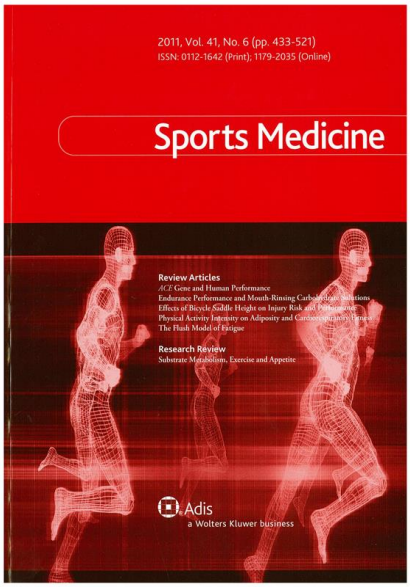

In press

Sprint running performance monitoring: methodological and practical considerations

Heading title: Sprint performance monitoring

Authors: Thomas Haugen[1] & Martin Buchheit[2-4]

[1]Norwegian Olympic Federation, Oslo, Norway

[2]Sport Science Department, Myorobie Association, Montvalezan, France

[3]Performance Department, Paris Saint Germain Football Club, Saint-Germain-en-Laye, France

[4]Institute of Sport, Exercise and Active Living, College of Sport and Exercise Science, Victoria University, Melbourne, Australia.

Corresponding author:
Thomas Haugen
Norwegian Olympic Federation, Sognsveien 228, 0840 Oslo, Norway
E-mail: thomas.haugen@olympiatoppen.no
Telephone 0047 41900313
Fax number 0047 38141301

Abstract

The aim of this review is to investigate methodological concerns associated with sprint performance monitoring, more specifically the influence and magnitude of varying external conditions, technology and monitoring methodologies not directly related to human physiology. The combination of different starting procedures and triggering devices can cause up to very large time differences, which may be many times greater than performance changes caused by years of conditioning. Wind, altitude, temperature, barometric pressure and humidity can all combine to yield moderate time differences over short sprints. Sprint performance can also be affected by the athlete's clothing, principally by its weight rather than its aerodynamic properties. On level surfaces, the track compliance must change dramatically before performance changes larger than typical variation can be detected. An optimal shoe bending stiffness can enhance performance by a small margin. Fully-automatic timing systems, dual-beamed photocells, laser guns and high-speed video are the most accurate tools for sprint performance monitoring. Manual timing and single-beamed photocells should be avoided over short sprint distances (10-20 m) due to large absolute errors. The validity of today's GPS technology is satisfactory for long distances (>30 m) and maximal velocity in team sports, but multiple observations are still needed due to questionable reliability. Based on different approaches used to estimate the smallest worthwhile performance change and the typical error of sprint measures, we have provided an assessment of the usefulness of speed evaluation from 5 to 40 m. Finally, we provide statistical guidelines to accurately assess changes in individual performance; i.e., considering both the smallest worthwhile change in performance and the typical error of measurement, which can be reduced while repeating the number of trials.

Key points

- Monitored sprint times over very short distances may vary up to 50-60% due to differences in equipment and methodology
- Presented calibration equations are needed to compare sprint times across varying settings
- We provide guidelines to accurately monitor and interpret sprint performance changes, based on established magnitude thresholds and practices to decrease typical errors with trials repetitions

1 Introduction

Valid and reliable performance assessments in sports are heavily dependent upon standardised procedures and precise equipment devices. While monitoring of fundamental physical motor skills like power, strength and aerobic performance/capacity has been extensively reviewed [1-4], assessment of sprinting speed has so far received less attention in research literature. Sprint performance is mainly dependent upon genetic predispositions [5, 6] and is quite resistant to training enhancement [7-9]. Beyond a certain level, athletes can spend years training to improve a few hundredths of a second over short distances [7, 9, 10]. However, varying technology and unaccounted extraneous variables can affect sprint running and change-of-direction performance with immediate effect. Thus, highly stringent methodological requirements are needed to detect "true" changes in performance.

The overall objective of this review was therefore to investigate methodological concerns associated with straight-line sprint performance monitoring. The aim was to synthesise the research that has been undertaken to date on the influence of varying external conditions, technology and monitoring methodologies not directly related to human physiology on sprint performance. Such information is of value both for practitioners and sport scientists/institutions/ laboratories. Hopefully, this review can contribute to increase the overall understanding of how sprint performance can be monitored and compared across scientific studies, practical training sessions/seasons and competitions.

2 Literature search

The databases of PubMed and SPORTDiscus were used to search for literature. The search was conducted at two levels: 1) type of skill measure, and 2) type of external variables that may potentially affect the skill measures. Regarding the first level, the following keywords were used: sprint speed, sprint velocity, sprint performance, sprint time, sprint timing, speed performance, anaerobic performance, running performance, running speed and running velocity. In the second level, the following keywords were used in different combinations with the results from the first search: photocell, timing gate, pod, global positioning system, GPS, micro technology, accelerometer, laser gun, radar, timing system, electronic timing, stopwatch, equipment, apparatus, weather, environment, wind, air, temperature, heat, cold, precipitation, rain, altitude, height, surface, superficial, turf, grass, field, exterior, footwear, shoe, outfit and clothing. This search identified 15777 and 2714 records in PubMed and SPORTDiscus, respectively. For scientific studies, only peer-reviewed articles written in English were included. Only the studies that investigated the effect of different external conditions on sprint performance were included.

In addition, the reference lists and citations (Google Scholar) of the identified studies were explored in order to detect further relevant papers. The final screening was based on the relevance of the identified items to assessment of sprinting speed.

3 Data analysis

A review of published studies monitoring sprint performance reveals considerable variation and/or insufficient information regarding method of reporting (e.g. best sprint vs. mean sprint time of several trials), timing methods, hardware manufacturers and testing procedures. Similarly, reliability data are lacking in the vast majority of identified studies. In cases where reliability data are reported, they are either insufficiently stated (e.g. only one measure used) or reported differently across studies. These circumstances make it challenging to compare and evaluate across studies. In the present review, the following aspects will be highlighted:

1. Differences between technologies, methodologies and environmental conditions and magnitude of their effects, and how to use data collected by different systems and/or with different starting procedures in combination
2. Validity (pros and cons of the different assessment methods)
3. Absolute (typical error of the measurement; TE, coefficient of variation; CV) and relative (intra-class correlation; ICC, ranking individuals) reliability associated with the measurement methods
4. Monitoring guidelines based on practical and statistical considerations

4 Timing technology

4.1 The gold standard: Fully-automatic timing systems in athletics

Fully-automatic timing systems used in international athletics have been considered the "gold standard" for accurately and reliably quantifying straight-line, still start sprint performance [11]. Fully-automatic timing systems include silent gun, photo-finish camera and pressure sensitive start blocks to detect false starts. High resolution photo-finish cameras capture thousands of frames per second, enabling the timing officials to estimate time with less than ± 0.0005 s resolution [11]. However, fully-automatic timing systems are expensive and impractical for most practitioners and scientists.

4.2 Manual timing

Manual, handheld timing was used in athletic sprint events until fully-automatic timing systems were introduced in the 1960-70s [50]. In theory, one should expect a time difference between handheld and fully-automatic timing similar to individual reaction time among the timekeepers, as they must react to the smoke of the start pistol. A correction factor of 0.2 s faster times with handheld timing has traditionally been used [50, 51]. Mayhew et al. [52] observed 0.19 ±0.14 s time differences among hand timers on any given trial. This large error is larger than the ~7% time difference between the 90th and 25th percentile over 20-m sprint in male soccer players [42]. Even though small mean errors (0.04-0.05 s) and very high ICC values (0.99) have been observed between handheld and electronic timing in collecting group data [52, 53], electronic timing is preferred due to the large absolute errors associated with handheld timing.

4.3 Photocell timing

4.3.1 Single-beamed photocells

Single-beamed photocells have been commonly used as a triggering device among practitioners and scientists [11-17]. A pair of single-beamed photocells consists of a transmitter emitting an infrared beam to a reflector (located directly opposite) that reflects the beam back to the transmitter. The problem with single-beamed photocells is that the beam can be triggered early by lifted knees or swinging arms. According to the International Association of Athletics Federations (IAAF), time shall be taken to the moment at which any part of the body of an athlete (i.e. torso, as distinguished from the head, neck, arms, legs, hands or feet) reaches the vertical plane of the nearer edge of the line [18]. Cronin & Templeton [19] revealed that inappropriate height adjustments of photocells increase the error of single-beamed timing. In photocells mounted at chest height, the beams are broken twice (arms and torso separately) in 60% of cases, while photocells at hip height were broken twice in just 4% of the cases [20]. Inspections of reliability data across short-sprint studies reveal 0.03 s standard error of measurement (SEM) and ~2% CV for single-beamed timing [21-24]. Ideally, single-beamed photocells should be mounted at a height at which only one part of the body usually breaks the beam, i.e. head height, as suggested by Dyas & Kerwin [25]. Although this is a violation of the IAAF regulations, there is no practical difference in horizontal position between the forehead and the chest when athletes sprint in an upright position.

4.3.2 Dual-beamed photocells

Numerous studies have used dual-beamed photocells over the last decade [26-37]. Here, two photocells are set at different heights and both beams have to be broken to ensure time triggering. Not surprisingly, greater accuracy of dual-beamed versus single-beamed timing systems has been reported [20, 38], with 0.02 s SEM and ~1% CV for 10 or 20-m sprint times with dual-beamed timing [39, 40]. Comparisons between single- and dual-beamed timing systems have revealed absolute time differences in the range -0.05 to 0.06 s for 0-20-m sprint times during normal sprint action [40], which e.g. represents the ~4% time difference between the 25th and 70th percentile in male professional soccer players [41]. Therefore, dual-beamed timing is required for scientists and practitioners wishing to derive accurate and reliable short sprint results. However, it remains to be explored whether a lower placed photocell at the start (similar to time initiation in alpine skiing) can further reduce false signals.

It is important to note that the signal-to-noise ratio is inversely proportional to photocell separation, regardless of the photocells used [20, 32, 40, 42, 43]. Thus, a doubling of photocell separation is accompanied with a halving of the speed errors. Buchheit et al. [32] concluded that two to three 10-m intervals (leading to a flying 10-m split) are required to guarantee an accurate evaluation of maximal sprint speed in young players when using dual-beamed photocells.

4.3.3 Split-beamed and post-processing photocells

Some manufacturers have made split-beamed or post-processing photocells to increase the signal-to-noise ratio. In split-beamed photocells, the infrared beam emitted from the transmitter is split with a thin, metallic device, and two reflectors are placed directly opposite with 20-30 cm vertical space in between. Both beams must be broken to trigger the photocell. Haugen et al. [42, 43] reported ~0.04 s SEM and ~2% CV for such timing, practically identical to single-beamed timing and nearly a doubling of the noise reported in dual-beamed timing [21-24, 40]. The distances between the transmitter and corresponding reflectors are crucial in such settings. If the transmitter is 2 m away from the reflectors in the horizontal direction, and the two reflectors are vertically separated by 20 cm, the actual beam split separation is only 10 cm in the middle of the sprinting course. Due to the thicknesses of arms and thighs, a beam split of ~20 cm is most likely required in the centre of the lane.

In post-processing timing systems, internal software scans all signals from the timing gate in terms of frequency and duration. Several authors have suggested the start of the longest photocell break as a trigger criterion, as the torso will produce a longer break than an arm [20, 38, 44]. Earp & Newton [38] reported that signal processing

completely removed all false signals, but test-retest reliability within analysed timing systems during sprints was not reported. However, a leading thigh might still trigger the beam depending on the vertical height where the photocells are mounted [20]. Thus, all types of photocells should be mounted at least above hip height to avoid undue beam break caused by the lower limbs.

4.4 Floor pods

Pressure sensitive floor pods have sometimes been used as start triggering device [11, 39, 42, 43]. The finger pod developed by Brower Timing Systems (Draper, Colorado, USA) is made especially for timing of football or rugby players. The athletes assume a 3-point stance with feet split and one hand on the 12x5 cm pod placed at the start line. Timing is initiated when the hand pressure against the pod is released. Duthie et al. [39] reported 0.02 s TE and 1% CV for 10-m sprints when timing was initiated by a finger pod.

Foot pods are usually larger than finger pods, but construction details and calibration of pressure threshold varies across equipment manufacturers. The timer is typically triggered when the pressure from the foot (normally front foot) against the floor plate is removed. Duthie et al. [39] reported 0.02 s TE and 0.9% CV for 10-m sprints when timing was initiated by a floor pod. However, possible advantages of placing the back foot on the pressure pod remain to be explored. Since the back foot leaves the ground before the front foot in a correctly performed start, triggering will occur at an earlier stage with less forward motion prior to time initiation.

4.5 Audio and visual start sensors

Audio sensors can capture a sound of certain intensity and thereby start the timer. The audio sensor device developed by Brower Timing Systems is commonly used among track and field practitioners. In principle, such timing is nearly equivalent to athletics “loud-gun” (pistol loaded with blank cartridges) timing where reaction time is included. This provides that the audio device is placed next to the sound source to minimise the sound traveling time between the devices. Haugen et al. [11] reported identical results when the Brower audio sensor (start) combined with photocells (finish) was compared with Omega’s (Swiss Timing, Corgémont, Switzerland) fully-automatic timing system. The trivial errors observed (SEM 0.01 s) were related to the single-beamed photocells covering the finish line [11].

Impellizzeri et al. [45] used an acoustic signal with 5 s countdown (Microgate, Bolzano, Italy) for start triggering when athletes performed six repetitions of 40-m shuttle sprints (20+20 m). The authors reported 0.06 s SEM and 0.81 intra-class correlation (ICC) for mean sprint time. When using audio/acoustic-based timing devices, reaction

time is normally included in the total time. No studies have so far investigated how different countdown procedures prior to start signal affect monitored reaction time. Based on neuro-scientific literature, it is reasonable to assume that reaction times become lower the more "anticipated" the delivered go signal is [46]. This increases the need for more precise false-start monitoring, which is particularly important during repeated running tests where the athletes are counted down prior to each run by dedicated software and sound delivered through speakers. Fewer count down instructions (e.g. "5 s" and "go") might reduce the risk of false starts.

Visual signals have been used for time triggering on some occasions [47], but reliability data have not been reported. Logically, it is reasonable to argue that visual start signals during sprint testing are more valid in team sports, as the athletes continuously must react and respond according to ball position and movements from others during play.

4.6 Video timing

Recordings with video or high-speed camera of a certain start criterion (e.g. gun smoke, foot lift-off, finger lift-off) and sprinting athletes passing the finish line provide enough information for valid sprint time analysis when imported to a computer video analysis program. Concurrent measurements of athletics events using Omega's fully-automatic timing system and Dartfish-based video analysis (Dartfish, Fribourg, Switzerland) demonstrated that the latter measurement method was valid to the limits of precision (± 0.01 s) of the instruments [11]. Chelly et al. [48] reported almost perfect correlation (r = 0.99) when velocity calculations from video recordings (Sony DCR-PC105E, Japan) were compared to photocell timing. Regarding reliability, Harrison et al. [49] reported ICC > 0.98 when velocity measurements where assessed with 50 and 100 Hz cameras. Thus, video-based timing is highly reliable in sprint performance monitoring. However, a practical disadvantage is that sprint time is not presented immediately, since recordings must usually be transferred to dedicated software before they can be analysed. This is particularly impractical during multiple sprints or when testing large athlete groups.

4.7 Laser and radar devices

The LAVEG Sport laser speed gun developed by Jenoptik (Jena, Germany) has been used to obtain sprint velocity curves of world-class sprinters since the 1997 IAAF World Championships in Athens [54]. The laser gun is typically positioned behind the athletes at the starting line. An optical control device allows the operator to direct the beam to the athlete's lower back. During the entire sprint, the athlete's velocity and distance from the laser

speed gun is registered at 50 or 100 Hz. The velocity calculated from raw laser distance-time data must go through a filtering process, normally with a 3 Hz cut-off [49].

Regarding validity, the error of the LAVEG laser in determining the distance travelled has been estimated to 0.1 ± 0.06 m when compared to 50 Hz video measurements [55]. Compared to 100-Hz video technology, Bezodis et al. [56] observed that the highest velocity bias occurs at 1 m (0.41 $m \cdot s^{-1}$ ±0.18 $m \cdot s^{-1}$ random error), which then decreases as the measurement distance increases. Several authors have reported a perfect correlation (r^2=0.99, p<0.01) when a 35 Hz Stalker ATS radar gun (Radar Sales, Minneapolis, Minnesota, USA) was compared to photocells [57-59]. Regarding test-retest reliability measures for the LAVEG laser gun, ICC-values in the range 0.96-0.99 [49, 60, 61], TE 0.05 $m \cdot s^{-1}$ [59] and CV 0.7-1.9% [60, 62] have been reported for running velocity. Poulos et al. [62] reported 3.1 and 1.9% CV for 10 and 50-m sprint times, respectively. Overall, the LAVEG laser gun is a useful tool for assessing sprint performance from the mid-acceleration and maximum velocity phases [56]. However, some variables may not be so reproducible, such as the distance to peak speed, for which the CV can be as high as 18% [62]. Exclusively straight-line sprints have been assessed with the LAVEG laser guns. A new combination of two synchronized devices has recently been shown to allow the precise monitoring of change of direction speed, and the various kinematic phases of the changes of direction (e.g., deceleration and acceleration phases). Using such a methodology, Hader et al. [63] reported acceptable levels of validity (e.g., small-to-moderate typical error of the estimate compared to single-beamed timing gates) and reliability (e.g., moderate CVs for peak deceleration and acceleration).

4.8 Global positioning systems

Global positioning systems (GPS) with integrated accelerometers have been extensively applied in a variety of team sports during the last decade, for example for measurement of running velocity in players during training sessions and games. The great advantage of GPS technology is that it allows the assessment in the field of many players simultaneously. Numerous studies have aimed to investigate GPS validity and reliability for acceleration or speed assessment [64-75], using photocells as the "gold standard" criterion in most of the cases. Unfortunately, most studies have investigated running velocities < 22 $km \cdot h^{-1}$. Aughey [76] points out the difficulties of using timing gates as the criterion measure, as there are some inherent errors (e.g. undue beam breaking, see section 4.3) associated with the ability of such equipment to accurately measure sprint time.

Validity and reliability of GPS within the same brand is affected by sample rate, running velocity, running distance and movement pattern. The lower the sample rate [68, 71, 76-79], the higher the running velocity [72, 79-81], the

shorter the activity duration [66, 68, 79-81] and the greater the number of changes of direction [78, 79, 81, 82], the lower the validity and reliability of the GPS. While a reduction in sampling frequency from 10 to 5 Hz can increase the magnitude of both the standard error of the estimate and the CV by a factor of ~2-3 [70], the bias in the distance covered may be twice as large for tight (5 m) vs. large (10 m) 90°-changes of direction runs, with a linear increase in the error with increasing running velocity (-5, -11 and -16% for walk, jog and sprint over tight 90°-changes of direction runs) [79]. Between-unit variations (up to 30% CV between some units of the same brand for accelerations >3 ms^{-2}) [73], software upgrades (i.e., large increase in the occurrence of accelerations) [73] and time-of-day (although unlikely substantial, i.e., within 1-2% for total distance covered) [80] also affect the measured velocity and are problematic issues associated with GPS monitoring.

Some authors have concluded that GPS have shown acceptable accuracy for sprint velocity when compared to timing lights or radar guns [67, 71, 72, 74]. However, typical errors in the range 3-15% or correlation coefficients in the range 0.93-0.96 do not necessarily indicate acceptable validity [71, 72, 74]. It is important to keep in mind that 2% sprint velocity errors are equivalent to the difference between the 50^{th} and 70^{th} percentile (small effect magnitude) among male team sport athletes over a 20-m sprint [41]. Additionally, 2% is also twice larger than the smallest worthwhile change (SWC) in performance for 20 m (see section 10). The value of GPS in determining acceleration in the field also appears questionable [73, 79, 83-85], with the validity and reliability shown to be inversely related to acceleration [86]. In fact, compared with timing gate- or radar-derived accelerations, correlations are only unclear to moderate, and typical errors of the estimate are generally small-to-moderate (CV ~5-10%) [71, 86, 87]. It is, however, worth noting that a proper examination of the validity of GPS to assess this specific fitness component is somewhat problematic, since the actual acceleration value is directly related to the time-window used to assess changes in speed, e.g. acceleration calculated from the change in speed over 0.5 vs. 0.8 s vs. 1 s (with the longer the time-window, the lower the mean acceleration value). Since GPS-derived acceleration can only be compared with the average acceleration over 5 or 10 m when using photocells, the eventual bias in the measures necessary to obtain calibration equations is difficult to predict. In line with these different limitations, today's GPS technology may not be a highly valid tool for accurate acceleration performance assessment. It is however important to keep in mind that the validity and reliability of GPS will probably be improved with the development of the technology (i.e. greater sampling rate) in coming years. Regarding sampling frequency and GPS accuracy however, what matters is the actual sampling frequency of the GPS receiver itself (e.g., 5 or 10 Hz), not the overall number of samples provided when exporting the data. In fact, by smoothing and processing data at a higher rate than actually collected (i.e., 15 extrapolated Hz obtained from 5 collected Hz),

some brands advertise higher sampling rates to increase product attractiveness, despite little or no beneficial impact on signal accuracy. Until large increases in sampling frequencies eventuate, and pending more evidence on the validity of promising new technologies such as local positional systems [87] or radio-frequency identification, practitioners still have the possibility to use multiple trials to improve the precision of GPS measurements in the field (see section 10.3).

5 Procedures

5.1 Starting positions

Today's regulations in track and field state that athletes must start from a 4-point position in sprinting distances up to 400 m [18]. However, such a starting position is only valid and relevant for athletic sprinters and hurdlers. In American Football, for example, sprint performance is typically assessed from a 3-point position [88, 89], while different types of standing start (either from fixed position, also termed "crouch start", or leaning backward before rolling forward) are commonly used in team sports like soccer and handball [32, 39, 42, 43, 90, 91]. The impact of different starting positions on monitored sprint performance must be seen in relation to the hardware devices used. The starting method and timing system used can combine to generate up to very large differences in sprint time [11,39]. At the extreme, a 40-m sprint time of 4.4 s measured from a standing start with triggering via floor sensor below the front foot is a poorer performance than 5.0 s measured from starting blocks with time initiated by a starter´s gun [11]. The differences are caused by inclusion/exclusion of reaction time, centre of gravity placement and velocity (momentum) at time triggering.

Figure 1 about here

5.2 Start signals

In sprint testing of team sports, athletes typically start running on their own initiative after being cleared to start by a test leader. Sprint races in athletics are started with the commands ''on your marks'', ''set,'' and the ''go'' signal. In dry air at 20˚C, the speed of sound is approximately 343 $m \cdot s^{-1}$, meaning ~3 ms for each metre of sound travel. Thus, 100-m contestants assigned in the inner-lane will hear the sound of a "loud" gun 0.02-0.03 s earlier than their outer-lane assigned competitors, as each lane is 1.22 m wide [18]. Corresponding time difference for 200 m sprint is 0.07-0.08 s because the contestants are separated by 3.5 m across the lanes for curve adjustment. In 1995, IAAF introduced the use of silent gun (start signal from speakers behind each athlete) in their international championships to overcome lane assignment handicaps. However, silent gun equipment is expensive

and most often not used in competitions at lower level. Brown et al. [92] observed that an increase in ‘‘go’’ signal intensity from 80 to 120 decibel lead to a small but significant decrease in reaction times in a group consisting of both trained and untrained sprinters. It has also been shown that starters’ holding time (time between “set” and “go”-signal) affects reaction time and thereby performance [93]. According to neuro-scientific research, reaction time increases as a function of the preparatory interval used in the setting [46].

5.3 False start regulations

According to IAAF’s competition rules, a reaction time < 0.10 s is considered a false start [18]. This criterion is based on an assumed auditory reaction time that includes the sound traveling time between the sound source and the athlete, the athlete’s reaction to the sound, and the mechanical delay of false start equipment integrated in the start block [94, 95]. Mean reaction times in male and female world-class sprinters increased by 20% during a 15-yr period (1997-2011) due to the introduction of stricter false start rules [93]. It is reasonable to assume that the fear of being disqualified from the competition has increased as a consequence of stricter false start rules.

5.4 Flying start

In photocell timing, the athlete must start a certain distance back from the initial timing gate to avoid premature triggering caused by a typical starting posture with a forward lean of the upper body. Thus, the athlete is already travelling at a certain speed as he/she passes the starting line, the so-called flying start [39]. Recorded sprint time decreases as a function of flying start distance up to a certain point as a typical sprint velocity curve follows a hyperbolic relationship [96]. Haugen et al. [96] showed that the time saving magnitudes are significantly influenced by starting distance behind the initial timing gate, sprint distance and athlete performance level. Signal-to-noise ratio is slightly lower for flying start distances up to 2 m compared to flying start distances in the range 5-20 m [96]. If noise minimising is the primary goal for dual-beamed photocell timing, flying start distances > 2 m should be used. This consideration must be balanced against the validity of the sprint distance tested. Most scientists and practitioners would probably argue that sprint testing of team sport athletes should be performed with time initiating from a nearly static position. However, about 75% of all sprints during soccer games are initiated from a jogging/striding condition, so called leading sprints [97, 98]. Sprint testing of such athletes should perhaps include a combination of stationary, flying and leading starts.

6 Environmental factors

Air resistance acts as a continuous retarding force on the athlete. Generally, the air resistance acting upon a body is determined by the body's velocity relative to the surrounding air, the size and shape of the body, the surface area of the body against the airflow, and the air density where the movement is taking place. The value of the body's relative velocity is squared in the general formula, demonstrating that this is a dominant factor. For sprint performance assessment purposes, the influence of wind is most pronounced. IAAF's competition rules state that results obtained with assisting wind speed > 2.0 $m \cdot s^{-1}$ are deemed illegal and not ratified for sprint record purposes [18]. Several authors have proposed theoretical models to simulate the effect of wind speed on sprint performance [99-104]. A limitation associated with such models is the assumption of constant wind speed in both magnitude and direction. In reality, wind is not constant, and grandstands may produce erratic winds in a stadium. The use of multiple wind gauges positioned alongside the entire lanes on both sides would certainly strengthen the validity of wind measurements, compared to today's regulations where only one single gauge is required to assess wind speed for 100-200 m sprints [18]. To the authors' knowledge, no studies have assessed wind gauges for reliability and accuracy.

A common conclusion is that the time hindrance produced by a head wind is larger than the time aid produced by a tail wind of the same intensity [100-102, 104]. This is explained by sliding filament mechanisms, as muscle force production declines with increasing velocity of contraction [105]. The advantage of a maximal legal tail-wind of +2.0 $m \cdot s^{-1}$ has been reported to yield 0.10-0.14 s faster 100-m sprint times, while a corresponding head wind yields 0.12-0.17 s slower times at sea level [101, 102]. Other studies with less reliable modelling approaches have reported either higher or lower 100-m time differences [100, 106-109]. However, individual differences are expected on both sides of the estimates due to varying anthropometric, technical and physiological characteristics among athletes.

Air density, and thereby drag force acting on the sprinter, decreases with increasing altitude. The air density at 2250 m (e.g. Mexico City) is ~20% lower than at sea level [110]. Several authors have reported a nearly proportional relationship between altitude and 100-m sprint time advantage in the range 0.02-0.05 s for each 1000 m above sea level [101, 106, 109, 111, 112]. The discrepancies are related to different modelling approaches across studies.

Atmospheric conditions like air temperature, barometric pressure and humidity also affect the effective altitude, also called density altitude. Higher temperatures and humidity levels decrease air density, while lower

temperatures and humidity are accompanied by increased air density. Mureika [113] reported that 100-m sprint times may vary up to 0.1 s across the combination of varying air temperatures (15-35°), humidity levels (0-100%) and atmospheric pressures (85-105 kPa).

7 Clothing and equipment

Two studies have reported no significant benefit of wearing compression clothing on sprint performance [114, 115]. Brechue et al. [116] reported that American Football equipment (6-8 kg total weight, depending on playing position) impaired 40-yd sprint performance by nearly 3% (0.15 s) on average. However, the choice of proper athletic clothing is important to minimise air drag and carried weight during sprinting. In wind tunnel tests, Kyle & Caiozzo [110] observed that it was possible to reduce the wind resistance of a runner by 6%, but such a wind resistance reduction provides practically no effects over short sprints. Taking all these observations together, it is reasonable to conclude that outfit weight affects sprint performance changes more than aerodynamic properties.

8 Running surface

Several authors have investigated the effects of varying running surfaces on monitored sprint performance. Gains et al. [117] and Ford et al. [118] reported no significant differences in sprint times between sprinting on artificial field turf and natural grass. Brechue et al. [116] observed that college football players ran ~2-3% faster (0.12-0.15 s over 40 yd) on an athletic rubberised track compared to natural grass. Stafilidis & Arampatzis [119] found no significant differences in sprint performance when sprinters ran on three different athletic track configurations. Consequently, it seems that sprint performance is more negatively affected by the roughness than the stiffness of the surface. On levelled surfaces, the stiffness must change dramatically before sprint performance changes larger than typical variation can be detected. Potential effects of varying rubberised track surface temperature on sprint performance remain to be explored.

9 Footwear

Research regarding the impact of footwear on sprint performance is limited. Stephanyshin & Fusco [120] reported 0.7% mean performance improvement in the 20-40 m interval of 40-m sprints after increasing the bending stiffness of sprint shoes (with carbon fibre plates inserted under the sock liner) among 34 national team and university track and field athletes. Thus, sprint performance was enhanced despite increased total weight of shoes. The optimal

stiffness differed among the athletes, and the stiffness was independent of body height, weight, shoe size and skill level. Among several plausible factors, it has been speculated that sprint performance improvements caused by increased shoe bending stiffness is the result of an improved running economy or a reduction in the energy lost at the metatarsophalangeal joint during ground contact [120-123].

10. Monitoring changes in sprint performance

10.1 Integrating data across technology, procedures and conditions

This review has shown that comparisons of sprint time results without consideration of timing technology, procedures, environmental factors, clothing, equipment, footwear and running surface can make for a lot of uncertainty. Fortunately, some authors have developed calibration equations to assist practitioners on the field in dealing with varying circumstances during sprint performance assessments [11, 39, 90, 96]. Table 1 shows mean time differences and effect magnitudes for the influence of varying methodological and external variables on monitored sprint performance, in addition to the magnitude of the typical error of estimate. It is important to note that some calibration equations are essentially absolute (e.g. variables related to reaction time) and independent of sprinting distance, while others are linearly related to sprint distance (e.g. footwear). However, the majority of the analysed variables are neither constant nor linear (e.g. variables related to flying start distances), but instead follow a hyperbolic relationship corresponding to typical sprint velocity curves. Thus, the presented calibration equations should be used with caution in settings other than those stated.

Table 1 about here

10.2 Defining the usefulness of speed testing

Practitioners wishing to optimally assess their athletes' sprinting performance would need to consider 1) the actual change in performance (the signal), 2) the typical error of measurement (TE, the noise, representing the uncertainty in that particular measure) and 3) the smallest practical or meaningful change (the so-called smallest worthwhile change, SWC) [124]. To assess the value of a given change in performance, practitioners would compare the change with the SWC, but would also need to consider the possible noise around the measure. To do so, practitioners may plot their data to see the latter variables in relation to each other (Fig. 2), or for more precision, use a specifically designed spreadsheet that provides probabilities for the changes to be true [125]. As shown in Fig. 2, with a SWC of 1%, the probability for a 1% increase in 20-m sprinting speed to be substantial (i.e., real) for individuals is never >50%, whatever the magnitude of the TE. In contrast, with a sprint performance change

of 1.5%, the change is likely with a TE of 0.5% (i.e., probability for an improvement >75%) but not with a TE of 3% (there are too many probabilities for the change to be trivial or even in the other direction). For individuals, changes are generally considered as substantial when the probabilities are ≥75%, which occurs when the change is clearly greater than the SWC, and when the TE is at least equal to or lower than the SWC (Fig. 2). If the SWC=TE, then a change of 2 x SWC (or 2 x TE) gives a 76% chance of improvement. Following these guidelines, the usefulness of a test measure (e.g. 10 or 40-m sprint) can be assessed by comparing its associated noise (TE) and the SWC (Table 2). A test can be considered as 'useful' when the noise is at least equal to or lower than the SWC [124].

Figure 2 about here

According to Hopkins et al. [126], SWC in team sports can be estimated in two ways: 1) based on empirical observations of direct performance benefits, such as a distance of 20-50 cm that one player needs to be ahead of the opponent to win a ball, corresponding to 0.03-0.06 s over 20-m sprint [41], or 2) statistical considerations, such as sports-specific standardized changes or differences. For the latter, 0.2 of the between-player standard deviation (SD) in team sport players is generally favoured to detect small changes [126]. Using this approach in studies with large sample sizes (n>50), sufficient timing/procedure information [10, 12, 15, 16, 26-29, 32, 36, 37, 42, 43, 127-129] and available calibration equations (Table 1) to adjust for varying circumstances during sprint performance assessments, the SWC is ~1.5% for 5-m sprints and ~1.0% for 10-40-m sprints and maximal sprint speed. However, a limitation of using the SD to estimate the SWC is that it is directly affected by group homogeneity. Subsequently, and because sprinting in soccer has a duelling aspect [130], the distance needed to win a ball is preferred as the method to determine the SWC (Table 2). In relation to monitoring changes in sprint performance for individual athletes (e.g. track and field), 0.3 of the within-athlete variability is generally accepted as the SWC. Finally, the signal-to-noise ratios shown in Table 2, when using the typical changes in sprint performance reported by Sander et al. [10] (two years of strength training) and the TE reported in Table 2, suggest that under this specific training setting, the most sensitive test measure may be a 10-m sprint time. It remains however to be examined whether the sensitivity of different sprint tests measures, e.g. 10 m vs. maximal sprinting speed (MSS), varies with training interventions (e.g. strength vs. speed vs. agility).

Table 2 about here

10.3 Multiple trials to decrease signal-to-noise ratio

When the TE is much larger than the SWC, repeating trials can be used to decrease the TE and increase the probabilities for the change to be true. In fact, the TE decreases by a factor of √n repetitions [131]. Fig. 3 shows how the number of trials affects the magnitude of the TE and how these changes in TE affect the probability of observing substantial changes for a given SWC. While in practice it may be challenging for athletes to repeat multiple maximal sprints, since fatigue might be expected after a couple of repetitions, the data from Haugen et al. [8] suggest otherwise for short distances. In fact, when junior soccer players repeated a set of fifteen 20-m sprints with 60 s of recovery, there was no fatigue occurrence within any of the test sessions [8]. Twenty metre time was actually 0.02 s faster for the last sprint compared with the first sprint in both the pre- and post-training test, despite athletes being specifically instructed to perform all sprints within each test session with maximal effort. Moreover, the % of speed decrement during the repeated-sprint sequence was only 0.2±0.1% for both the pre- and post-training tests. However, for longer sprint distances (e.g. 40 m), fatigue has been observed already after 3-4 repetitions, even when the recovery time between the sprints was as long as 6 min [11]. These findings must be taken into consideration when designing (repeated-) sprint test protocols. Fortunately, as shown in Table 2, it is the shorter sprints that present the poorer SWC-to-noise ratio (suggesting a lack of usefulness of the short distance test using a single measure), and which therefore need to be repeated a greater number of times. Table 2 also shows, for each sprint distance and MSS, the expected (theoretical) number of trials required to decrease TE to a similar value as the SWC (making each measure useful), both in team sport and solo athletes.

Figure 3 about here

10.4 Practical examples of real life data in football

A limited number of studies have used the statistical approach described above (section 10.3) to monitor speed changes over time in athletes. A study of 98 soccer academy players during a 3-month period in-season revealed that nine players showed a likely increase in 10-m sprint performance and four players showed a likely decrease, while 33 showed a likely increase in MSS, and four showed a likely decrease [36]. Longitudinal changes in 10-m sprint and MSS in a young soccer player over six years are illustrated in Fig. 4, together with the associated probabilities of the changes being true. Finally, in addition to the probabilities of the changes being true, the actual magnitude of the changes can be assessed using multiples of the SWC based on Cohen's effect size principle, where 1, 3 and 6 multiples of the SWC stand for small, moderate and large changes.

Figure 4 about here

11 Conclusion

Procedures and methods of sprint timing can result in trivial-to-very large differences in sprint time (Table 1). In most cases, their relative impact on sprint performance increase with shorter sprint distance. At the extreme, the combination of starting procedures and triggering devices used can cause many times greater sprint time differences than what is typically associated with several years of conditioning [7, 9, 10]. Time differences over short sprint distances caused by air resistance, clothing, footwear and running surface are either trivial or small (Table 1). However, in combination these variables can cause moderate and even large time differences. Fully automatic timing systems represent the gold standard for accurately and reliably assessing sprint performance. However, dual-beamed photocells, post-processing photocells, laser guns and high speed video timing are cheaper and more practical tools with acceptable accuracy. In contrast, manual timing and single-beamed photocells (without post-processing software) should be avoided when assessing sprint performance over 10-20 m due to large absolute errors. The validity of today's GPS technology in monitoring sprint performance is only satisfactory for distances >30-40 m and to assess maximal velocity in team sports, but its reliability is still questionable, increasing the need for multiple observations. For accurate estimation of changes in athletes' sprint performance, practitioners should also consider the SWC and TE for that given test. When TE is too large (>SWC) and limits the usefulness of the test when relying on a single test measure, the use of 4-9 repeats of the measures (Table 2) can decrease the TE and allow a better estimation of the true changes.

Compliance with Ethical Standards

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Conflicts of Interest

Thomas Haugen and Martin Buchheit declare that they have no conflicts of interest relevant to the content of this review.

Informed Consent

Informed consent was obtained from the individual participant for whom identifying information is included in this article.

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Table caption

Table 1 Mean time differences and typical error of estimate with effect magnitudes across varying methodological variables on monitored sprint performance

Table 2 Practical considerations when monitoring changes in sprint performance in athletes

Figure caption

Fig 1 Typical starting positions used for sprint performance monitoring purposes: a) block start, b) three-point finger pod start, c) standing static start (front foot placed 0.5 m behind the start line) with photocell trigger, d) standing start (leaning back before rolling forward, so called "rocking motion") with photocell trigger, and e) standing start with floor pod trigger. The sources of time differences include the starting device (gun, pod and photocells), inclusion of reaction time, vertical and horizontal placement of starting device related to the start line, body configuration and center of gravity velocity at triggering point.

Fig 2 Interpretation of different changes in 20-m sprinting speed in an individual athlete when considering 1) different magnitudes of improvement (i.e., 1, 1.5 and 2 times the smallest worthwhile change, SWC [grey area]) and 2) typical errors of measurement (TE, shown with the error bars) of varying size. The numbers refer to the probabilities for the change to be an increase/no change/decrease using Hopkins' spreadsheet [122]. These probabilities were then used to make a qualitative probabilistic mechanistic inference about the true effect: if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as unclear; the effect was otherwise clear and reported as the magnitude of the observed value. The scale was as follows: 25−75%, possible; 75−95%, likely; 95−99%, very likely; >99%, almost certain. For individuals, changes are generally considered as substantial when the probabilities are ≥75%, which occurs when the change is greater than the SWC, and when the TE is at least equal to or lower than the SWC. If the SWC = TE, then a change of 2 x SWC (or 2 x TE) gives a 76% chance of improvement. The grey area represents trivial changes.

Fig 3 Probabilities for different changes in 20-m sprinting speed (i.e., 1, 1.5 and 2 times the smallest worthwhile change, SWC) to be substantial in a single athlete (a), considering 1) a smallest worthwhile change of 1%, and 2) the typical error (TE) of the measurement (b), which is initially 2% with a single trial (i.e. one sprint repetition), but varies as a function of the number of trials by a factor of √(n). Only "clear" inferences are reported (if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as

unclear; the effect was otherwise clear and reported as the magnitude of the observed value). For individuals, changes are generally considered as substantial when the probabilities are ≥75%, i.e., above the grey area. In practice, these data suggest that at least four sprint repetitions may be required to decrease the TE to ≤1%, with little further decrease with more repetitions (16 repetitions needed to decrease the TE to 0.5%). For performance changes in the typical training-induced range of 2% [10], and considering a SWC of 1%, at least four sprint repetitions may be required to confirm a likely improvement. For smaller changes in performance such as 1.5%, averaging the performance over 14 repetitions may be required; changes of 1% may never be assessed as clear, irrespective of the number of trials.

Fig 4 Percentage changes in 10-m sprint time and maximal sprinting speed (best 10-m split during a 40-m sprint, MSS) in a well-trained young soccer player. Error bars represent the typical error of each variable (i.e., 1.6 and 2.9% for 10-m and maximal sprinting speed (MSS), respectively, Table 2). Details of the methods have been published elsewhere [34]. The grey area represents trivial changes. *: likely change, **: very likely change and ***: almost certain change. Multiples of the smallest worthwhile changes (SWC) were used to assess the magnitude of the changes based on Cohen's effect size principle, where 1, 3 and 6 multiples of the SWC stand for small, moderate and large changes.

Table 1.

Analysed methodological variables	**Mean difference (s; magnitude)**	**Standardised TEE (%); magnitude**
Timing technology and procedures		
Omega fully-automatic timing system vs. Dartfish video timing [11]	0.00; trivial	0.00 (0.1%); trivial
Omega fully-automatic timing system vs. Brower's audio sensor (start) and SB photocells (finish) [11]	0.00; trivial	0.00 (0.1%); trivial
SB vs. DB photocell timing for 20-40 m sprint split time [40]	0.00; trivial	0.13 (0.8%); trivial
Faster times with SB vs. DB photocells for 0-20 m sprint split time [40]	0.02; trivial	0.25 (1.3%); small
Faster reaction times when increasing "go" signal intensity from 80 to 120 dB [92]	0.02; trivial	-
Faster reaction times when decreasing starters' holding time from 1.3 to 2.2 s [93]	0.02; trivial	-
Faster reaction time when one false start per athlete was allowed vs. no false starts allowed [93]	0.03; trivial/small[a]	-
Faster reaction times with silent gun vs. loud gun 10 m away from athletes [92]	0.03; trivial/small[a]	-
Faster times with Dartfish video timing vs. Brower hand pod (start) and SB photocells (finish)[11]	0.04; trivial/small[a]	0.09 (0.6%); trivial
Faster 5, 10 and 20 m times with 1 m vs. 0.5 m flying start [91, 96]	0.06-0.08; small[b]	0.25-0.36 (1.6-2.2%); small
Faster 40-m times with standing photocell start (rocking motion) vs. 3-point finger pod start [11]	0.10; small	0.23 (1.5%); small
Faster 40-m times with 3-point finger pod start vs. athletic block starts with gunfire [11]	0.17; small	0.19 (1.4%); trivial
Faster 20-m times with 1.5 m vs. 0.5 m flying start [96]	0.14-0.17; moderate[b]	0.22 (1.4%); small
Faster 10-m times with standing and static photocell start vs. 3-point finger pod start [39]	0.16; moderate	-
Faster 40-m times with standing photocell start and rocking motion vs. block starts [11]	0.27; moderate	0.23 (1.5%); small

Faster 10-m times with 1.5 m vs. 0.5 m flying start [96]	0.13-0.15; large[b]	0.46 (2.8%); small
Faster 20-m times with 2 m vs. 0.5 m flying start [96]	0.19-0.22; large[b]	0.31 (1.9%); small
Faster 40-m times with standing floor pod start (rocking motion) vs. 3-point finger pod start [11]	0.52; large	0.23 (1.6%); small
Faster 10-m times with foot pod start vs. standing static start with photocells [39]	0.22; very large	-
Faster 10-m times with 2 m vs. 0.5 m flying start [96]	0.18-0.20; very large[b]	0.56 (3.4%): small
Faster 10-m times with standing floor pod start (static position) vs. 3-point finger pod start [39]	0.38; very large	-
Faster 10-m times with 5 m vs. 0.5 m flying start [96]	0.36-0.40; very large[b]	0.28 (1.7%); small
Faster 20-m times with 5 m vs. 0.5 m flying start [96]	0.40-0.42; very large[b]	0.22 (1.4%); small
Faster 20-m times with 10 m vs. 0.5 m flying start [96]	0.55-0.57; very large[b]	0.26 (1.6%); small
Faster 40-m times with standing floor pod start (rocking motion) vs. block start with gunfire [11]	0.69; very large	0.21 (1.5%); small
Faster 10-m times with 10 m vs. 0.5 m flying start [96]	0.48-0.51; nearly perfect[b]	0.39 (2.3%); small
Environmental factors		
Impact of ±2.0 $m \cdot s^{-1}$ wind speed on 0-20 m sprint performance [101, 102]	≤ 0.02; trivial	-
Faster 20-m sprint times at 2000 m altitude vs. sea level [101, 106, 109, 111, 112]	< 0.02; trivial	-
Impact of varying air temperature, barometric pressure and humidity on 0-20 m sprint time [113]	< 0.02; trivial	-
Clothing and equipment		
Impact of aerodynamic properties related to clothing on 20-m sprint performance [110]	< 0.01; trivial	-
Faster 10-m sprint times with compression garments vs. no compression garments [114]	0.01-0.02; trivial	-

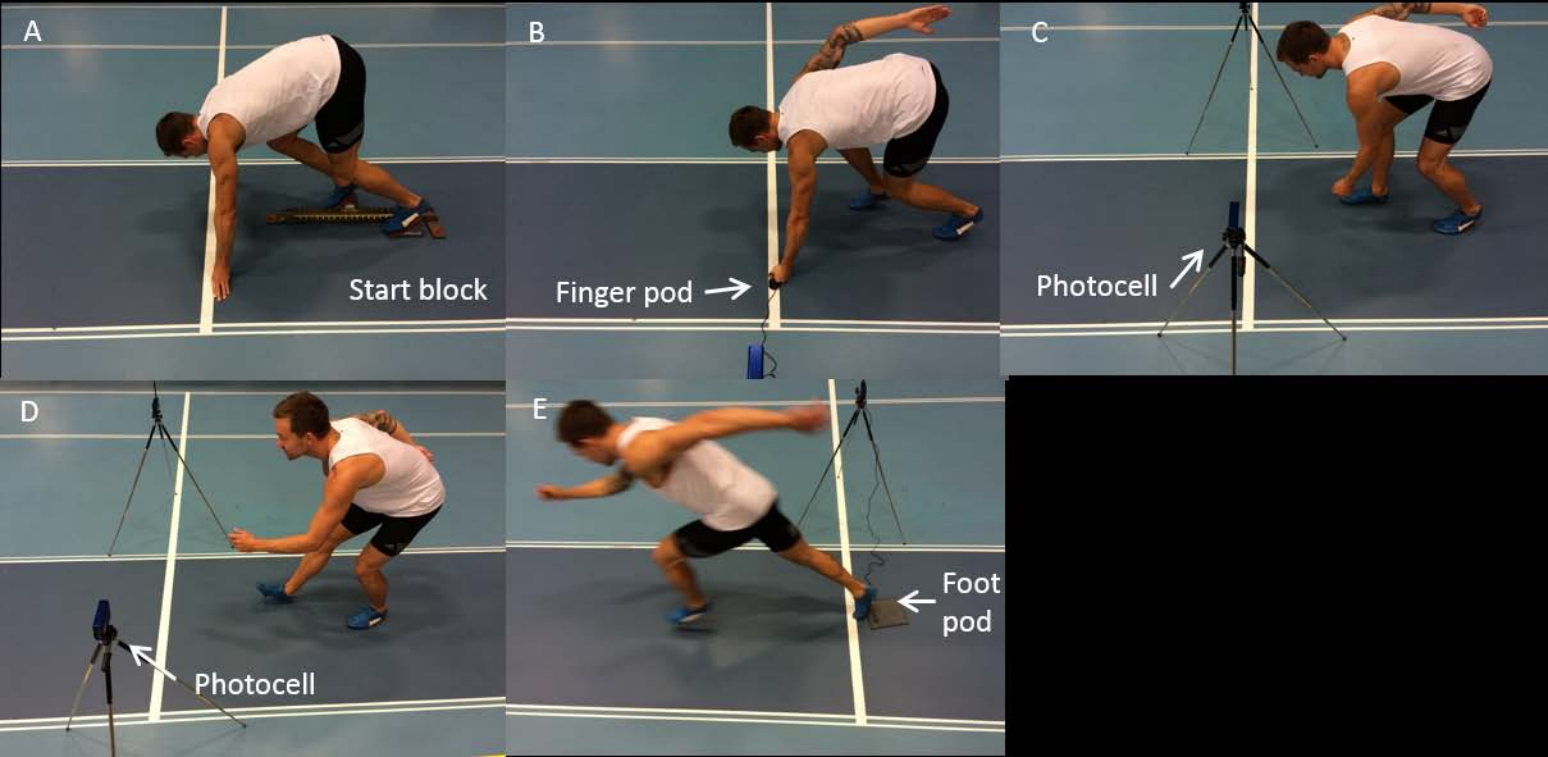
Faster 20-m sprint times with compression garments vs. no compression garments [114]	0.06-0.08; small	-
Slower 40-yd sprint times when running with American football equipment (weight 6-8 kg) [116]	0.12-0.17; small	-
Running surface		
Sprinting on artificial turf vs. natural grass over 40-yd [117]	≤ 0.01; trivial	-
Impact of varying synthetic track configurations on 0-30 m sprint time [119]	≤ 0.03; trivial	-
Faster 40-yd times with sprinting on rubberized track vs. sprinting on natural grass [116]	0.12-0.15; small	-
Footwear		
Impact of varying shoe bending stiffness on 20-40 m sprint time [120]	≤ 0.03; trivial	-
Faster 20-m sprint times with running spike shoes vs. regular running shoes [132]	0.03-0.05; trivial/small	0.25 (1.4%); small

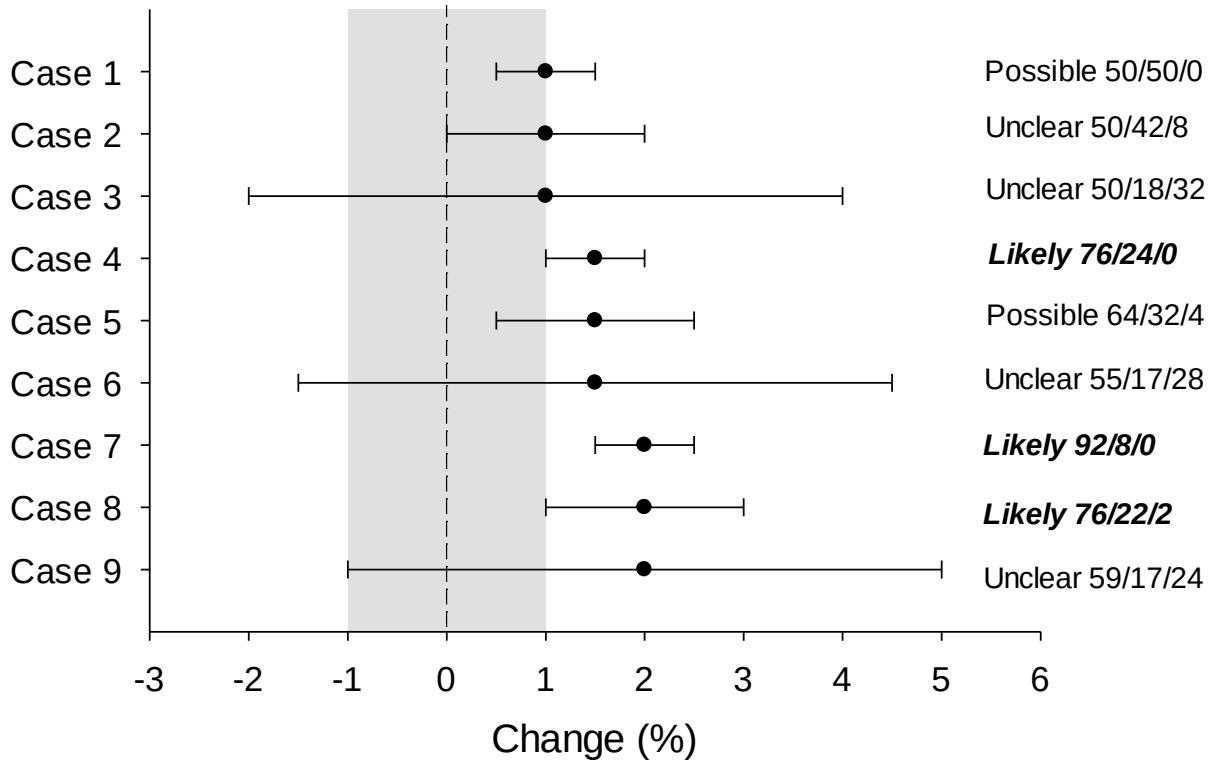
Calculation of mean difference effect magnitudes are based on standard deviation for corresponding sprint distances (0.09 s for 10-m, 0.15 s for 20-m, 0.22 s for 30-m and 0.31 s for 40-m sprints) in two pooled databases consisting of 939 male [43] and 194 female [42] team sport athletes. Hopkins' spreadsheet [133] was used to standardise typical error of estimate. SB = single-beamed, DB = dual beamed, dB = decibel, TEE = typical error of estimate. [a]Effect magnitude depends on distance sprinted. [b]Time savings depend on athlete sprint performance level.

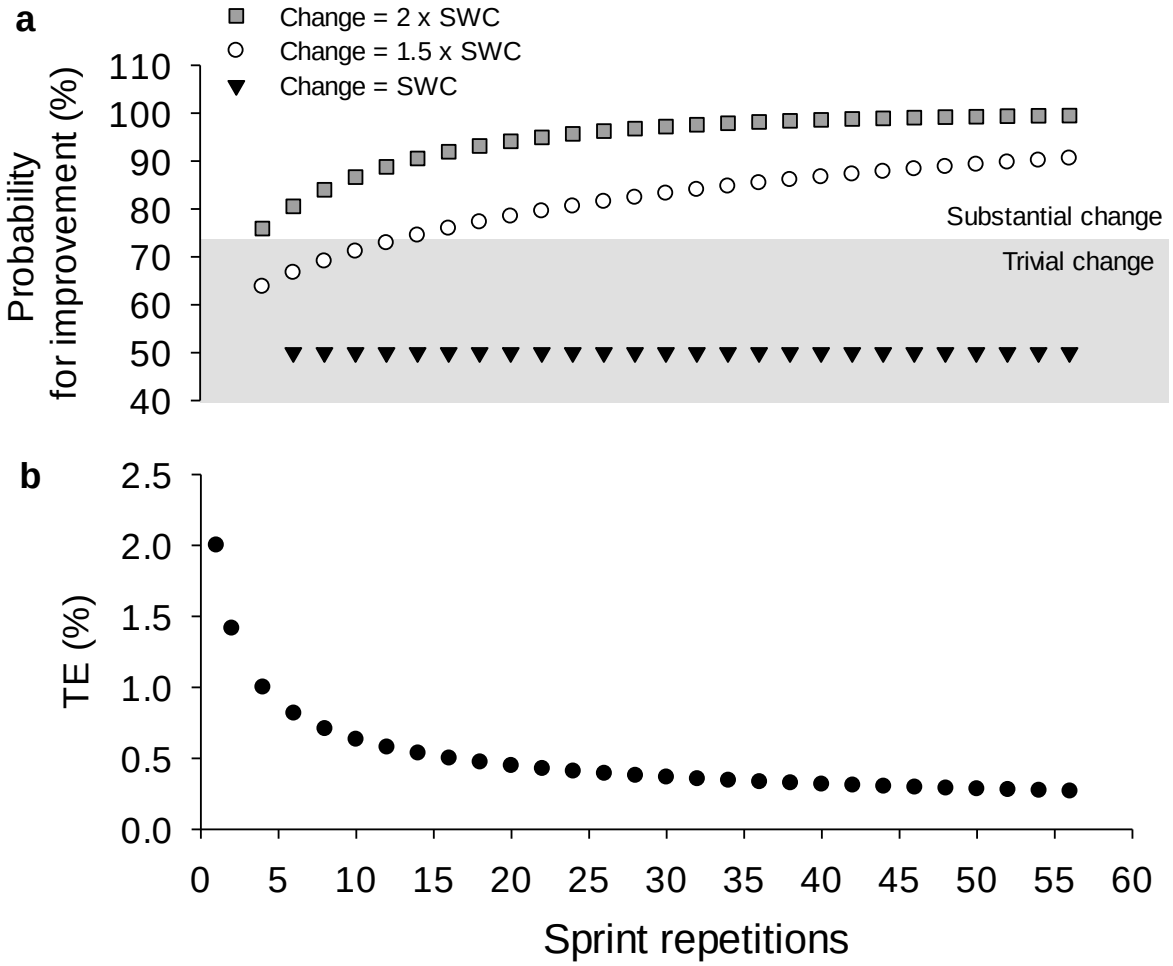
Table 2.

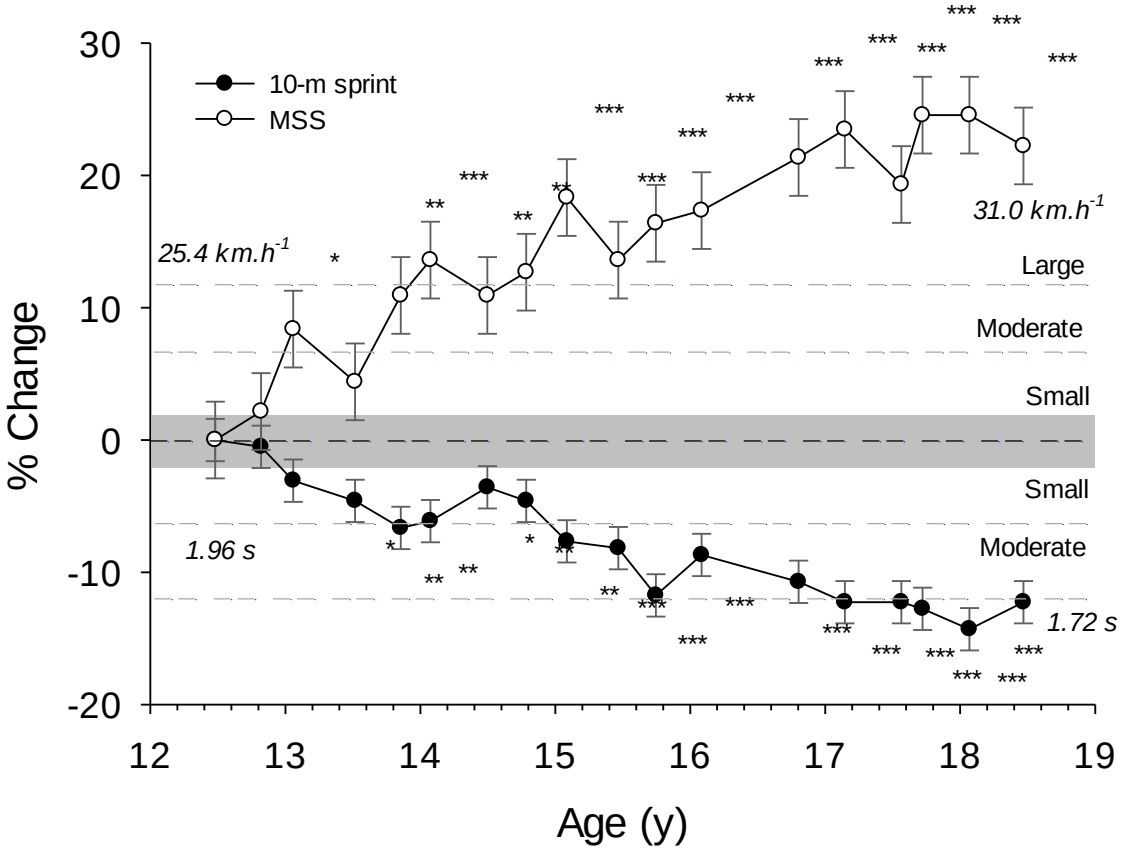
Sprint test	**{n} for TE**	**TE (%)** % ± 90% CL	**Team sport athletes: winning a ball (20-cm difference)** SWC (%)	Usefulness with 1 trial	# Trials required	**Typical training-induced change** % ± 90% CL [10]	**Magnitude of the changes** [10]	**Signal to noise ratio**	**Solo athlete: small fraction of the CV_{ind}** SWC (%)	Usefulness with 1 trial	# Trials required
5 m	1	5.1 ± N/A	~4	Poor	2	-3.1 ± 1.4	-0.8 (trivial)	-0.6	0.3 x CV_{ind}	Poor	9
10 m	5	1.6 ± 0.8	~2	Good	1	-1.9 ± 1.3	-1.0 (small)	-1.2	0.3 x CV_{ind}	Poor	9
20 m	1	1.9 ± N/A	~1	Poor	4	-1.9 ± 0.9	-1.9 (small)	-1.0	0.3 x CV_{ind}	Poor	9
40 m	1	0.7 ± N/A	~0.5	Moderate	1	N/A			0.3 x CV_{ind}	Poor	9
MSS	4	2.9 ± 0.7	~2	Poor	2	0.5 ± 0.3	0.3 (trivial)	0.2	0.3 x CV_{ind}	Poor	9

TE= typical error of measurement (as a CV), {n} = number of studies the TE calculations were based on, SWC= smallest worthwhile change, CL= confidence limit, CV_{ind}= individual coefficient of variation, # trials required= the number of trials required to decrease the TE to a similar value to the SWC. Magnitude of the changes = as multiple of the SWC (with rating). MSS=maximal sprinting speed. N/A= not available. The probability for a change of the same magnitude as the SWC, when SWC = TE, is 50%. A likely change (probability >75%) is obtained for a change of 2 times the SWC (or TE). See Figure 1 and 2 and section 10 for details. Note that the estimation of the SWC for team sport athletes is based on the running speed improvement required to win a ball (20 cm). While greater distance may actually be required to win a ball (e.g. 30-50 cm), as suggested by Haugen et al. [41], the present SWC estimation provides the smaller range for the SWC; twice greater SWC could therefore be considered using a 40-cm advantage for example – the number of trials required should therefore be doubled accordingly. Note also that the signal-to-noise ratio is based on a single study [10] (strength training in junior soccer players performed weekly twice over two years, with special emphasis on parallel squats) where all sprint-distances were reported together. Different results may be observed in other populations undertaking different types of training.


A
Start block
B
Finger pod
C
Photocell
D
Photocell
E
Foot
pod


Case 1
Case 2
Case 3
Case 4
Case 5
Case 6
Case 7
Case 8
Case 9
Possible 50/50/0
Unclear 50/42/8
Unclear 50/18/32
Likely 76/24/0
Possible 64/32/4
Unclear 55/17/28
Likely 92/8/0
Likely 76/22/2
Unclear 59/17/24
-3
-2
-1
0
1
2
3
4
5
6
Change (%)


a
Change = 2 x SWC
Change = 1.5 x SWC
Change = SWC
Probability for improvement (%)
110
100
90
80
70
60
50
40
Substantial change
Trivial change
b
TE (%)
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
35
40
45
50
55
60
Sprint repetitions


10-m sprint
MSS
25.4 km.h-1
31.0 km.h-1
1.96 s
1.72 s
Large
Moderate
Small
Small
Moderate
% Change
Age (y)
30
20
10
0
-10
-20
12
13
14
15
16
17
18
19