194.

Gabbett, T. J., Carius, J., & Mulvey, M. (2008a). Does improved decision-making ability reduce the physiological demands of game-based activities in field sport athletes? *The Journal of Strength & Conditioning Research, 22*(6), 2027–2035.

Gabbett, T. J., Kelly, J. N., & Sheppard, J. M. (2008b). Speed, change of direction speed, and reactive agility of rugby league players. *Journal of Strength and Conditioning Research, 22*(1), 174–181.

Gabbett, T. J., & Mulvey, M. J. (2008). Time-motion analysis of small-sided training games and competition in elite women soccer players. *Journal of Strength and Conditioning Research, 22*(2), 543–552.

Gabbett, T. J., Wiig, H., & Spencer, M. (2013). Repeated High-Intensity Running and Sprinting in Elite Women's Soccer Competition. *International journal of sports physiology and performance, 8*(2), 130–138.

Gallivan, J. P., Chapman, C. S., Wolpert, D. M., & Flanagan, J. R. (2018). Decision-making in sensorimotor control. *Nature reviews. Neuroscience, 19*(9), 519–534.

Gander, R. E., McClements, J. D., Sanderson, L. K., Rostad, B. A., Josephson, K. E., & Pratt, A. J. (1994). Sprint start instrumentation. *IEEE transactions on instrumentation and measurement, 43*(4), 637-643.

García-López, J., Morante, J. C., Ogueta-Alday, A. C., González-Lázaro, J., Rodríguez-Marroyo, J. A., & Villa, G. (2012). El uso de fotocélulas de haz simple y doble para medir la velocidad en carreras®. The use of single- and dual-beam photocells to measure the sprint time®. *RICYDE. Revista Internacional de Ciencias del Deporte, 8*(30), 324–333.

Gelen, E. (2010). Acute effects of different warm-up methods on sprint, slalom dribbling, and penalty kick performance in soccer players. *Journal of Strength and Conditioning Research, 24*(4), 950–956.

Gil, S., Loturco, I., Tricoli, V., Ugrinowitsch, C., Kobal, R., Abad, C. C. C., & Roschel, H. (2015). Tensiomyography parameters and jumping and sprinting performance in Brazilian elite soccer players. *Sports biomechanics, 14*(3), 340–350.

Girard, O., Brocherie, F., & Bishop, D. J. (2015a). Sprint performance under heat stress: A review. *Scandinavian journal of medicine & science in sports, 25 Suppl 1*, 79–89.

Girard, O., Brocherie, F., Morin, J.-B., & Millet, G. P. (2015b). Neuro-mechanical determinants of repeated treadmill sprints - Usefulness of an "hypoxic to normoxic recovery" approach. *Frontiers in physiology, 6*, 260.

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability - part I: Factors contributing to fatigue. *Sports medicine (Auckland, N.Z.), 41*(8), 673–694.

Gonzalez-Balzar, P. (2007). *Konditionstraining und sportmedizinische Betreuung in der 1. Fußballbundesliga [Strength and conditioning practices and medical support in the German football Bundesliga.]*. Dissertation.

González-Víllora, S., Serra-Olivares, J., Pastor-Vicedo, J. C., & Da Costa, I. T. (2015). Review of the tactical evaluation tools for youth players, assessing the tactics in team sports: football. *SpringerPlus, 4*, 663.

Gorostiaga, E. M., Izquierdo, M., Ruesta, M., Iribarren, J., González-Badillo, J. J., & Ibáñez, J. (2004). Strength training effects on physical performance and serum hormones in young soccer players. *European journal of applied physiology, 91*(5-6), 698–707.

Gregson, W., Drust, B., Atkinson, G., & Salvo, V. D. (2010). Match-to-match variability of high-speed activities in premier league soccer. *International journal of sports medicine, 31*(4), 237–242.

Hachana, Y., Chaabène, H., Nabli, M. A., Attia, A., Moualhi, J., Farhat, N., & Elloumi, M. (2013). Test-retest reliability, criterion-related validity, and minimal detectable change of the Illinois agility test in male team sport athletes. *Journal of Strength and Conditioning Research, 27*(10), 2752–2759.

Hader, K., Palazzi, D., & Buchheit, M. (2015). Change of direction speed in soccer: How much braking is enough? *Kinesiology: International journal of fundamental and applied kinesiology, 47*(1), 67–74.

Harland, M. J., & Steele, J. R. (1997). Biomechanics of the sprint start. *Sports medicine (Auckland, N.Z.), 23*(1), 11–20.

Harper, D. J., Carling, C., & Kiely, J. (2019). High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies. *Sports medicine (Auckland, N.Z.)*.

Harper, L. D., Hunter, R., Parker, P., Goodall, S., Thomas, K., Howatson, G., et al. (2016). Test-Retest Reliability of Physiological and Performance Responses to 120 Minutes of Simulated Soccer Match Play. *Journal of Strength and Conditioning Research, 30*(11), 3178–3186.

Harries, S. K., Lubans, D. R., & Callister, R. (2012). Resistance training to improve power and sports performance in adolescent athletes: a systematic review and meta-analysis. *Journal of science and medicine in sport, 15*(6), 532–540.

Haugen, T., & Buchheit, M. (2016). Sprint Running Performance Monitoring: Methodological and Practical Considerations. *Sports Medicine, 46*(5), 641–656.

Haugen, T., McGhie, D., & Ettema, G. (2019). Sprint running: from fundamental mechanics to practice-a review. *European journal of applied physiology*.

Haugen, T., & Seiler, S. (2015). Physical and physiological testing of soccer players: why, what and how should we measure. *Sportscience*. (19), 10–26.

Haugen, T., Tønnessen, E., Hisdal, J., & Seiler, S. (2014a). The role and development of sprinting speed in soccer. *International journal of sports physiology and performance, 9*(3), 432–441.

Haugen, T., Tønnessen, E., Leirstein, S., Hem, E., & Seiler, S. (2014b). Not quite so fast: effect of training at 90% sprint speed on maximal and repeated-sprint ability in soccer players. *Journal of sports sciences, 32*(20), 1979–1986.

Haugen, T., Tønnessen, E., & Seiler, S. (2015a). 9.58 and 10.49: Nearing the citius end for 100 m? *International journal of sports physiology and performance, 10*(2), 269–272.

Haugen, T., Tønnessen, E., & Seiler, S. (2015b). Correction Factors for Photocell Sprint Timing With Flying Start. *International journal of sports physiology and performance, 10*(8), 1055–1057.

Haugen, T. A. (2017). Sprint conditioning of elite soccer players: Worth the effort or let‘s just buy faster players? *Sport Performance & Science Reports, 1*(1), 1–2.

Haugen, T. A., Breitschädel, F., & Samozino, P. (2018). Power-Force-Velocity Profiling of Sprinting Athletes: Methodological and Practical Considerations When Using Timing Gates. *Journal of Strength and Conditioning Research*.

Haugen, T. A., Tønnessen, E., & Seiler, S. K. (2012a). The difference is in the start: impact of timing and start procedure on sprint running performance. *Journal of Strength and Conditioning Research, 26*(2), 473–479.

Haugen, T. A., Tønnessen, E., & Seiler, S. (2012b). Speed and countermovement-jump characteristics of elite female soccer players, 1995-2010. *International journal of sports physiology and performance, 7*(4), 340–349.

Haugen, T. A., Tønnessen, E., & Seiler, S. (2013a). Anaerobic performance testing of professional soccer players 1995-2010. *International journal of sports physiology and performance, 8*(2), 148–156.

Haugen, T. A., Tønnessen, E., & Seiler, S. (2013b). Anaerobic Performance Testing of Professional Soccer Players 1995–2010. *International journal of sports physiology and performance, 8*(2), 148–156.

Haugen, T. A., Tønnessen, E., Svendsen, I. S., & Seiler, S. (2014c). Sprint time differences between single- and dual-beam timing systems. *Journal of Strength and Conditioning Research, 28*(8), 2376–2379.

Healy, R., Norris, M., Kenny, I. C., & Harrison, A. J. (2016). *A novel protocol to measure short sprint performance:* Procedia Engineering 147, 706-711.

Henry, G., Dawson, B., Lay, B., & Young, W. (2012). Effects of a feint on reactive agility performance. *Journal of sports sciences, 30*(8), 787–795.

Hetzler, R. K., Stickley, C. D., Lundquist, K. M., & Kimura, I. F. (2008). Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. *Journal of Strength and Conditioning Research, 22*(6), 1969–1976.

Hohmann, A., Lames, M., & Letzelter, M. (2007). *Einführung in die Trainingswissenschaft* (4th ed.). Limpert.

Hopkins, W. G. (2002). A scale of magnitudes for effect statistics. *A new view of statistics*, Available at: http://www.sportsci.org/resource/stats/effectmag.html.

Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sport sci*. (8), 1–7.

Hoppe, M. W., Baumgart, C., Polglaze, T., & Freiwald, J. (2018). Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PloS one, 13*(2), e0192708.

Houser, J. J., Mayhew, J. L., Meinke, A. H., Dodge, L. M., Jones, D. P., Anders, G. I., et al. (2010). Determining The Source Of Temporal Differences Between Electronic And Hand Timing Systems In The 40 Yard Dash: … & Horschig, A. D. *Journal of Strength and Conditioning Research, 24*, 1.

Howard, R. M., Conway, R., & Harrison, A. J. (2018). Muscle activity in sprinting: A review. *Sports biomechanics, 17*(1), 1–17.

Hristovski, R. (2007). Genetic and environmental influences on expert performance: Conflicting commonalities-toward bridging the gap. *International journal of sport psychology, 38*(1), 78.

Huijgen, B. C. H., Elferink-Gemser, M. T., Lemmink, K. A. P. M., & Visscher, C. (2014). Multidimensional performance characteristics in selected and deselected talented soccer players. *European journal of sport science, 14*(1), 2–10.

IAAF (2017). *International Association of Athletics Federations (IAAF). Competition rules 2018–2019. https://www.iaaf.org/about-iaaf/documents/rules-regulations. Assessed November 7, 2019.*

Iaia, F. M., Fiorenza, M., Perri, E., Alberti, G., Millet, G. P., & Bangsbo, J. (2015). The Effect of Two Speed Endurance Training Regimes on Performance of Soccer Players. *PloS one, 10*(9), e0138096.

Impellizzeri, F. M., Rampinini, E., Castagna, C., Bishop, D., Bravo, D. F., Tibaudi, A., & Wisloff, U. (2008). Validity of a repeated-sprint test for football. *International journal of sports medicine, 29*(11), 899–905.

Ingebrigtsen, J., Bendiksen, M., Randers, M. B., Castagna, C., Krustrup, P., & Holtermann, A. (2012). Yo-Yo IR2 testing of elite and sub-elite soccer players: performance, heart rate response and correlations to other interval tests. *Journal of sports sciences, 30*(13), 1337–1345.

Ingebrigtsen, J., Brochmann, M., Castagna, C., Bradley, P. S., Ade, J., Krustrup, P., & Holtermann, A. (2014). Relationships between field performance tests in high-level soccer players. *Journal of Strength and Conditioning Research, 28*(4), 942–949.

Ingebrigtsen, J., Dalen, T., Hjelde, G. H., Drust, B., & Wisløff, U. (2015). Acceleration and sprint profiles of a professional elite football team in match play. *European journal of sport science, 15*(2), 101–110.

Inglis, P., & Bird, S. P. (2016). Reactive agility tests: review and practical applications. *Journal of Australian Strength and Conditioning*. (24), 62-69.

Ispirlidis, I., Fatouros, I. G., Jamurtas, A. Z., Nikolaidis, M. G., Michailidis, I., Douroudos, I., et al. (2008). Time-course of changes in inflammatory and performance responses following a soccer game. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine, 18*(5), 423–431.

Issurin, V. B. (2013). Training transfer: scientific background and insights for practical application. *Sports medicine (Auckland, N.Z.), 43*(8), 675–694.

Jeffreys, I., Huggins, S., & Davies, N. (2018). Delivering a Gamespeed-Focused Speed and Agility Development Program in an English Premier League Soccer Academy. *Strength and Conditioning Journal, 40*(3), 23–32.

Jemni, M., Prince, M. S., & Baker, J. S. (2018). Assessing Cardiorespiratory Fitness of Soccer Players: Is Test Specificity the Issue?-A Review. *Sports medicine - open, 4*(1), 28.

Jennings, D., Cormack, S., Coutts, A. J., Boyd, L., & Aughey, R. J. (2010). The Validity and Reliability of GPS Units for Measuring Distance in Team Sport Specific Running Patterns. *International journal of sports physiology and performance, 5*(3), 328–341.

Johnson, T. M., Brown, L. E., Coburn, J. W., Judelson, D. A., Khamoui, A. V., Tran, T. T., & Uribe, B. P. (2010). Effect of four different starting stances on sprint time in collegiate volleyball players. *Journal of Strength and Conditioning Research, 24*(10), 2641–2646.

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., & Pruyn, E. C. (2012). The validity and reliability of 5-Hz global positioning system units to measure team sport movement demands. *Journal of Strength and Conditioning Research, 26*(3), 758–765.

Jordan, J. B., Korgaokar, A., Farley, R. S., Coons, J. M., & Caputo, J. L. (2014). Caffeine supplementation and reactive agility in elite youth soccer players. *Pediatric Exercise Science, 26*(2), 168–176.

Kadlubowski, B., Keiner, M., Hartmann, H., Wirth, K., & Frick, U. (2019). The Relationship between Change of Direction Tests in Elite Youth Soccer Players. *Sports (Basel, Switzerland), 7*(5).

Kaplan, T. (2010). Examination of repeated sprinting ability and fatigue index of soccer players according to their positions. *Journal of Strength and Conditioning Research, 24*(6), 1495–1501.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology, 9*(6), 718–727.

Keiner, M., Sander, A., Wirth, K., & Schmidtbleicher, D. (2014). Long-term strength training effects on change-of-direction sprint performance. *Journal of Strength and Conditioning Research, 28*(1), 223–231.

Kobal, R., Loturco, I., Gil, S., Cal Abad, C. C., Cuniyochi, R., Barroso, R., & Tricoli, V. (2016). Comparison of physical performance among Brazilian elite soccer players of different age-categories. *The Journal of sports medicine and physical fitness, 56*(4), 376–382.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility: a model and taxonomy. *Psychological Review, 97*(2), 253–270.

Kraan, G. A., van Veen, J., Snijders, C. J., & Storm, J. (2001). Starting from standing; why step backwards? *Journal of Biomechanics, 34*(2), 211–215.

Kraemer, W. J., Hakkinen, K., Triplett-Mcbride, N. T., Fry, A. C., Koziris, L. P., Ratamess, N. A., et al. (2003). Physiological changes with periodized resistance training in women tennis players. *Medicine and Science in Sports and Exercise, 35*(1), 157–168.

Kuntsi, J., Rogers, H., Swinard, G., Börger, N., van der Meere, J., Rijsdijk, F., & Asherson, P. (2006). Reaction time, inhibition, working memory and 'delay aversion' performance: genetic influences and their interpretation. *Psychological medicine, 36*(11), 1613–1624.

Kutlu, M., Yapici, H., & Yilmaz, A. (2017). Reliability and Validity of a New Test of Agility and Skill for Female Amateur Soccer Players. *Journal of human kinetics, 56*, 219–227.

Kutlu, M., Yapıcı, H., Yoncalık, O., & Celik, S. (2012). Comparison of a new test for agility and skill in soccer with other agility tests. *Journal of human kinetics, 33*, 143–150.

Lago, C., Casais, L., Dominguez, E., & Sampaio, J. (2010). The effects of situational variables on distance covered at various speeds in elite soccer. *European journal of sport science, 10*(2), 103–109.

Lamas, L., Drezner, R., Otranto, G., & Barrera, J. (2018). Analytic method for evaluating players' decisions in team sports: Applications to the soccer goalkeeper. *PloS one, 13*(2), e0191431.

Lämmle, L., Tittlbach, S., Oberger, J., Worth, A., & Bös, K. (2010). A Two-level Model of Motor Performance Ability. *Journal of Exercise Science & Fitness, 8*(1), 41–49.

Lee, M.J.C., Lloyd, D. G., Lay, B. S., Bourke, P. D., & Alderson, J. A. (2013). Effects of different visual stimuli on postures and knee moments during sidestepping. *Medicine and Science in Sports and Exercise, 45*(9), 1740–1748.

Lee, M.J.C., Lloyd, D. G., Lay, B. S., Bourke, P. D., & Alderson, J. A. (2017). Different visual stimuli affect body reorientation strategies during sidestepping. *Scandinavian journal of medicine & science in sports, 27*(5), 492–500.

Linke, D., Link, D., & Lames, M. (2018). Validation of electronic performance and tracking systems EPTS under field conditions. *PloS one, 13*(7), e0199519.

Linthorne, N. P. (1994). The Effect of Wind on 100-m Sprint Times. *Journal of Applied Biomechanics, 10*(2), 110–131.

Lippi, G., Longo, U. G., & Maffulli, N. (2010). Genetics and sports. *British medical bulletin, 93*, 27–47.

Little, T., & Williams, A. G. (2005). Specificity of acceleration, maximum speed, and agility in professional soccer players. *Journal of Strength and Conditioning Research, 19*(1), 76–80.

Lockie, R. G., Schultz, A. B., Callaghan, S. J., Jeffriess, M. D., & Berry, S. P. (2013). Reliability and Validity of a New Test of Change-of-Direction Speed for Field-Based Sports: the Change-of-Direction and Acceleration Test (CODAT). *Journal of Sports Science & Medicine, 12*(1), 88–96.

López-Segovia, M., Dellal, A., Chamari, K., & González-Badillo, J. J. (2014). Importance of muscle power variables in repeated and single sprint performance in soccer players. *Journal of human kinetics, 40*, 201–211.

López-Segovia, M., Marques, M. C., van den Tillaar, R., & González-Badillo, J. J. (2011). Relationships between vertical jump and full squat power outputs with sprint times in u21 soccer players. *Journal of human kinetics, 30*, 135–144.

López-Segovia, M., Pareja-Blanco, F., Jiménez-Reyes, P., & González-Badillo, J. J. (2015). Determinant factors of repeat sprint sequences in young soccer players. *International journal of sports medicine, 36*(2), 130–136.

Lorains, M., Ball, K., & MacMahon, C. (2013). Performance analysis for decision making in team sports. *International Journal of Performance Analysis in Sport, 13*(1), 110–119.

Los Arcos, A., Mendiguchia, J., & Yanci, J. (2017). Specificity of jumping, acceleration and quick change of direction motor abilities in soccer players. *Kinesiology: International journal of fundamental and applied kinesiology, 49*(1), 22–29.

Loturco, I., Kobal, R., Maldonado, T., Piazzi, A. F., Bottino, A., Kitamura, K., et al. (2017). Jump Squat is More Related to Sprinting and Jumping Abilities than Olympic Push Press. *International journal of sports medicine, 38*(8), 604–612.

Loturco, I., Nimphius, S., Kobal, R., Bottino, A., Zanetti, V., Pereira, L. A., & Jeffreys, I. (2018). Change-of direction deficit in elite young soccer players. *German Journal of Exercise and Sport Research, 48*(2), 228–234.

Loturco, I., Pereira, L. A., Kobal, R., Maldonado, T., Piazzi, A. F., Bottino, A., et al. (2016). Improving Sprint Performance in Soccer: Effectiveness of Jump Squat and Olympic Push Press Exercises. *PloS one, 11*(4), e0153958.

Loturco, I., Pereira, L. A., Kobal, R., Zanetti, V., Kitamura, K., Abad, C. C. C., & Nakamura, F. Y. (2015). Transference effect of vertical and horizontal plyometrics on sprint performance of high-level U-20 soccer players. *Journal of sports sciences, 33*(20), 2182–2191.

Loureiro, J., L. D. F. B., & Freitas, P. B. de (2016). Development of an Agility Test for Badminton Players and Assessment of Its Validity and Test-Retest Reliability. *International journal of sports physiology and performance, 11*(3), 305–310.

Ma, F., Yang, Y., Li, X., Zhou, F., Gao, C., Li, M., & Gao, L. (2013). The association of sport performance with ACE and ACTN3 genetic polymorphisms: a systematic review and meta-analysis. *PloS one, 8*(1), e54685.

Mackenzie, R., & Cushion, C. (2013). Performance analysis in football: a critical review and implications for future research. *Journal of sports sciences, 31*(6), 639–676.

Majumdar, A. S., & Robergs, R. A. (2011). The Science of Speed: Determinants of Performance in the 100 m Sprint. *International Journal of Sports Science & Coaching, 6*(3), 479–493.

Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2017). Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. *International journal of sports physiology and performance, 12*(Suppl 2), S218-S226.

Mann, D., Dicks, M., Cañal-Bruland, R., & van der Kamp, J. (2013). Neurophysiological studies may provide a misleading picture of how perceptual-motor interactions are coordinated. *i-Perception, 4*(1), 78–80.

Mann, D. T.Y., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-Cognitive Expertise in Sport: A Meta-Analysis. *Journal of Sport and Exercise Psychology, 29*(4), 457–478.

Mann, J. B., Ivey, P. J., Brechue, W. F., & Mayhew, J. L. (2015). Validity and reliability of hand and electronic timing for 40-yd sprint in college football players. *Journal of Strength and Conditioning Research, 29*(6), 1509–1514.

Manson, S. A., Brughelli, M., & Harris, N. K. (2014). Physiological characteristics of international female soccer players. *Journal of Strength and Conditioning Research, 28*(2), 308–318.

Martin, V., Sanchez-Sanchez, J., Ramírez-Campillo, R., Nakamura, F. Y., & Gonzalo-Skok, O. (2018). Validity of the RSA-RANDOM Test for Young Soccer Players. *International journal of sports medicine, 39*(11), 813–821.

Matlák, J., Tihanyi, J., & Rácz, L. (2016). Relationship Between Reactive Agility and Change of Direction Speed in Amateur Soccer Players. *Journal of Strength and Conditioning Research, 30*(6), 1547–1552.

Mayhew, J. L., Houser, J. J., Briney, B. B., Williams, T. B., Piper, F. C., & Brechue, W. F. (2010). Comparison between hand and electronic timing of 40-yd dash performance in college football players. *Journal of Strength and Conditioning Research, 24*(2), 447–451.

McCunn, R., Fünten, K. a. d., Fullagar, H. H. K., McKeown, I., & Meyer, T. (2016). Reliability and Association with Injury of Movement Screens: A Critical Review. *Sports medicine (Auckland, N.Z.), 46*(6), 763–781.

McFarland, I. T., Dawes, J. J., Elder, C. L., & Lockie, R. G. (2016). Relationship of Two Vertical Jumping Tests to Sprint and Change of Direction Speed among Male and Female Collegiate Soccer Players. *Sports (Basel, Switzerland), 4*(1).

McGawley, K., & Andersson, P.-I. (2013). The order of concurrent training does not affect soccer-related performance adaptations. *International journal of sports medicine, 34*(11), 983–990.

McLeod, P. (1987). Visual reaction time and high-speed ball games. *Perception, 16*(1), 49–59.

McMahon, J. J., Kyriakidou, I., Murphy, S., Rej, S. J., Young, A. L., & Comfort, P. (2017). Reliability of five-, ten- and twenty-metre sprint times in both sexes assessed us ing single-photocell electronic timing gates. *Professional Strength and Conditioning, 44*, 17–21.

McMorris, T. (2014). *Acquisition and performance of sports skills.* Chichester: John Wiley & Sons.

Meckel, Y., Machnai, O., & Eliakim, A. (2009). Relationship among repeated sprint tests, aerobic fitness, and anaerobic fitness in elite adolescent soccer players. *Journal of Strength and Conditioning Research, 23*(1), 163–169.

Mendez-Villanueva, A., & Buchheit, M. (2013). Football-specific fitness testing: adding value or confirming the evidence? *Journal of sports sciences, 31*(13), 1503–1508.

Mero, A. (1981). Relationships between the maximal running velocity, muscle fiber characteristics, force production and force relaxation of sprinters. *Scand J Sports Sci*. (3), 16–22.

Mero, A., Komi, P. V., & Gregor, R. J. (1992). Biomechanics of sprint running: A review. *Sports medicine (Auckland, N.Z.), 13*(6), 376–392.

Meyer, T., & Faude, O. (2006). Feldtests im Fußball. *Deutsche Zeitschrift für Sportmedizin, 57*, 147–148.

Meyer, T., Ohlendorf, K., & Kindermann, W. (2000). Konditionelle Fähigkeiten deutscher Spitzenfußballer im Längsschnitt: Analytischer Vergleich mit Videoanalyse-Daten der Fußball-Bundesliga (Conditional abilities of German elite football players in longitudinal section: Analytical comparison with video analysis in the first German national league.). *Deutsche Zeitschrift für Sportmedizin, 51*(7&8), 271–277.

Meylan, C., Trewin, J., & McKean, K. (2017). Quantifying Explosive Actions in International Women's Soccer. *International journal of sports physiology and performance, 12*(3), 310–315.

Miller, D. K., Kieffer, H. S., Kemp, H. E., & Torres, S. E. (2011). Off-season physiological profiles of elite National Collegiate Athletic Association Division III male soccer players. *Journal of Strength and Conditioning Research, 25*(6), 1508–1513.

Miller, M. G., Herniman, J. J., Ricard, M. D., Cheatham, C.C., & Michael, T. J. (2006). The Effects of a 6-Week Plyometric Training Program on Agility. *Journal of Sports Science & Medicine, 5*(3), 459–465.

Mirkov, D., Nedeljkovic, A., Kukolj, M., Ugarkovic, D., & Jaric, S. (2008). Evaluation of the reliability of soccer-specific field tests. *Journal of Strength and Conditioning Research, 22*(4), 1046–1050.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS medicine, 6*(7), e1000097.

Mohr, M., Krustrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of sports sciences, 21*(7), 519–528.

Moir, G., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of Strength and Conditioning Research, 18*(2), 276–280.

Morin, J. B., Jeannin, T., Chevallier, B., & Belli, A. (2006). Spring-mass model characteristics during sprint running: correlation with performance and fatigue-induced changes. *International journal of sports medicine, 27*(2), 158–165.

Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *International journal of sports physiology and performance, 11*(2), 267–272.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J.-R. (2012). Mechanical determinants of 100-m sprint running performance. *European journal of applied physiology, 112*(11), 3921–3930.

Mujika, I., Santisteban, J., & Castagna, C. (2009a). In-season effect of short-term sprint and power training programs on elite junior soccer players. *Journal of Strength and Conditioning Research, 23*(9), 2581–2587.

Mujika, I., Santisteban, J., Impellizzeri, F. M., & Castagna, C. (2009b). Fitness determinants of success in men's and women's football. *Journal of sports sciences, 27*(2), 107–114.

Mureika, J. R. (2006). The effects of temperature, humidity, and barometric pressure on short-sprint race times. *Canadian Journal of Physics, 84*(4), 311–324.

Nakamura, F. Y., Pereira, L. A., Loturco, I., Rosseti, M., Moura, F. A., & Bradley, P. S. (2017). Repeated-Sprint Sequences During Female Soccer Matches Using Fixed and Individual Speed Thresholds. *Journal of Strength and Conditioning Research, 31*(7), 1802–1810.

Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2014). The influence of soccer playing actions on the recovery kinetics after a soccer match. *Journal of Strength and Conditioning Research, 28*(6), 1517–1523.

Nikolaidis, P. T., Knechtle, B., Clemente, F., & Torres-Luque, G. (2016). Reference values for the sprint performance in male football players aged from 9–35 years. *Biomedical Human Kinetics, 8*(1), 103–112.

Nimphius, S., Callaghan, S. J., Bezodis, N. E., & Lockie, R. G. (2018). Change of Direction and Agility Tests: Challenging Our Current Measures of Performance. *Strength and Conditioning Journal, 40*(1), 26–38.

Nuri, L., Shadmehr, A., Ghotbi, N., & Attarbashi Moghadam, B. (2013). Reaction time and anticipatory skill of athletes in open and closed skill-dominated sport. *European journal of sport science, 13*(5), 431–436.

O'Donoghue, P. (2004). Sources of variability in time-motion data; measurement error and within player variability in work-rate. *International Journal of Performance Analysis in Sport, 4*(2), 42–49.

Oliver, J. L., & Meyers, R. W. (2009). Reliability and Generality of Measures of Acceleration, Planned Agility, and Reactive Agility. *International journal of sports physiology and performance, 4*(3), 345–354.

Palucci Vieira, L. H., Carling, C., Barbieri, F. A., Aquino, R., & Santiago, P. R. P. (2019). Match Running Performance in Young Soccer Players: A Systematic Review. *Sports medicine (Auckland, N.Z.)*.

Pareja-Blanco, F., Suarez-Arrones, L., Rodríguez-Rosell, D., López-Segovia, M., Jiménez-Reyes, P., Bachero-Mena, B., & González-Badillo, J. J. (2016). Evolution of Determinant Factors of Repeated Sprint Ability. *Journal of human kinetics, 54*, 115–126.

Paul, D. J., Bradley, P. S., & Nassis, G. P. (2015). Factors affecting match running performance of elite soccer players: shedding some light on the complexity. *International journal of sports physiology and performance, 10*(4), 516–519.

Paul, D. J., Gabbett, T. J., & Nassis, G. P. (2016). Agility in Team Sports: Testing, Training and Factors Affecting Performance. *Sports medicine (Auckland, N.Z.), 46*(3), 421–442.

Paul, D. J., & Nassis, G. P. (2015a). Physical Fitness Testing in Youth Soccer: Issues and Considerations Regarding Reliability, Validity, and Sensitivity. *Pediatric Exercise Science, 27*(3), 301–313.

Paul, D. J., & Nassis, G. P. (2015b). Testing strength and power in soccer players: the application of conventional and traditional methods of assessment. *Journal of Strength and Conditioning Research, 29*(6), 1748–1758.

Pesce, C. (2012). Shifting the Focus from Quantitative to Qualitative Exercise Characteristics in Exercise and Cognition Research. *Journal of Sport and Exercise Psychology, 34*(6), 766–786.

Petrakos, G., Morin, J.-B., & Egan, B. (2016). Resisted Sled Sprint Training to Improve Sprint Performance: A Systematic Review. *Sports Medicine, 46*(3), 381–400.

Pitsiladis, Y., Davis, A., & Johnson, D. (2011). The Science of Speed: Determinants of Performance in the 100 m Sprint. *International Journal of Sports Science & Coaching, 6*(3), 495–498.

Pojskic, H., Åslin, E., Krolo, A., Jukic, I., Uljevic, O., Spasic, M., & Sekulic, D. (2018). Importance of Reactive Agility and Change of Direction Speed in Differentiating Performance Levels in Junior Soccer Players: Reliability and Validity of Newly Developed Soccer-Specific Tests. *Frontiers in physiology, 9*.

Portas, M. D., Harley, J. A., Barnes, C. A., & Rush, C. J. (2010). The Validity and Reliability of 1-Hz and 5-Hz Global Positioning Systems for Linear, Multidirectional, and Soccer-Specific Activities. *International journal of sports physiology and performance, 5*(4), 448–458.

Portas, M. D., Rush, C. J., Barnes, C. A., & Batterham, A. M. (2007). Method comparison of linear distance and velocity measurements with global positioning satellite (GPS) and the timing gate techniques. *J Sports Sci Med*. (6, (Suppl 10)).

Pyne, D. B., Saunders, P. U., Montgomery, P. G., Hewitt, A. J., & Sheehan, K. (2008). Relationships between repeated sprint testing, speed, and endurance. *Journal of Strength and Conditioning Research, 22*(5), 1633–1637.

Pyne, D. B., Spencer, M., & Mujika, I. (2014). Improving the value of fitness testing for football. *International journal of sports physiology and performance, 9*(3), 511–514.

Ramirez-Campillo, R., Alvarez, C., García-Pinillos, F., Sanchez-Sanchez, J., Yanci, J., Castillo, D., et al. (2018). Optimal Reactive Strength Index: Is It an Accurate Variable to Optimize Plyometric Training Effects on Measures of Physical Fitness in Young Soccer Players? *Journal of Strength and Conditioning Research, 32*(4), 885–893.

Rampinini, E., Bishop, D., Marcora, S. M., Ferrari Bravo, D., Sassi, R., & Impellizzeri, F. M. (2007a). Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *0172-4622, 28*(3), 228–235.

Rampinini, E., Coutts, A. J., Castagna, C., Sassi, R., & Impellizzeri, F. M. (2007b). Variation in top level soccer match performance. *0172-4622, 28*(12), 1018–1024.

Rampinini, E., Sassi, A., Morelli, A., Mazzoni, S., Fanchini, M., & Coutts, A. J. (2009). Repeated-sprint ability in professional and amateur soccer players. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme, 34*(6), 1048–1054.

Randers, M. B., Mujika, I., Hewitt, A., Santisteban, J., Bischoff, R., Solano, R., et al. (2010). Application of four different football match analysis systems: a comparative study. *Journal of sports sciences, 28*(2), 171–182.

Rauter, S., Coh, M., Vodicar, J., Zvan, M., Krizaj, J., Simenko, J., et al. (2018). Analysis of reactive agility and change-of-direction speed between soccer players and physical education students. *Human Movement, 2018*(2), 68–74.

Rawstorn, J. C., Maddison, R., Ali, A., Foskett, A., & Gant, N. (2014). Rapid directional change degrades GPS distance measurement validity during intermittent intensity running. *PloS one, 9*(4), e93693.

Rebelo, A., Brito, J., Maia, J., Coelho-e-Silva, M. J., Figueiredo, A. J., Bangsbo, J., et al. (2013). Anthropometric characteristics, physical fitness and technical performance of under-19 soccer players by competitive level and field position. *International journal of sports medicine, 34*(4), 312–317.

Rehhagel, J. (2011). *Entwicklung einer Testbatterie zur Diagnostik und Steuerung der Schnelligkeit im Sportspiel Fußball*. Dissertation.

Requena, B., Sáez-Sáez de Villarreal, E., Gapeyeva, H., Ereline, J., García, I., & Pääsuke, M. (2011). Relationship between postactivation potentiation of knee extensor muscles, sprinting and vertical jumping performance in professional soccer players. *Journal of Strength and Conditioning Research, 25*(2), 367–373.

Rey, E., Padrón-Cabo, A., Costa, P. B., & Barcala-Furelos, R. (2017). The Effects of Foam Rolling as a Recovery Tool in Professional Soccer Players. *Journal of Strength and Conditioning Research*.

Richards, J. G. (1999). The measurement of human motion: A comparison of commercially available systems. *Human movement science, 18*(5), 589–602.

Risso, F. G., Jalilvand, F., Orjalo, A. J., Moreno, M. R., Davis, D. L., Birmingham-Babauta, S. A., et al. (2017). Physiological Characteristics of Projected Starters and Non-Starters in the Field Positions from a Division I Women's Soccer Team. *International Journal of Exercise Science, 10*(4), 568–579.

Robertson, S., Kremer, P., Aisbett, B., Tran, J., & Cerin, E. (2017). Consensus on measurement properties and feasibility of performance tests for the exercise and sport sciences: A Delphi study. *Sports medicine - open, 3*(1), 2.

Robinson, G., O'Donoghue, P., & Wooster, B. (2011). Path changes in the movement of English Premier League soccer players. *The Journal of sports medicine and physical fitness, 51*(2), 220–226.

Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., & Jones, B. (2017). Validity of 10-HZ GPS and Timing Gates for Assessing Maximum Velocity in Professional Rugby Union Players. *International journal of sports physiology and performance, 12*(6), 836–839.

Romeas, T., Guldner, A., & Faubert, J. (2016). 3D-Multiple Object Tracking training task improves passing decision-making accuracy in soccer players. *Psychology of Sport and Exercise, 22*, 1–9.

Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., et al. (2017). Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods: Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., … & Balsalobre-Fernández, C. *European journal of sport science, 17*(4), 386–392.

Ronnestad, B. R., Kvamme, N. H., Sunde, A., & Raastad, T. (2008). Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *Journal of Strength and Conditioning Research, 22*(3), 773–780.

Ross, A., Leveritt, M., & Riek, S. (2001). Neural influences on sprint running: training adaptations and acute responses. *Sports medicine (Auckland, N.Z.), 31*(6), 409–425.

Rouissi, M., Chtara, M., Owen, A., Burnett, A., & Chamari, K. (2017). Change of direction ability in young elite soccer players: determining factors vary with angle variation. *The Journal of sports medicine and physical fitness, 57*(7-8), 960–968.

Rumpf, M. C., Cronin, J. B., Oliver, J. L., & Hughes, M. (2011). Assessing Youth Sprint Ability–Methodological Issues, Reliability and Performance Data. *Pediatric Exercise Science, 23*(4), 442–467.

Rumpf, M. C., Lockie, R. G., Cronin, J. B., & Jalilvand, F. (2016). Effect of Different Sprint Training Methods on Sprint Performance Over Various Distances: A Brief Review. *Journal of Strength and Conditioning Research, 30*(6), 1767–1785.

Ruscello, B., Tozzo, N., Briotti, G., Padua, E., Ponzetti, F., & D'Ottavio, S. (2013). Influence of the number of trials and the exercise to rest ratio in repeated sprint ability, with changes of direction and orientation. *Journal of Strength and Conditioning Research, 27*(7), 1904–1919.

Russell, M., Benton, D., & Kingsley, M. (2010). Reliability and construct validity of soccer skills tests that measure passing, shooting, and dribbling. *Journal of sports sciences, 28*(13), 1399–1408.

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Morin, J. B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian journal of medicine & science in sports, 26*(6), 648–658.

Sarmento, H., Marcelino, R., Anguera, M. T., CampaniÇo, J., Matos, N., & LeitÃo, J. C. (2014). Match analysis in football: a systematic review. *Journal of sports sciences, 32*(20), 1831–1843.

Sassi, R. H., Dardouri, W., Yahmed, M. H., Gmada, N., Mahfoudhi, M. E., & Gharbi, Z. (2009). Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. *Journal of Strength and Conditioning Research, 23*(6), 1644–1651.

Sawczuk, T., Jones, B., Scantlebury, S., Weakley, J., Read, D., Costello, N., et al. (2017). Between-Day Reliability and Usefulness of a Fitness Testing Battery in Youth Sport Athletes: Reference Data for Practitioners. *Measurement in Physical Education and Exercise Science, 53*, 1–8.

Sayers, A. L., Farley, R. S., Fuller, D. K., Jubenville, C. B., & Caputo, J. L. (2008). The effect of static stretching on phases of sprint performance in elite soccer players. *Journal of Strength and Conditioning Research, 22*(5), 1416–1421.

Sayers, M. (2000). Running techniques for field sport players. *Sports Coach: Australian coaching magazine, 23*(1), 26–27.

Scanlan, A., Humphries, B., Tucker, P. S., & Dalbo, V. (2014). The influence of physical and cognitive factors on reactive agility performance in men basketball players. *Journal of sports sciences, 32*(4), 367–374.

Schimpchen, J., Skorski, S., St. Nopp, & Meyer, T. (2016). Are "classical" tests of repeated-sprint ability in football externally valid? A new approach to determine in-game sprinting behaviour in elite football players. *Journal of sports sciences, 34*(6), 519–526.

Schmidt, R., & Lee, T. (2011). *Motor Control & Learning–5th ED.* Champaign: Human Kinetics.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*(4), 225–260.

Schnabel, G., & Witt, M. (2017). Die motorische Schnelligkeit: Positionen, Untersuchungsergebnisse und Folgerungen. In J. Hartmann, J. Krug, P. Ragert, & M. Witt (Eds.), *Motorik - Leistung - Training (Sport und Wissenschaft). Festschrift zum 90. Geburtstag von Prof. Dr. sc. Günter Schnabel, 13, 17.* (pp. 42–55). Lehmanns Media.

Scott, M. T., Scott, T. J., & Kelly, V. G. (2016). The Validity and Reliability of Global Positioning Systems in Team Sport: A Brief Review. *Journal of Strength and Conditioning Research, 30*(5), 1470–1490.

Serpell, B. G., Ford, M., & Young, W. B. (2010). The development of a new test of agility for rugby league. *Journal of Strength and Conditioning Research, 24*(12), 3270–3277.

Serpell, B. G., Young, W. B., & Ford, M. (2011). Are the perceptual and decision-making components of agility trainable? A preliminary investigation. *Journal of Strength and Conditioning Research, 25*(5), 1240–1248.

Serpiello, F. R., Duthie, G. M., Moran, C., Kovacevic, D., Selimi, E., & Varley, M. C. (2018). The Occurrence of Repeated High Acceleration Ability (RHAA) in Elite Youth Football. *International journal of sports medicine, 39*(7), 502–507.

Shadmehr, R. (2017). Learning to Predict and Control the Physics of Our Movements. *The Journal of neuroscience : the official journal of the Society for Neuroscience, 37*(7), 1663–1671.

Shalfawi, S. A., Enoksen, E., Tønnessen, E., & Ingebrigtsen, J. (2012). Assessing test-retest reliability of the portable Brower speed trap II testing system. *International Journal of Fundamental and Applied Kinesiology, 44*(1), 24–30.

Shalfawi, S. A., Young, M., Tønnessen, E., Haugen, T. A., & Enoksen, E. (2013a). The effect of repeated agility training vs. repeated sprint training on elite female soccer playsers physical performance. *Kinesiologia Slovenica, 19*(3), 29–42. Retrieved November 07, 2018.

Shalfawi, S. A. I., Haugen, T., Jakobsen, T. A., Enoksen, E., & Tønnessen, E. (2013b). The effect of combined resisted agility and repeated sprint training vs. strength training on female elite soccer players. *Journal of Strength and Conditioning Research, 27*(11), 2966–2972.

Sheppard, J., Dawes, J. J., Jeffreys, I., Spiteri, T., & Nimphius, S. (2014). Broadening The View Of Agility: A Scientific Review Of The Literature. *Journal of Australian Strength and Conditioning, 22*(3), 6–25.

Sheppard, J. M., & Young, W. B. (2006). Agility literature review: classifications, training and testing. *Journal of sports sciences, 24*(9), 919–932.

Sheppard, J. M., Young, W. B., Doyle, T. L. A., Sheppard, T. A., & Newton, R. U. (2006). An evaluation of a new test of reactive agility and its relationship to sprint speed and change of direction speed. *Journal of science and medicine in sport, 9*(4), 342–349.

Sheppard, L. D., & Vernon, P. A. (2008). Intelligence and speed of information-processing: A review of 50 years of research. *Personality and Individual Differences, 44*(3), 535–551.

Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: translating research into clinical practice.* Lippincott: Williams & Wilkins.

Silva, J. R., Ascensão, A., Marques, F., Seabra, A., Rebelo, A., & Magalhães, J. (2013a). Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *European journal of applied physiology, 113*(9), 2193–2201.

Silva, J. R., Magalhães, J. F., Ascensão, A. A., Oliveira, E. M., Seabra, A. F., & Rebelo, A. N. (2011). Individual match playing time during the season affects fitness-related parameters of male professional soccer players. *Journal of Strength and Conditioning Research, 25*(10), 2729–2739.

Silva, J. R., Magalhães, J., Ascensão, A., Seabra, A. F., & Rebelo, A. N. (2013b). Training status and match activity of professional soccer players throughout a season. *Journal of Strength and Conditioning Research, 27*(1), 20–30.

Silvestre, R., Kraemer, W. J., West, C., Judelson, D. A., Spiering, B. A., Vingren, J. L., et al. (2006a). Body composition and physical performance during a National Collegiate Athletic Association Division I men's soccer season. *Journal of Strength and Conditioning Research, 20*(4), 962–970.

Silvestre, R., West, C., Maresh, C. M., & Kraemer, W. J. (2006b). Body composition and physical performance in men's soccer: a study of a National Collegiate Athletic Association Division I team. *Journal of Strength and Conditioning Research, 20*(1), 177–183.

Šimonek, J., Horička, P., & Hianik, J. (2017). The differences in acceleration, maximal speed and agility between soccer, basketball, volleyball and handball players. *Journal of Human Sport and Exercise, 12*(73-82).

Simperingham, K. D., Cronin, J. B., & Ross, A. (2016). Advances in Sprint Acceleration Profiling for Field-Based Team-Sport Athletes: Utility, Reliability, Validity and Limitations. *Sports Medicine, 46*(11), 1619–1645.

Sjökvist, J., Laurent, M. C., Richardson, M., Curtner-Smith, M., Holmberg, H.-C., & Bishop, P. A. (2011). Recovery from high-intensity training sessions in female soccer players. *Journal of Strength and Conditioning Research, 25*(6), 1726–1735.

Slimani, M., & Nikolaidis, P. T. (2017). Anthropometric and physiological characteristics of male Soccer players according to their competitive level, playing position and age group: a systematic review. *J Sports Med Phys Fitness, 59*(1), 141–163.

Small, K., McNaughton, L. R., Greig, M., Lohkamp, M., & Lovell, R. (2009). Soccer fatigue, sprinting and hamstring injury risk. *International journal of sports medicine, 30*(8), 573–578.

Smith, D. M. (2016). Neurophysiology of action anticipation in athletes: A systematic review. *Neuroscience and biobehavioral reviews, 60*, 115–120.

Sonderegger, K., Tschopp, M., & Taube, W. (2016). The Challenge of Evaluating the Intensity of Short Actions in Soccer: A New Methodological Approach Using Percentage Acceleration. *PloS one, 11*(11), e0166534.

Spasic, M., Krolo, A., Zenic, N., Delextrat, A., & Sekulic, D. (2015). Reactive Agility Performance in Handball; Development and Evaluation of a Sport-Specific Measurement Protocol. *Journal of Sports Science & Medicine, 14*(3), 501–506.

Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities:specific to field-based team sports. *Sports medicine (Auckland, N.Z.), 35*(12), 1025–1044.

Spierer, D. K., Petersen, R. A., & Duffy, K. (2011). Response time to stimuli in division I soccer players. *Journal of Strength and Conditioning Research, 25*(4), 1134–1141.

Spiteri, T., McIntyre, F., Specos, C., & Myszka, S. (2018). Cognitive Training for Agility. *Strength and Conditioning Journal, 40*(1), 39–46.

Spiteri, T., Newton, R. U., Binetti, M., Hart, N. H., Sheppard, J. M., & Nimphius, S. (2015). Mechanical Determinants of Faster Change of Direction and Agility Performance in Female Basketball Athletes. *Journal of Strength and Conditioning Research, 29*(8), 2205–2214.

Spiteri, T., Nimphius, S., & Wilkie, J. (2012). Comparison of running times during reactive offensive and defensive agility protocols. *Journal of Australian Strength & Conditioning*.

Sporis, G., Jukic, I., Milanovic, L., & Vucetic, V. (2010). Reliability and factorial validity of agility tests for soccer players. *Journal of Strength and Conditioning Research, 24*(3), 679–686.

Sporis, G., Jukic, I., Ostojic, S. M., & Milanovic, D. (2009). Fitness profiling in soccer: physical and physiologic characteristics of elite players. *Journal of Strength and Conditioning Research, 23*(7), 1947–1953.

Stalker Radar (2010). *ATS II Professional Sports Radar: owner's manual.*

Stanton, R., Hayman, M., Humphris, N., Borgelt, H., Fox, J., Del Vecchio, L., & Humphries, B. (2016). Validity of a Smartphone-Based Application for Determining Sprinting Performance. *Journal of sports medicine (Hindawi Publishing Corporation)*, 7476820.

Stefanyshyn, D., & Fusco, C. (2004). Increased shoe bending stiffness increases sprint performance. *Sports biomechanics, 3*(1), 55–66.

Stølen, T., Chamari, K., Castagna, C., & Wisløff, U. (2005). Physiology of Soccer: An Update. *Sports Medicine, 35*(6), 501–536.

Svensson, M., & Drust, B. (2005). Testing soccer players. *Journal of sports sciences, 23*(6), 601–618.

Sweeting, A. J., Cormack, S. J., Morgan, S., & Aughey, R. J. (2017). When Is a Sprint a Sprint? A Review of the Analysis of Team-Sport Athlete Activity Profile. *Frontiers in physiology, 8*, 432.

Taatgen, N. A. (2013). The nature and transfer of cognitive skills. *Psychological Review, 120*(3), 439–471.

Taube, W., Leukel, C., & Gollhofer, A. (2012). How neurons make us jump: the neural control of stretch-shortening cycle movements. *Exercise and sport sciences reviews, 40*(2), 106–115.

Taylor, J., Macpherson, T., Spears, I., & Weston, M. (2015). The Effects of Repeated-Sprint Training on Field-Based Fitness Measures: A Meta-Analysis of Controlled and Non-Controlled Trials. *Sports Medicine, 45*(6), 881–891.

Taylor, J. B., Wright, A. A., Dischiavi, S. L., Townsend, M. A., & Marmon, A. R. (2017). Activity Demands During Multi-Directional Team Sports: A Systematic Review. *Sports Medicine, 47*(12), 2533–2551.

Taylor, J. M., Macpherson, T. W., Spears, I. R., & Weston, M. (2016). Repeated Sprints: An Independent Not Dependent Variable. *International journal of sports physiology and performance, 11*(7), 693–696.

Terwee, C. B., Mokkink, L. B., Knol, D. L., Ostelo, R. W., Bouter, L. M., & Vet, H. C. de (2011). Rating the methodological quality in systematic reviews of studies on measurement properties: a scoring system for the COSMIN checklist. *Quality of Life Research, 21*(4), 651–657.

Thomas, K., French, D., & Hayes, P. R. (2009). The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *Journal of Strength and Conditioning Research, 23*(1), 332–335.

Tønnessen, E., Shalfawi, S. A., Haugen, T., & Enoksen, E. (2011). The effect of 40-m repeated sprint training on maximum sprinting speed, repeated sprint speed endurance, vertical jump, and aerobic capacity in young elite male soccer players. *Journal of Strength and Conditioning Research, 25*(9), 2364–2370.

Tønnessen, E., Svendsen, I. S., Olsen, I. C., Guttormsen, A., & Haugen, T. (2015). Performance development in adolescent track and field athletes according to age, sex and sport discipline. *PloS one, 10*(6), e0129014.

Travassos, B., Araújo, D., Davids, K., O'Hara, K., Leitão, J., & Cortinhas, A. (2013). Expertise effects on decision-making in sport are constrained by requisite response behaviours – A meta-analysis. *Psychology of Sport and Exercise, 14*(2), 211–219.

Trecroci, A., Longo, S., Perri, E., Iaia, F. M., & Alberti, G. (2018). Field-based physical performance of elite and sub-elite middle-adolescent soccer players. *Research in sports medicine*, 1–12.

Trewin, J., Meylan, C., Varley, M. C., & Cronin, J. (2017). The influence of situational and environmental factors on match-running in soccer: a systematic review. *Science and Medicine in Football, 1*(2), 183–194.

Tucker, R., & Collins, M. (2012). What makes champions? A review of the relative contribution of genes and training to sporting success. *British journal of sports medicine, 46*(8), 555–561.

Turner, A., Walker, S., Stembridge, M., Coneyworth, P., Reed, G., Birdsey, L., et al. (2011). A testing battery for the assessment of fitness in soccer players. *Strength & Conditioning Journal, 33*(5), 29–39.

Turner, A. N., & Stewart, P. F. (2013). Repeat Sprint Ability. *Strength and Conditioning Journal, 35*(1), 37–41.

Turner, A. N., & Stewart, P. F. (2014). Strength and Conditioning for Soccer Players. *Strength and Conditioning Journal, 36*(4), 1–13.

Varley, M. C., & Aughey, R. J. (2013). Acceleration profiles in elite Australian soccer. *International journal of sports medicine, 34*(1), 34–39.

Varley, M. C., Gabbett, T., & Aughey, R. J. (2014). Activity profiles of professional soccer, rugby league and Australian football match play. *Journal of sports sciences, 32*(20), 1858–1866.

Veale, J. P., Pearce, A. J., & Carlson, J. S. (2010). Reliability and Validity of a Reactive Agility Test for Australian Football. *International journal of sports physiology and performance, 5*(2), 239–248.

Verkhoshansky, Y. V. (1996). Quickness and velocity in sports movements. *New Studies in Athletics*. (11), 29–38.

Vescovi, J. D. (2012). Sprint speed characteristics of high-level American female soccer players: Female Athletes in Motion (FAiM) study. *Journal of science and medicine in sport, 15*(5), 474–478.

Vescovi, J. D., & McGuigan, M. R. (2008). Relationships between sprinting, agility, and jump ability in female athletes. *Journal of sports sciences, 26*(1), 97–107.

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., & Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PloS one, 7*(4), e34731.

Vestberg, T., Reinebo, G., Maurex, L., Ingvar, M., & Petrovic, P. (2017). Core executive functions are associated with success in young elite soccer players. *PloS one, 12*(2), e0170845.

Vicente-Rodríguez, G., Rey-López, J. P., Ruíz, J. R., Jiménez-Pavón, D., Bergman, P., Ciarapica, D., et al. (2011). Interrater reliability and time measurement validity of speed-agility field tests in adolescents. *Journal of Strength and Conditioning Research, 25*(7), 2059–2063.

Vigh-Larsen, J. F., Dalgas, U., & Andersen, T. B. (2018). Position-Specific Acceleration and Deceleration Profiles in Elite Youth and Senior Soccer Players. *Journal of Strength and Conditioning Research, 32*(4), 1114–1122.

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., & Roberts, B. (2010). Are expert athletes ‘expert’ in the cognitive laboratory?: A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology, 24*(6), 812–826.

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011). Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *Journal of sports sciences, 29*(15), 1613–1619.

Walker, S., & Turner, A. N. (2009). A One-Day Field Test Battery for the Assessment of Aerobic Capacity, Anaerobic Capacity, Speed, and Agility of Soccer Players. *Strength and Conditioning Journal, 31*(6), 52–60.

Wallace, J. L., & Norton, K.I. (2014). Evolution of World Cup soccer final games 1966-2010: Game structure, speed and play patterns. *Journal of science and medicine in sport, 17*(2), 223–228.

Wang, G., Padmanabhan, S., Wolfarth, B., Fuku, N., Lucia, A., Ahmetov, I. I., et al. (2013). Genomics of elite sporting performance: what little we know and necessary advances. *Advances in genetics, 84*, 123–149.

Ward-Smith, A. J. (1999). New insights into the effect of wind assistance on sprinting performance. *Journal of sports sciences, 17*(4), 325–334.

Weinhandl, J. T., Earl-Boehm, J. E., Ebersole, K. T., Huddleston, W. E., Armstrong, B.S.R., & O'Connor, K. M. (2013). Anticipatory effects on anterior cruciate ligament loading during sidestep cutting. *Clinical biomechanics (Bristol, Avon), 28*(6), 655–663.

Wheeler, K. W., & Sayers, M.G.L. (2010). Modification of Agility Running Technique in Reaction to a Defender in Rugby Union. *Journal of Sports Science & Medicine, 9*(3), 445–451.

White, A., Hills, S. P., Cooke, C. B., Batten, T., Kilduff, L. P., Cook, C. J., et al. (2018). Match-Play and Performance Test Responses of Soccer Goalkeepers: A Review of Current Literature. *Sports Medicine, 48*(11), 2497–2516.

Whitehead, S., Till, K., Weaving, D., & Jones, B. (2018). The Use of Microtechnology to Quantify the Peak Match Demands of the Football Codes: A Systematic Review. *Sports Medicine, 48*(11), 2549–2575.

Whitting, J. W., de Melker Worms, J. L., Maurer, C., Nigg, S. R., & Nigg, B. M. (2013). Measuring lateral shuffle and side cut performance. *Journal of Strength and Conditioning Research, 27*(11), 3197–3203.

Williams, A. M., & Ford, P. R. (2008). Expertise and expert performance in sport. *International Review of Sport and Exercise Psychology, 1*(1), 4–18.

Williams, A. M., Ford, P. R., Eccles, D. W., & Ward, P. (2011). Perceptual-cognitive expertise in sport and its acquisition: Implications for applied cognitive psychology. *Applied Cognitive Psychology, 25*(3), 432–442.

Williams, J. D., Abt, G., & Kilding, A. E. (2010). Ball-Sport Endurance and Sprint Test (BEAST90): validity and reliability of a 90-minute soccer performance test. *Journal of Strength and Conditioning Research, 24*(12), 3209–3218.

Winter, E. M., Abt, G., Brookes, F. B. C., Challis, J. H., Fowler, N. E., Knudson, D. V., et al. (2016). Misuse of "Power" and Other Mechanical Terms in Sport and Exercise Science Research. *Journal of Strength and Conditioning Research, 30*(1), 292–300.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature neuroscience, 3 Suppl*, 1212–1217.

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks, 11*(7-8), 1317–1329.

Wong, D. P., Chan, G. S., & Smith, A. W. (2012). Repeated-sprint and change-of-direction abilities in physically active individuals and soccer players: training and testing implications. *Journal of Strength and Conditioning Research, 26*(9), 2324–2330.

Wong, M. A., Dobbs, I. J., Watkins, C. M., Barillas, S. R., Lin, A., Archer, D. C., et al. (2017). Sled Towing Acutely Decreases Acceleration Sprint Time. *Journal of Strength and Conditioning Research, 31*(11), 3046–3051.

World Medical Association (WMA) (2013). World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. *JAMA, 310*(20), 2191–2194.

Wragg, C. B., Maxwell, N. S., & Doust, J. H. (2000). Evaluation of the reliability and validity of a soccer-specific field test of repeated sprint ability. *European journal of applied physiology, 83*(1), 77–83.

Wright, M., Geus, E. de, Ando, J., Luciano, M., Posthuma, D., Ono, Y., et al. (2001). Genetics of Cognition: Outline of a Collaborative Twin Study. *Twin Research, 4*(01), 48–56.

Yanci, J., Calleja-Gonzalez, J., Cámara, J., Mejuto, G., San Román, J., & Los Arcos, A. (2017). Validity and reliability of a global positioning system to assess 20 m sprint performance in soccer players. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 231*(1), 68–71.

Yanci, J., Los Arcos, A., & Brughelli, M. (2014). Relationships between sprint, agility, one- and two-leg vertical and horizonztal jump in soccer players. *Kinesiology: International journal of fundamental and applied kinesiology, 46*(2), 194–201.

Yeadon, M. R., Kato, T., & Kerwin, D. G. (1999). Measuring running speed using photocells. *Journal of sports sciences, 17*(3), 249–257.

Yeo, S.-H., Franklin, D. W., & Wolpert, D. M. (2016). When Optimal Feedback Control Is Not Enough: Feedforward Strategies Are Required for Optimal Control with Active Sensing. *PLoS computational biology, 12*(12), e1005190.

Young, W., & Farrow, D. (2013). The Importance of a Sport-Specific Stimulus for Training Agility. *Strength and Conditioning Journal, 35*(2), 39–43.

Young, W., & Rogers, N. (2014). Effects of small-sided game and change-of-direction training on reactive agility and change-of-direction speed. *Journal of sports sciences, 32*(4), 307–314.

Young, W. B., Dawson, B., & Henry, G. J. (2015). Agility and Change-of-Direction Speed are Independent Skills: Implications for Training for Agility in Invasion Sports. *International Journal of Sports Science & Coaching, 10*(1), 159–169.

Young, W. B., McDowell, M. H., & Scarlett, B. J. (2001). Specificity of Sprint and Agility Training Methods. *Journal of Strength and Conditioning Research, 15*(3), 315–319.

Young, W. B., & Willey, B. (2010). Analysis of a reactive agility field test. *Journal of science and medicine in sport, 13*(3), 376–378.

Zaciorskij, V. M. (1968). Die körperlichen Eigenschaften des Sportlers. *Theorie und Praxis der Körperkultur, 17*(Beiheft 1).

Zentgraf, K., Heppe, H., & Fleddermann, M.-T. (2017). Training in interactive sports. *German Journal of Exercise and Sport Research, 47*(1), 2–14.

Zois, J., Bishop, D. J., Ball, K., & Aughey, R. J. (2011). High-intensity warm-ups elicit superior performance to a current soccer warm-up routine. *Journal of science and medicine in sport, 14*(6), 522–528.

Zouhal, H., Abderrahman, A. B., Dupont, G., Truptin, P., Le Bris, R., Le Postec, E., et al. (2019). Effects of Neuromuscular Training on Agility Performance in Elite Soccer Players. *Frontiers in physiology, 10*, 947.