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REVIEW ARTICLE

Sprint Start Regulation in Athletics: A Critical Review

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Abstract

The sprint start in athletics is strictly controlled to ensure the fairness of competition. World athletics (WA)-certified start information systems (SIS) record athletes' response times in competition to ensure that no athletes gain an unfair advantage by responding in < 100 ms after the start signal. This critical review examines the legitimacy of the 100 ms rule, the factors that affect response times and the technologies and rules that support the regulation of the start in competition. The review shows that several SIS use different technologies to deliver the start signal and record response time (RT). The lack of scientific evidence about the definition of the 100 ms false start threshold by the WA is criticized in the literature and the 100 ms rule is challenged. SIS technologies, expertise and sex appear to affect the RT detected in competition. A lack of standardization in event detection has led to validity and reliability problems in RT determination. The onset of the foot response on the blocks is currently used to assess RT in athletics via block-mounted sensors; however, research shows that the onset of arm force reaction is the first detectable biomechanical event in the start. Further research and development should consider whether the onset of arm force can be used to improve the false start detection in competition. Further research is also needed to develop a precise understanding of the event sequence and motor control of the start to improve the SIS technology and rigorously determine the minimum limit of RT in the sprint start.

Key Points

The validity and reliability of technologies used to detect false starts in athletics are questioned in the literature.

The current 100 ms false start limit is not supported by robust scientific evidence.

Further research is needed to map the event sequence and motor control during the sprint start and provide support for sprint start regulations in athletics.

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1 Introduction

Despite accounting for only 5% of the total 100 m race time [1], the sprint start in athletics is an important performance element since the margin of victory in short sprints can be as small as a few milliseconds. The starting procedures in competition follow the World athletics (WA) Federation Book of Rules [2] for competition, which aim to ensure fairness for all competitors. After the "set" command, all sprinters assume a steady crouch position in starting blocks (see Fig. 1). When the starter is satisfied that all athletes are steady in the "set" position, the start signal is delivered. The duration of the "set" or fore-period (FP) is at the discretion of the starter and wherever possible, the athlete response time (RT) is recorded by a Start Information System (SIS) which determines the time between the start signal and the first detectable response from sensors in the starting blocks. If the RT is less than 100 ms, the athlete is assumed to have anticipated the start signal and the race is automatically recalled. The starter may examine RT and other available information from the SIS to confirm the false start(s) and disqualify athlete(s) that has/have committed a false start. If athletes trigger the SIS without a hand or foot losing contact with the ground or the starting blocks (i.e. have not

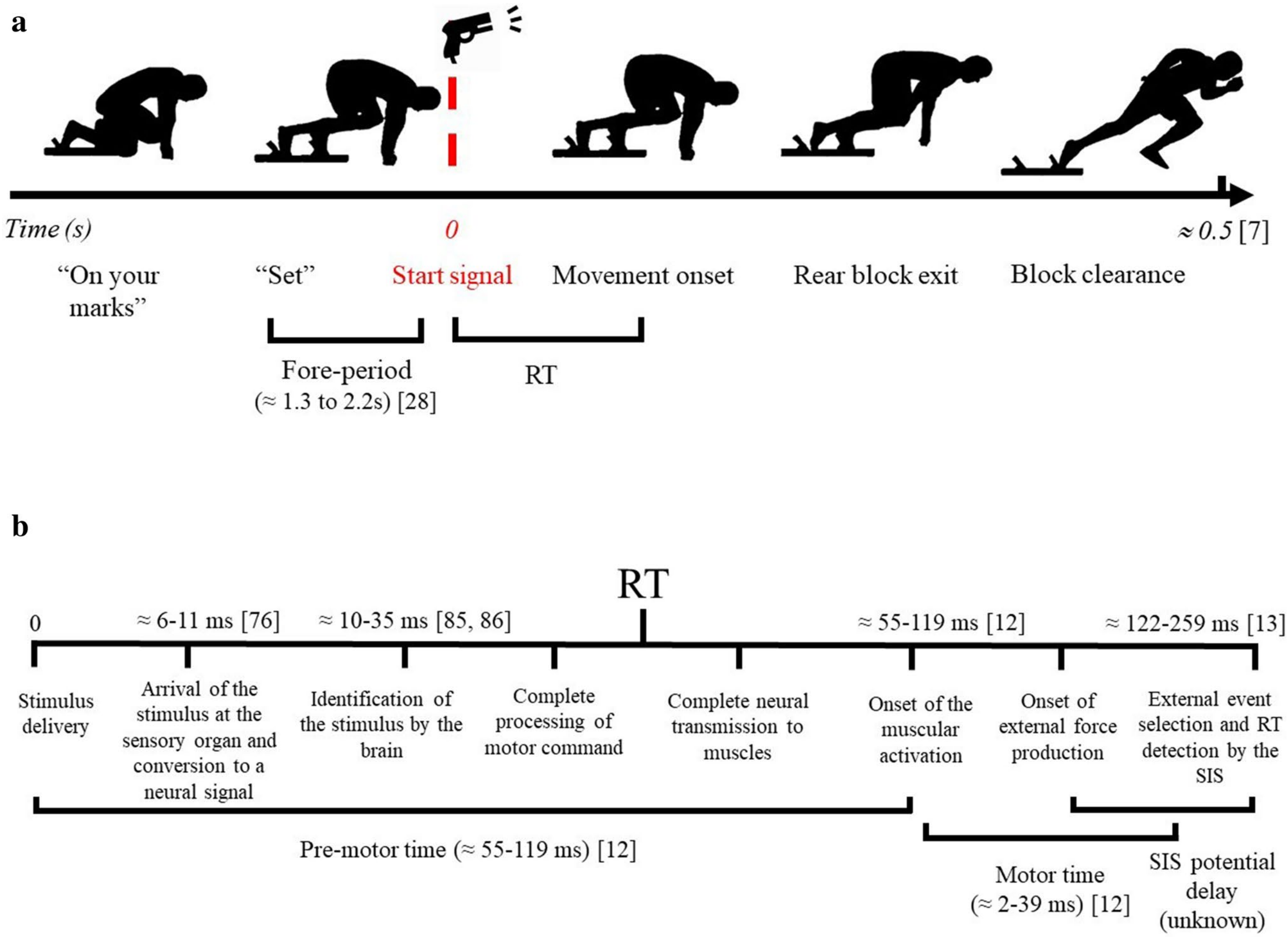

Fig. 1 **a** Sprint start sequence of events. **b** Response time (RT) components during sprint start

completed a start action), the starter will issue a warning to the athlete(s). Two warnings result in automatic disqualification. The sprint start procedures are strictly controlled to ensure all athletes can respond as quickly as possible without anticipation and a resulting false start.

A precise understanding of the event sequence and motor control of the start is crucial to ensure fairness in sprint start regulation. The official RT in athletics includes various components from the start signal delivery to the RT recorded by the SIS (Fig. 1). This includes neuro-physiological and non-neuro-physiological components defined as the time between the stimulus delivery and the arrival to the sensory organ, and the time delay caused by the SIS processing. RT is recorded by the SIS to a precision of one millisecond and the response event is determined by evaluating force or acceleration changes recorded by sensors integrated in or secured to the starting blocks. A new generation of instrumented starting blocks was developed in the 1990s [1, 3, 4] and several WA approved SIS are currently used to record athletes' RT in competition [5]. It is expected that RT should be measured in uniform conditions [6] and false starts across all systems are determined using the same 100 ms false start RT limit. Since RT is determined using accelerometers or force sensors on blocks, RT detection is a biomechanical and technological challenge. In the literature, two reviews of sprint start biomechanics have been published in the 1990s [1, 6] and a further review was published recently to update the current understanding on this topic [7]. None of these review articles evaluated the appropriateness of the 100 ms false start threshold or the technologies involved in RT detection, which are critical to sprint start regulation. While SIS require certification by WA for use in competition, the precise requirements of the certification procedure are not available on the WA website or in publicly available documentation. Research has shown that despite certification, several SIS show variable results, highlighting the challenges in detecting the true and therefore valid athlete RT [5, 8, 9]. The use of different technologies to deliver the start signal and to detect RT could have an impact on specific components of RT and could explain the variable results across studies. Some studies claim that the minimum RT is shorter than the current 100 ms false start threshold [10–12], while other studies suggest the 100 ms false start threshold should be increased [13, 14]. This emphasizes the difficulties in determining a universally agreed minimum RT in athletics since SIS technologies [5, 12], sex [14] and expertise [15] could have an impact on RT. Consequently, there is an urgent need to revisit the regulations of the sprint start to ensure consistency and fairness in competition. Therefore, this literature review has three major aims. (1) To provide an evaluative synopsis of current SIS technologies and their influences on RT detection; (2) to re-evaluate the scientific basis and validity of the 100 ms false start threshold and; (3) to propose practically acceptable ways for improving the validity of false start detection.

1.1 Response Time and Reaction Time Definition

Confusion exists between the terms reaction time and response time in athletics arising from inappropriate use of terminology. The WA and many sprint start scientific studies have used the term reaction time to describe the period between presentation of the start signal and detection of the athlete response. Reaction time is a measurement of how long it takes an individual to perceive, process, and initiate a movement in response to a stimulus [16]. It does not include any movement component. The onset of the response should be use to assess RT, not the response itself. This problem of measuring only components of the neuro-physiological reaction time is present to varying degrees in all reaction time research [12]. In athletics, the same "reaction" would yield different "reaction times" depending on the SIS [5]. The term "response time" is hence more appropriate, and includes neuro-physiological components and potentially a movement time and technological components induced by the SIS processing. However, the scientific literature and WA frequently use the term reaction time instead of the term response time. The term response time is, therefore, preferred for the purposes of this review; however, the term reaction time was used in the literature search.

1.2 Delimitations of the Review

The articles discussed in this review were initially sourced using a combination of the keywords (sprint AND "reaction time" AND ("athletics" OR "track and field")) in PubMed and Google Scholar databases. The literature search period started in 1990, when the International Association of Athletics Federations (now WA) adopted the 100 ms false start rule and the new generation of instrumented starting blocks was used. A first selection was made by reading the titles and the abstracts to judge the relevance of articles. Initial exclusion criteria were applied, namely articles where full text was not available, were not in English or French or where there was no use of starting blocks. Given the narrative nature of this review, searches of the reference lists of these articles were also undertaken to identify any further potentially relevant articles for the review. Furthermore, a bibliographic search on the reaction time topic was carried out in the archive of the WA publication, New Studies in Athletics, available in the WA web site. Lastly, some additional manual research was undertaken as the review progressed to explain more general scientific aspects relevant to this review.

2 Influence of SIS Technologies on RT

2.1 Technologies Used in the Start Signal Delivery

Historically, the start signal was provided by a gun using a blank cartridge. In this procedure, athletes who were further away from the starter were disadvantaged since the speed of sound delayed the transmission of the signal to the athletes. The speed of sound in air is about 350 m/s, so 0.01 s is added to the RT for each 3.5 m between the starter and the athlete. Currently, an electronic gun is used to give the start signal and trigger the SIS timing system. The gun is connected to speakers integrated on each starting block to deliver the signal simultaneously to all athletes. For this procedure, two technologies have been used. The "silent gun" system uses an electric gun which makes no sound but sends an electrical signal to the speakers on the starting blocks which then produce a sharp sound. All athletes, therefore, hear the starting signal at the same time. The "loud gun" system uses a microphone to pick up the sound of the gunshot, and transmits the sound as an electrical signal to speakers. In the loud gun system, athletes may theoretically hear the start signal twice because the speed of electricity through a wire is much quicker than the speed of sound in air (3×10^8 m/s vs 350 m/s) [8]. However, various studies showed a significant effect of the start lane on RT resulting from the use of the "loud gun" system manufactured by Omega (Bienne, Switzerland) in the 1996 and 2004 Olympic Games [8, 9, 11]. The effect was greater for the 200 m, 400 m, and relays than for the 100 m, emphasizing that athletes did not respond to the sound of the gun through the speakers [8]. Since 2010, the Omega SIS adopted a "silent gun" to solve this problem. However, there is currently at least one certified SIS that still uses a "loud gun" system (FalseStart III Pro, Times Tronics NV, Olen, Belgium). No recent scientific study has formally assessed the validity of the start signal delivery or evaluated the problems associated with the use of a "loud gun" system. Therefore, the use of a "silent gun" system should be prioritized in competition.

While scientific studies need to consider the type of start signal delivery system used in the SIS, most studies have failed to find a statistically significant relationship between RT and performance in short sprint events such as 60 m and 100 m or have found inconsistent results [6, 17–19]. Such studies concluded that RT is not an important component of the performance in sprint; however, studies about RT collected during official competitions did not provide the SIS used to record RT and did not take into consideration the effect of "silent gun" or "loud gun" systems [17, 18]. It is known that Omega, the official SIS provider for the Olympic Games [11], manufactured a "loud gun" system until 2010. The lack of consideration of the "loud gun" effect on the lane could explain the inconsistent results for the relationship between RT and performance in short sprint events during the Olympic Games before 2010. Tønnessen et al. [20] analyzed RT only from a "silent gun" system and found a significant relationship ($p > 0.01$) between RT and 100 m running time, with shared variances of 8.5% and 10.8% for males ($r = 0.292$) and females ($r = 0.328$), respectively. While the correlation is small [21], these results emphasize the potential importance of RT in short sprint events. A recent study also found a significant relationship between RT and 60 m performance during World championships from 2010 to 2018 [22]. The use of SIS in research, without taking into account the potential effects of the start signal delivery technology, could, therefore, produce conflicting results and further research needs to be carried out using uniform technologies to assess the potential relationship between RT and performance in sprint events. The SIS start signal delivery technology should, therefore, be tested to ensure all athletes hear the start signal in the same way before being used in competition or in scientific studies.

The nature and loudness of the sound of the start signal has an influence on RT. Experimentally, Brown et al. [11] showed that start signal intensities from 80–100–120 dB significantly decreased RT from 138 ± 30 to 128 ± 25 to 120 ± 20 ms, respectively, the sprint start which is consistent with laboratory studies on simple RT [23–25]. The loudness reduces the time to identify the stimulus [24], and the time to initiate the response [23]. A sound of 120 dB increased the occurrence of a startle response and could induce RT under the 100 ms false start threshold [11] by reducing the premotor time via a faster neural pathway [26]. To our knowledge, there does not seem to be a precise regulation by the WA on the start signal intensity. Any differences in signal intensities of the various certified SIS could, therefore, have an effect on the athletes' RT and the resulting performance. No study has yet been conducted to test the potential difference of the start signal intensity between the various certified SIS and the effects on athlete's RT. Based on the literature, it is recommended that the WA set a standard start signal intensity for the SIS, whether using a "loud gun" or "silent gun" system, to avoid an effect of the SIS start signal intensity on athlete RT. Further research is, therefore, required to set a standard for start signal intensity, which allows athletes to respond immediately without provoking an increase of the startle response occurrence and potentially invoking a false start.

Normally, it is intended that the starter gives the start signal after ensuring that all athletes are steady in their starting blocks. The FP duration is necessarily varied to prevent athletes anticipating the start. At present, the WA rules provide no regulation about the FP duration despite its known effect on RT. In practice, the FP duration in competition is on average 1.780 ± 0.158 s [27]. The FP duration has been shown to have a small but significant effect on athlete reaction time ($r = 0.16$, $p < 0.001$ for males and $r = 0.17$, $p < 0.001$ for females between 1997 and 2003) [28]. Otsuka et al. [27] tested FP durations ranging from 1.465 to 2.096 s based on the distribution of the FP length in competition. They found RT was significantly shorter when the FP duration was longer which is consistent with the other studies on RT [29–31]. RT often decreases monotonically as a function of the FP duration when FP duration is variable, because the certainty of the imperative stimulus' presentation increases with time [29]. The shortest FP durations within the above range did not give sprinters enough time to prepare the appropriate motor program in starting blocks, resulting in a RT delay which could reach 0.039 ± 0.007 s between the shortest and the longest FP duration [27]. The effect of FP duration on RT may, therefore, cause difficulties when comparing results from different race performances or competitions and could be recorded during competition, as is currently done for the wind and RT. Consequently, Otsuka et al. [27] suggested the implementation an automatic start signal timing in SIS with a fixed FP duration. To prevent athlete anticipation, Otsuka et al. [27] suggested the addition of "catch trials" where no start signal would be delivered. Further studies are recommended to determine an optimal FP duration which does not delay the athlete RT and to evaluate the use of a catch trial system in competition. In practice, however, the use of a catch trial system does not seem appropriate in international competition, as it may be perceived as an unnecessary antagonist of athlete concentration or a way to encourage risk/reward behaviors by athletes.

2.2 Technologies Used in RT Detection

All SIS integrate or attach sensors in starting blocks and convert the leg actions on the blocks into a signal which is processed by an event detection algorithm to determine RT. SIS are provided by various manufacturers and all use different types of sensor technology such as force transducers, accelerometers or force dependent closure switches [5]. The precise details of event detection algorithms are not made public by SIS manufacturers [14] and in the absence of a reference criterion, the use of different algorithms can be expected. Most of the scientific studies use a simple arbitrary force threshold to assess RT [10, 14, 32–35], or use a simple threshold computed using the mean and standard deviation or a predetermined percentage threshold of the baseline signal [5, 36–40].

Willwacher et al. [5] developed a method to evaluate and compare SIS. They built a robot to apply a consistent pattern of force on the various SIS starting blocks across many trials. The results on four systems tested showed substantial differences in RT detection. In particular, one of the systems (system 2) exhibited a RT delay of around 20 ms in comparison with the three other tested SIS and this highlighted a validity problem between the systems. Two other systems (systems 3 and 4) exhibited greater intra-system variations when the same pattern was applied many times on the starting blocks, thereby indicating a lack of reliability. No study to date has assessed whether different sensors (force transducers, accelerometers, or closure switches) have the same accuracy to detect a false start. Babiç & Delalija [41] suggested that the push on the starting blocks begins with a near isometric contraction, in the set position, followed by isotonic explosive contraction of leg muscles. While acceleration and force are linked by Newton's second law, the force sensor is theoretically more appropriate because of its capacity to detect the relatively small increases in resultant force acting on the blocks from the action of the legs, whereas accelerometers and closure switches require a change in the motion status of the blocks/sensor. Due to lack of control of extraneous external forces, vibrations and mounting conditions, accelerometers are likely to be prone to higher levels of noise from a variety of other sources and this could in part explain the differences in RT between systems.

RT detection algorithms can also have a substantial effect on the outcome. The use of a simple force threshold has been shown to increase the measurement of RT by 26 ms on average in comparison with the use of a more sophisticated algorithm that detected the rate of change in force with respect to time [12]. This demonstrates the limitation of force threshold based algorithms. Nevertheless, the use of more sophisticated algorithms in a few studies has been problematic because they were not fully automatic [12, 27], and results had to be visually checked. RT differences resulting from the use of different event detection algorithms highlight a technological component of RT determination, which should be standardized to ensure validity across the various SIS. Some studies overcame the computational problem of RT detection by using a visual determination of the first detectable change in the force or acceleration curve signal [10, 42–44]. The RT difference between visual detection and one certified SIS was 7 ms for women and 11 ms for men on average [43] and 35 ms between visual detection and a simple force threshold [10]. No significant correlations were found between the RT given by a certified SIS (ReacTime RT8LWL by Lynx Developers USA) and the RT visually determined as the first detectable change of force in the instrumented blocks [43] highlighting that SIS did not reliably predict the true first athlete response. Visual detection is currently more sensitive and accurate than automated detection to detect the onset of an EMG signal [45–47], and has been used to detect the onset of force reaction as a gold standard [48]. However, visual detection of RT is not compatible with the real time requirements in competition. Further studies are therefore required to improve the event detection algorithms used in athletics, and visual detection may be used as a reference criterion to assess the precision of the detection algorithm. The lack of a clear regulation by WA on the validity and reliability of the SIS, and a reference criterion for RT detection, are ultimately detrimental to the fairness of competition, emphasizing the urgent need to revisit the SIS certification.

2.3 Validity of Assessing RT from Starting Blocks

All current SIS use sensors on the starting blocks to detect leg-pushing actions on the starting blocks as this is currently considered the most appropriate event for detecting a false start. The leg-pushing actions on the starting blocks contribute overwhelmingly to the normalized average horizontal external power of the sprinter center of mass, highlighting the predominant role of the legs on the sprint start performance [49]. Consequently, the normalized average horizontal external power has been proposed as the most important parameter for measuring performance during the sprint start [50]. The sprint start is, however, not just a simple leg movement, but rather a very comprehensive whole body movement [10, 27, 32, 33, 37, 51–53] and, therefore, the leg-pushing action may not be the most appropriate external event to detect RT in athletics [10]. The head, trunk and arms all play important roles in a sprint start. The head and trunk extension contributes to create a high velocity of the center of mass during the pushing phase in the sprint start [51]. The maximum kinetic energy of the head–trunk segments is not significantly different from the maximum kinetic energy of the lower limbs, highlighting the important role of the head and trunk segment during the sprint start [52]. The role of arms is often underestimated in the scientific studies [32]. Many studies computed global kinetic variables (i.e. total impulse, normalized average horizontal block power etc.) without taking account of the arm contribution [54–59] despite the substantial effect of the arms on some variables [32, 37]. The arms contribute approximatively 18% to the total vertical impulse [32] and 22% to the kinetic energy of the total body during a sprint start [52]. The arms generate a negative horizontal impulse to counteract the pre-tension generated by the legs in the set position [32, 33] and better sprint starters distribute more weight on their hands in the set position, further highlighting the importance of the arms to sprint start performance [60]. The arms support the leg pushing phase by a movement of extension [52] to preserve whole body-balance and support forward-lean and application of ground reaction force after the hands lift off the ground [33]. A review of the literature about the role of the arms during sprinting concluded that they have an important role during the start and early acceleration phase of the sprint [61].

While an understanding of the contributions of various body segments in the sprint start is important from a performance perspective, the sequencing of events is much more important when attempting to determine the RT in the sprint start. The sequence of events during the sprint start shows that the arms consistently respond before the legs [10, 42]. Kinematic analysis showed that arm joints (wrist, elbow, shoulder) respond sooner in comparison with the leg joints (ankle, knee, hip) according to the respective RT generated by the moment in each joint [27]. It should be noted that determination of joint responses using kinematic analysis would be time consuming to process and would not meet the requirement for immediate detection in competition settings. This event sequence was confirmed by an analysis of forces [32, 42]. Moreover, the onset of arm force reaction was the first event on average among many kinetic, kinematic and EMG variables recorded during the sprint start [10]. Furthermore, the mean onset of arm force reaction was 69 ± 12 ms while the mean onset of leg force reaction was 98 ± 23 ms (both obtained by visual detection). Otsuka et al. [27] provided an example trial where the front-arm shoulder joint RT was 61 ms but the whole-body RT was > 100 ms when assessed from the sum of the ground reaction forces from arms and legs with a custom-made algorithm. While this trial would not be considered as a false start by a current SIS, the data indicated that the athlete reacted well before the 100 ms false start threshold and challenge the expected limits of onset of muscle force (see Fig. 1). This example highlights the need to revisit false start detection regulation. Komi et al. [10] suggested that RT should be determined with a system of high-speed cameras, but evidence from the same study [10] indicated the first detectable movements of the head or hands obtained by visual detection of reflective markers (110 ± 17 ms and 108 ± 20 ms, respectively) occurred after the onset of arm force reaction (69 ± 12 ms). Furthermore, using high-speed video to detect the onset of the first visible movement increased RT detection by 60 ms on average in comparison with RT detection from the starting blocks [12]. Otsuka et al. [49] used a sophisticated method based on video analysis to detect RT, which showed good agreement with RT computed from the force responses of the legs and the arms. However, the methodology based on tracking reflective markers would be impossible to use in competition. It is reasonable to expect that RT should be determined from the first practically detectable biomechanical event that accompanies the response. Further research is, therefore, needed to improve the current understanding of the event sequence and motor control of the start and determine the first practically detectable biomechanical event. Based on current knowledge of the event sequence during the start, the onset of arm force reaction consistently precedes the onset of the leg push and, therefore, may be a suitable event to assess RT in athletics. RT determined from the leg push during the start demonstrated a lack of inter-trial reliability among sprinters with a low intraclass correlation coefficient ICC (1.3) of 0.355 [62]. RT recorded with a WA certified SIS (ReacTime, Lynx System Developers, Inc., Haverhill, USA) presented a high variability within day and between days in healthy male subjects while their sprint performance was reliable [63]. The reasons for this lack of reliability are unclear, but could be explained by variability in neurophysiological and/or technological components of the RT. Further studies are required to evaluate whether other biomechanical events, such as the onset of arm force reaction, provide improved validity and reliability compared with the onset of the leg push to detect RT during the sprint start. WA should, therefore, re-evaluate SIS technologies, and examine whether the onset of arm force reaction provides an appropriate signal to detect RT in athletics. Extensive research and testing would also be required to ensure that the detection of arm force onset could be validly determined and reliably used in competition settings.

3 Validity of the 100 ms False Start Threshold

3.1 ms False Start Threshold Assessment

The notion of a RT delay is conceptually sound; however, the evidence supporting the current threshold of 100 ms is limited. The false start threshold should prevent athletes from anticipating the start cue and, therefore, it is assumed that the threshold represents the minimum RT in executing a sprint start. This RT includes the neuro-physiological limit for perception and processing of the start signal, the initiation period of the sprint start motor response, and any potential delay induced by the SIS technology to detect RT. This threshold should be specifically determined relative to the response measured because RT is influenced by the nature of the stimulus and the nature of the required response [16]. The RT in athletics is classified as a simple auditory RT which is the quickest kind of reaction time according the majority of studies [64, 65]. There is no official statement from WA about the justification for the 100 ms false start threshold. According to Lipps et al. [14], part of the 100 ms false start threshold determination is based on an empirical study conducted in the early 1990s [39]. In this study, only eight national level Finnish sprinters were tested; consequently there is only a small likelihood that the 100 ms threshold was defined according to robust scientific evidence. Some recent scientific studies have carried out statistical analyses with large samples of RT recorded during the major international competitions to revisit the false start threshold [13, 14]. Brosnan et al. [13] suggested increases were required in the false start threshold to 115 ms for men and 119 ms for women. Nevertheless, the proposition to increase the threshold from data recorded in competition is questionable. Evidence showed sprinters do not respond as quickly as they could in competition. RT recorded in competition increased or tended to increase with the evolution of false start rules [13, 28, 66, 67]. Before 2004, a false start resulted in a warning for a sprinter, and he or she was disqualified for two false starts in a race. Since 2004 to 2010, only one false start per race was allowed. Any sprinter registering a false start after the first recall was automatically disqualified regardless of whether he or she was the original offender. Since 2010, any sprinter who false starts is immediately disqualified and removed from the race. The evolution of stricter rules most likely resulted in increased caution by sprinters who preferred to respond later instead of risking disqualification for a false start [28]. Moreover, a recent analysis of the FP duration in international competitions showed that FP durations are too short and did not allow sprinters to respond as quickly as they could [27]. The combined effect of the start rules and the FP duration would increase the RT by 0.05 s [28]. Consequently, RT recorded in competition does not reflect the true athlete ability to react quickly and should not be used to assess the minimum limit RT in athletics.

It has been proposed that the sprint start RT minimum limit should be less than the current 100 ms false start threshold. Experimentally, sprinters can react before 100 ms [11, 12]. Approximately 20% of the recorded RT was shorter than 100 ms in both these studies, yet their protocols were set to prevent anticipation. Various ideas could be proposed to explain the difference between these shorter RT and RT recorded during competition. Firstly, since there is no pressure to be disqualified in laboratory studies, the sprinter responses could be closer to their physiological limits. The neuromuscular-physiological limit of simple auditory RT could be under 80–85 ms [10, 12]. According to this hypothesis, the WA should therefore reduce the 100 ms false start threshold and not limit sprinters' ability to respond very quickly. Alternatively, these RT differences could be explained by the different methods used to detect RT. Pain and Hibbs [12] used their own custom algorithm to detect RT which was 26 ms shorter on average in comparison with a simple threshold of force detection. Of note, in the 1990s, Mero and Komi [39] used a simple threshold (10% above the baseline) to assess RT. Brown et al. [11], for their part, seemed to use visual detection to assess RT. Since the algorithms used to detect RT have a substantial effect on the final result, a specific false start threshold should be associated with each event detection algorithm but this would be impracticable. The development of a reference algorithm to support the statistical determination of the RT minimum limit is urgently needed to ensure the validity of the false start threshold.

3.2 Relevance of the Use of a Single False Start Threshold

Currently, the same 100 ms false start RT threshold is used for all sprinters, irrespective of sex, level of performance or sensor type. According to Lipps et al. [14], the 100 ms rule was based on a study which recorded RT only from Finnish national level male sprinters [39]; therefore, the issue of whether RT thresholds should be adjusted for sex or performance level has never been addressed within WA rules.

3.2.1 The Expertise and Response Time Relationship

The simple RT is generally seen as a motor ability; it does not change over the course of a person's adult lifetime, it cannot be improved with practice and is mainly genetically determined [16]. The ability to respond very fast should be therefore difficult to train [68], nevertheless, some studies have challenged this assumption. It is known that athletes have a better auditory RT than non-athletes [69–71] and similar results were found with visual RT [70, 72, 73]. Akarsu et al. [73] found a correlation between sporting age (total duration of participation in sports) and eye-hand visual RT, suggesting that practice of sport seems to reduce the athlete RT. Evidence suggests that improvement would be partly sport specific since sprinters have shorter auditory RT but less visual anticipatory skills than volley ball players [74]. In practice, sprinters are conditioned to start on some auditory stimuli, while volleyball players are required to continuously visually predict where the ball is going to be during the game. Moreover, a recent study showed that specific auditory stimulus training improved the RT of competitive swimmers [75], suggesting that the ability to react very fast is not only genetically determined but is a skill developed by hours of practice and training.

In athletics, some studies showed that RTs were quicker on average during the final round of international competitions compared with the first-round heats [13, 15, 20], emphasizing perhaps that the faster sprinters who took part in final rounds had better RT from slower sprinters eliminated in first round heats. However, Cŏh et al. [56] found that international level sprinters had a significantly longer rear block RT compared with national level sprinters measured in a laboratory situation. No significant differences were found for the front block RT but on average, it occurred later than the rear block RT (332 ± 28.73 vs 162 ± 9.47 ms) and so is less important in the assessment of athlete RT. The study did not provide any details about how RT was assessed from the blocks or propose any explanation for this counter-intuitive result. Moreover, Eikenberry et al. [35] did not find a significant difference in RT between experienced and novice sprinters. The experienced sprinter group however consisted of some sprinters with only 1 year of experience and this could have been a confounding factor. Further studies are required to determine whether performance level affects RT. If it can be shown that top level sprinters have shorter RT and that RT is trainable, then the 100 ms false start threshold may require adjustment, since the 100 ms threshold was most likely determined based on RT from a limited sample of non-elite athletes [14]. Using RT from international top-level athletes to assess the RT minimum limit may be more appropriate if elite athletes react quicker than less skilled athletes; however, at present the evidence for this is limited.

3.2.2 Sex and Reaction Time Relationship

The question of whether female sprinters need a specific RT threshold is complex. The characteristics of the female cochlea (inner ear anatomy) which converts a sound to a neural impulse allows them to have shorter auditory latencies than men [76]. Furthermore, women generally have a shorter stature [34, 77] and therefore a shorter neural pathway, which facilitates a faster response to sound. These characteristics would allow women to have auditory RT of approximately 1 ms shorter than men, which could be considered as negligible. Despite this, female sprinters have 22% lower rate of force development in their plantar flexors in comparison with male sprinters [14]. Since various SIS use a simple force threshold to detect RT [14], this peripheral difference in strength qualities could explain why many studies have found that female sprinters react slower than male sprinters in most international competitions [11, 13, 14, 17, 20, 66, 78, 79]. This lower rate of force development would increase the technological component of RT for women. The average male RT is approximately 5 ms shorter than the female RT in international athletics competition [13]; however, no sex difference was found in some events and competitions. Mirshams Shahshahani et al. [78] found an abrupt decrease for women's RT at the 2012 Olympic Games which eliminated the sex difference found in other competitions, suggesting that the women's force threshold may have been reduced in this championship due to a reduction in the technological component of RT. This may have followed the recommendation of Lipps et al. [14], who found significant differences in RT between men and women at the 2008 Olympic Games and recommended that the force threshold for women should be reduced. Furthermore, Babiç and Delalija [79] found significant differences in RT between men and women in the 110 m and 100 m hurdles events and 100 m flat sprinters in the qualification round but not in the final round at the 2004 Olympic Games. Since there is no substantive physiological reason why women should respond slower than men in their central auditory processing time [76], the RT difference between males and females in the qualification rounds could be due to men being more likely to risk anticipating the start in the earlier rounds compared to women [13]. Several studies showed no systematic sex differences [6, 17, 38, 78–81] while others have identified sex differences [13, 14, 20]. These contradictory findings could be explained by the effect of sample size on the statistical tests, different methodologies, or the different SIS event detection algorithms used. Assessing a potential neuro-physiological sex difference in athletics competition data will remain difficult since the precise details of RT detection are not made public by the SIS suppliers.

At a more general level, Der and Deary [82] examined RT in a sample of 7,130 British adults and showed that women have a slower and more variable simple visual RT than men, although this difference disappeared in team sport players. Spierer et al. [83] analyzed auditory and visual simple RT from male soccer players and female lacrosse players and found a significant difference for auditory simple RT but not for visual simple RT. These two team sports require anticipatory skills and quick visual RT, and therefore the absence of visual RT difference between male and female players could result from a practice effect since the improvement of sensory-cognitive skills is sport specific [74]. This hypothesis is strengthened by the fact that the magnitude of the sex differences in simple visual RT has reduced over time secondary to the increase in women's participation in fast-action sports and driving [84]. In summary, there is no clear evidence to support the notion that female sprinters react slower than their male counterparts; however, the use of a simple force threshold is not appropriate to detect RT because of its tendency to increase women's RT due to their lower rate of force development. An algorithm with the ability to detect RT using the onset of the change in force, instead of a simple fixed force threshold, should be recommended. This would allow false start regulation to remain the same for both sexes. Further studies are required to statistically determine minimum RT for both females and males using a qualitative algorithm, which should minimize the RT technological component and remove any sexual differentiation in RT measurement.

4 Conclusion

This critical literature review has highlighted some serious limitations of the regulation of the sprint start. The absence of agreed reference standards to assess RT is problematic and the inconsistencies in SIS technologies leads to validity and reliability problems despite the various SIS being certified by the WA using the same 100 ms false start criterion. Since a starter confirmed false start now leads to immediate disqualification of the athlete, it is vital that the technology used in competition is robust and the decisions on false starts are correct. This lack of regulation highlights the technological and scientific challenges in assessing RT in athletics. While acknowledging the many challenges of precisely regulating the sprint start, it is important that WA should introduce more rigorous standards for event detection to ensure more consistent SIS performance.

The lack of scientific evidence for the 100 ms false start threshold has been consistently criticized in the literature for more than 10 years without resulting revisions to the rules. The inconsistent results in the literature on changes to the false start thresholds reveal complex interactions between the sensor used by the SIS, the algorithm which detects RT, and the final result of RT. The SIS technologies and event detection algorithms should be improved and standardized to ensure validity and very high levels of reliability. This is a necessary first step to attempt to redefine/revise the false start 100 ms limit.

The literature demonstrates various shortcomings in sprint start technology, regulation and false start detection that need to be addressed to ensure fairness in competition. A set of revised criteria is required to improve and standardize the event detection algorithm and ensure immediate detection of the onset of force change in the waveform signal. Recent research indicates the onset of arm forces occur before onset of block forces; therefore, further research and development should explore the validity, reliability and feasibility of using arm force responses to detect false starts in a competition setting. These two revisions could provide a basis for defining new standards for RT measurement in sprint events and improve false start detection.

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Declarations

Conflicts of interest Andrew Harrison and Kevin Hayes have the following patent application pending: 'A hand plate sensor for sprint start reaction time detection; WOPCT/EP2018/070449'. Matthieu Milloz declares he has no potential conflicts of interest relevant to the content of this review.

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