Sprint start performance: the potential influence of triceps surae electromechanical delay

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In the sprint start, a defined sequence of distinct response delays occurs before the athlete produces a movement response. Excitation of lower limb muscles occurs prior to force production against the blocks, culminating in a movement response. The time delay between muscle excitation and movement, electromechanical delay (EMD), is considered to influence sprint start response time (SSRT). This study examined the delay in sprint start performance from EMD of the triceps surae muscle and examined whether certain sprinters gain an advantage in SSRT. Nineteen experienced sprinters performed sprint starts from blocks, with SSRT measured by an International Association of Athletics Federations (IAAF)-approved starting block system. EMD times were detected during a heel-lift experiment. Using revised SSRT limits, based on concerns over the validity of the IAAF 100 ms false start limit, EMD produced a significant moderate correlation with SSRT ($r = 0.572$, $p = 0.011$). Regression analysis determined that together, EMD and signal processing time (the delay between the auditory signal and muscle excitation) accounted for 37% of the variance in SSRT. Initial results suggest EMD is part of the response time process and that certain athletes may gain a performance advantage due to reduced EMD.

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Introduction

In short sprint events, the sprint start contributes to an athlete’s overall performance, accounting for approximately 5% of an athlete’s 100 m race time (Tellez & Doolittle, 1984). The ability to generate force rapidly using the body’s musculotendinous structures is important for an effective sprint start (Clegg & Harrison, 2005). In the sprint start response sequence, individuals must perceive a stimulus (auditory signal) and initiate a neural response before muscle force can develop. Consequently, delays in the sprint start response can be mapped to an established sequence of events (Figure 1). This delay sequence can be sub-divided into signal processing and electromechanical delay (EMD) periods. Each event on the timeline of responses has an associated processing time, which contributes to the athlete’s overall response time. Muscle pre-tensing during the sprint start may reduce some of these delays and therefore measures of the sprint start response time (SSRT) can be different from the measurement of response times in other activities. In practice, SSRT is measured as the time elapsed between the presentation of the starter’s stimulus and the moment the athlete exerts a predetermined force against the starting blocks (Mero, Komi, & Gregor, 1992).

[Figure 1 near here]

Mapping and measuring the sequence of physiological and mechanical delays is important for a precise understanding of the SSRT. Research to date has demonstrated that SSRT is dependent on several factors: the time taken for the start signal stimulus to arrive at the sensory organ, the delay for conversion by the sensory organ to a neural signal, the delays for neural transmissions and processing, activation of the muscles, soft tissue compliance and selection of the external measurement parameter used to detect the response (Komi, Ishikawa, & Salmi, 2009). Signal processing time encompasses the delays between the stimulus onset and
muscle activation. Following the presentation of the stimulus, a delay exists before the athlete hears the signal, this is estimated to be 3 ms for each metre the sound has to travel. Generally successful attempts have been made to reduce this delay period by ensuring speakers are positioned behind the athlete’s blocks (Dapena, 2005). From the ear, the stimulus travels through the brain stem to the auditory cortex and then the motor cortex. A further delay exists between the stimulus arriving at the motor cortex, through the reticulospinal tract of the spinal cord, to its arrival at the muscles, i.e. the electromyographic (EMG) activity onset (Winter & Brookes, 1991). EMD is the delay between the onset of EMG activity and joint motion. EMD can be subdivided into two distinct time periods; force development time representing the delay between muscle activation and the onset of muscle tension, and elastic charge time, representing the delay between muscle tension onset and movement (Winter & Brookes, 1991). EMD contains several components: the conduction of an action potential through the T-tubule system, calcium release from the sarcoplasmic reticulum, the cross-bridge formation of actin and myosin filaments, and the development of tension in the contractile component. The main determinant of the EMD is the time taken for the muscle-tendon unit to stretch in vivo. This period is determined by the elastic properties of the muscle-tendon unit and its capability to remove inherent series elastic ‘slack’ (Cavanagh & Komi, 1979; Viitasalo & Komi, 1981). More precisely, this ‘slack’ refers to the time required to stretch the series elastic component and initiate movement of the joint following contraction in the sarcomeres (Muraoka, Muramatsu, Fukunaga, & Kanehisa, 2004).

In the sprint start, the athlete’s muscles tend to be pre-tensed in the ‘set’ position and this may effectively reduce the inherent series elastic slack, a central component of EMD. Despite this, EMD has been proposed as a contributing factor to SSRT that may constitute approximately 10 ms of the delay process (Komi et al., 2009). Sprint training aims to increase the rate of force development and therefore could reduce mechanical delays in force generation
such as EMD. Reductions in EMD following a period of endurance training has been previously shown in the literature (Grosset, Piscione, Lambertz, & Perot, 2009), however, there is limited research to demonstrate that sprint training influences EMD. Grosset et al. (2009) also highlighted a direct association between EMD and musculotendinous stiffness changes after the training period. Higher musculotendinous stiffness levels facilitate greater force per unit of length change, thus removing series elastic ‘slack’ at a greater rate (Blackburn, Bell, Norcross, Hudson, & Engstrom, 2009; Wilson, Murphy, & Pryor, 1994). Given the likely influence of tendon stiffness on the rate of force transmission, it is reasonable to expect tendon stiffness to influence force transmission delays (i.e. response time) during sprint performance. Sprinters that produce lesser EMD values may be indicative of increased plantar flexor tendon stiffness.

To date, there is a lack of experimental evidence to demonstrate the degree to which EMD may influence SSRT. Previous research has examined response delays and SSRT in sprinters during the block start using normal, pre-tensed and relaxed starting techniques (Pain & Hibbs, 2007). In this research, pseudo-motor time (defined as ‘onset of EMG to onset of increased force’) was quantified, which can be considered as analogous to force development time as defined by Winter and Brookes (1991). Since EMD is muscle specific, and only the net force could be calculated for each leg, Pain and Hibbs (2007) provided an indication that force development related mechanical delays are involved in the SSRT process. Average pseudo-motor times for normal, preloaded and relaxed conditions were 17, 17 and 25 ms respectively. However, pseudo-motor time was analysed in only two sprinters, thus a robust measure of variation in mechanical delays on SSRT could not be provided. Additionally, since pseudo motor time was derived from EMG to the onset of force rather than first movement, elastic charge time could not be determined. Elastic charge time has been suggested as a surrogate measure of musculotendinous stiffness in sprinters, and therefore could contribute to an athlete’s response time (Clegg & Harrison, 2005).
This research is one element of the FASST programme of research (Feasibility Analysis of Sprint Start Technologies). The FASST research programme aims to quantify and map out the kinetic sequence of events during the sprint start and address uncertainties surrounding the International Association of Athletics Federations (IAAF) 100 ms false start rule and the detection of SSRT. The IAAF false start rule states that a sprinter is automatically disqualified when the official starter confirms that they register a SSRT <100 ms after the gun (International Association of Athletics Federations [IAAF], 2015). IAAF quantify SSRT as the time taken to exceed a predefined force or acceleration threshold on the starting-blocks (International Association of Athletics Federations [IAAF], 2015). The failure of the various IAAF-approved starting block systems to standardise detection methods causes significant variability in measured SSRT across systems. Research has shown that SSRT detection is dependent on the nature of the threshold-based algorithm used, which may induce delays in the detection of actual SSRT (Brosnan, Hayes, & Harrison, 2016; Holmes, Hayes, & Harrison, 2018; Lipps, Galecki, & Ashton-Miller, 2011). Additionally, the thresholds may not account for strength and rate of force development differences between athletes and this leads to a delayed SSRT detection in weaker athletes (Lipps et al., 2011). A re-evaluation of detection methods in determining SSRT is required. The IAAF false start limit of 100 ms is based on an assumed minimum auditory response time, and the validity of this limit has also been questioned. Komi et al. (2009) proposed that genuine SSRT’s lower than the 100 ms IAAF criteria, potentially as low as 80 – 85 ms, are possible. Based on the assertions of Komi et al. (2009) that mechanical delays appear to be a component of SSRT, an investigation of the influence these components have on SSRT (i.e. EMD, force development time, elastic charge time) and the variances in the size of these times across sprinters, is required. We hypothesised that triceps surae EMD constitutes an element of the response time process and thus would result in a significant correlation between mechanical delays in the heel-lift experiment (Winter & Brookes, 1991) and SSRT in the sprint.
The triceps surae was chosen as this is the main muscle group involved in ankle plantar flexion and is the joint action nearest the starting blocks. Increases in propulsive force from the starting blocks is primarily developed by ankle plantar flexor moments (Mero & Komi, 1990; Mero & Komi, 2006).

The extant literature has highlighted a need to establish typical mechanical delay parameters in sprinters and the examination of elastic charge time advances previous research and is more reflective of the sequence of delays in a SSRT. The primary aim of this experiment was to examine the correlations between simulated competition SSRT and mechanical delays (EMD, force development time, and elastic charge time) in the triceps surae muscle of sprinters. Mechanical delays were quantified using a previously established heel-lift technique by Winter and Brookes (1991). The SSRT was obtained using an IAAF-approved starting block system. A relationship between mechanical delays and SSRT would provide evidence to support coaching of muscle pretension in the ‘set’ position of the sprint start as a means for reducing SSRT.

Methods

Participants

Nineteen national and international level sprinters (16 ♂, 3 ♀, age 23 ± 3 years, height 1.77 ± 0.09 m, body mass 73.4 ± 9.3 kg, athletics training experience 7.4 ± 3.0 years, IAAF scoring points 953 ± 116 points) participated in the study. Since the athletes participated across a number of sprint events, their relative abilities in their specific sprint event were defined using the IAAF scoring tables of athletics (Spiriev & Spiriev, 2017a; Spiriev & Spiriev, 2017b). Athlete personal best ranges for the male participants (n = 16) were as follows: 60 m (7.12 – 7.24), 100 m (10.72 – 11.54), 110 m H (13.87), 200 m (21.03 – 22.05), 400 m (48.89 – 50.12). Athlete personal bests for the female participants (n = 3) were as follows: 60 m (7.81), 200 m
All athletes were proficient with the block starting technique and had extensive starting block experience. Participants were informed of the requirements, potential risks and benefits of participating in the study and were required to be injury-free at the time of testing. Written informed consent was obtained from all participants and parental consent from participants under the age of 18. Ethical approval for this study was obtained from the University of Limerick, Faculty of Education and Health Sciences Research Ethics Committee.

**Heel-lift experiment set-up and protocol**

The EMD in the triceps surae muscle of the participants’ preferred front starting block leg was determined using a simple heel-lift activity described by Winter and Brookes (1990). In this procedure, participants sat on a plastic chair with the knee of the chosen leg flexed to 90°. The ball of the foot was positioned on the force platform of the experimental rig which was used to detect the onset of muscle tension, with the heel resting on a heel switch integrated into the experimental rig which was used to identify movement (Figure 2). Skin preparation techniques were used to prepare for EMG data capture to reduce the inter-electrode resistance. The selected area was shaven and cleaned with alcohol wipes and EMG electrodes were placed on the skin over the soleus and the lateral epicondyle of the femur, which were identified by inspection and palpation using the SENIAM guidelines. The soleus electrode was positioned at the point 2/3 of the distance from the proximal end of the leg. The soleus muscle was selected as it is a single-joint muscle, thus differences attributable to joint laxity were reduced. Additionally, flexion of the knee minimised the contribution of the gastrocnemius muscle during plantar flexion (Winter & Brookes, 1991). To ensure the first onset of triceps surae muscle activity was detected, additional electrodes were placed on the lateral and medial gastrocnemius. This acted as a cross-check, in the event that soleus wasn’t the first triceps surae muscle to activate. For identifying the first movement of the heel, individualised rigid plastic
‘cut-outs’ were attached inferior to the plantar surface of the participant’s heel using double-sided sticky tape. This reduced any onset error from soft tissue movement (i.e. subcutaneous fat) on the heel switch. It also enabled a more precise identification of the first instant of heel movement by triggering the heel-switch once the plastic ‘cut-outs’ lifted from the switch. Prior to experimentation, participants performed two familiarisation trials. Following a verbal warning of the commencement of the trial, an auditory electronic signal was delivered and the participant was required to plantar flex the foot as quickly as possible (Figure 2). The switch for the electronic signal was hidden from the vision of the participant to minimise the chance of anticipation of the signal. Ten trials were performed for each participant. Rest periods between trials were 30 to 60 seconds between trials and trials were repeated if participants clearly anticipated the signal or moved before the signal. EMG, force plate, electronic signal and heel switch data was collected using a PowerLab 4/20 system and LabChart 8 software (AD Instruments, Sydney, Australia) connected to the experimental rig (Figure 2) and a standard laptop. Surface EMG was recorded using pregeled disposable bipolar differential disc electrodes (diameter: 2.5 cm, Meditrace, Kendall Co., Mansfield, MA, USA). The electrodes were applied with a centre-to-centre distance of 2 cm over the middle of the muscle bellies. An EMG was detected from electrodes connected to the PowerLab 4/20 system and amplified by its wide band, differential input, AC coupled amplifier. Data was sampled synchronously at 1000 Hz and stored on a hard drive for later analysis on LabChart 8.

[Figure 2 near here]

**Heel-lift experiment data analysis**

All muscle activation and force onsets were visually analysed using LabChart 8 software. Pilot work confirmed this as the most consistent method of determining muscle activity and force
onset as using 2 or 3 standard deviations from baseline for determining onsets introduced errors in detection. EMG was first full-wave rectified. Any random ‘spikes’, due to ‘noise’ were not counted as the EMG onset/force production. The muscle was considered activated at the first time point a consistent increase >2 millivolts (µV) to above 4 µV in the EMG signal was observed. Plantarflexor force was determined from a force platform on the experimental rig placed under the sole of the foot. Force onset was visually determined from an uncalibrated curve as the first time point where the slope of the curve exceeded 1 mv/ms (Figure 3). The activation of the heel-switch due to heel movement was defined as the instant where the curve rapidly deviated from 0 V (Figure 3).

The data analysis focused on the quantification of five characteristics:

1. Signal processing time: the time interval from the application of the electronic signal to the onset of EMG activity.
2. Force development time: the time interval from the onset of EMG activity to force onset.
3. Elastic charge time: the time interval between force onset to the activation of the heel switch due to heel movement.
4. Electromechanical delay (EMD): the time interval from the onset of EMG activity to the activation of the heel switch due to heel movement.
5. Heel-lift response time: the time interval between the auditory signal to the activation of the heel switch due to heel movement.

[Figure 3 near here]
Following the recommendations of Winter and Brookes (1991), the mean time intervals of each participant’s ten trials were calculated for signal processing time, force development time, elastic charge time, EMD and heel-lift response time using Microsoft Excel (Microsoft Inc., Washington, USA). Some trials contained erroneous activations of the heel switch and these were eliminated from the data analysis. However, each participant had a minimum of eight valid trials included for data analysis. The reliability of quantifying EMD using this experimental set-up has been previously established, with test-retest coefficients of variation of 11.5 % for males and 8.6 % for females, (Winter and Brookes, 1991).

Sprint start set-up and protocol

For the SSRT portion of the study, testing was conducted at an international standard indoor 60m sprint track. All sprint trials were completed at least five minutes prior to the heel-lift experiment test to mitigate the effects of fatigue. IAAF-approved starting blocks were used (Stadium, Gimtrac, Centurion, South Africa). The system which determined the participant’s SSRT was Starting Module (TimeTronics, Olen, Belgium) and was mounted on the rear of the block rail (Figure 4) and wirelessly connected to the IAAF-approved starting block system, FalseStart III Pro (TimeTronics). Participants were permitted to set block spacing’s and obliquity to their individual preferences prior to trials. Movement of the block rail was prohibited for technical reasons but this did not prevent participants from setting the blocks to their own preferences. All participants wore their own track spikes during testing.

[Figure 4 near here]
All participants were asked to perform their individualised and standard race-day warm-up before testing. Additionally, three practice sprint starts were performed, in an adjacent lane to the lane where the recorded sprint trials were being conducted. These practice starts coincided with a testing set for another participant. This ensured a competition-like environment for the performance of all sprint starts. Non-participating athletes performed the starts when one of the two lanes were not occupied by a participant (i.e. for participants 1 and 19). Sprint trials were conducted in accordance with IAAF starting procedures (International Association of Athletics Federations [IAAF], 2015) and performed by an IAAF-qualified starter. Participants completed three maximal effort 15 m sprints from starting blocks with 2-3 minutes of recovery given between sprints to mitigate any effects of fatigue. Trials were determined valid if the participant’s SSRT was equal to or greater than the IAAF legal limit of 100 ms.

**Sprint start data analysis**

SSRT’s for each trial were obtained from the FalseStart III Pro system (TimeTronics). This technology utilises a sensitivity value (threshold) which must be exceeded for a SSRT to be registered. A representation of output data from a sprint start trial is provided in Figure 5. SSRTs for each trial were extracted from this system and recorded in Excel (Microsoft Inc.). A total of 3 participants recorded a false start in violation of the IAAF 100 ms rule and so had to perform an additional trial. Each SSRT was examined and trials that satisfied the IAAF 100 ms rule were used to calculate a mean SSRT for each participant. Additionally, the mean SSRT was calculated for each participant for legal trials in accordance with Brosnan et al. (2016) revised response time thresholds of 115 ms (men) and 119 ms (women). The primary difference between the IAAF threshold and Brosnan et al. (2016) revised response time thresholds is the latter reduces the likelihood of false starts going undetected when using IAAF-approved
starting block systems. An examination of response times from the 2008 Beijing Olympics concluded that using the current IAAF response time detection thresholds, neither men nor women were unlikely to produce legal response times of 100 ms (Lipps et al., 2011). Rather, Lipps et al. (2011) suggested, the use of sex-specific response time thresholds of 109 ms for men and 121 ms for women, due to the known strength and rate of force development difference between men and women. Brosnan et al. (2016) examined a larger dataset of response times (European and World Championships from 1999 to 2014), and in agreement with Lipps et al. (2011), proposed the use of sex-specific false-start thresholds. When using IAAF-approved starting block systems, thresholds of 115 ms for men and 119 ms for women were recommended (Brosnan et al., 2016).

A total of 58 legal trials were included for analysis in accordance with IAAF 100 ms rule. Following the screening of trials in accordance with Brosnan et al. (2016) revised response time thresholds, a total of 49 legal trials were included for analysis. Each participant had a minimum of three trials included for statistical analysis for legal trials in accordance with IAAF rule, and a minimum of two trials included in accordance with Brosnan et al. (2016) legal limits.

[Figure 5 near here]

Statistical analysis

All statistical calculations were performed using SPSS V24.0 (IBM Co., NY, USA). Normality of data was determined using the Shapiro-Wilk’s test. Statistical significance was set at p < 0.05 for all analyses. Two bivariate correlation analyses were conducted. The first approach used Brosnan et al. (2016) SSRT limits to investigate the association between SSRT and heel-lift experimental variables. The second approach used the IAAF limit. Means and standard
deviations were calculated for all variables. Bootstrapping was used and bias, standard error, and 95% confidence intervals were calculated. Correlation coefficients ($r$) and coefficients of determination ($r^2$) were also calculated. Correlations were calculated using Pearson’s $r$ with the magnitude of the correlation classified as strong ($r = 0.70 - 1.00$), moderate ($r = 0.30 - 0.69$) or weak ($r = 0.00 - 0.30$) based on Cohen (1988).

Multivariate forced entry linear regression analysis was conducted to determine the relative contribution of the heel-lift variables on the prediction of SSRT. Selection of the input variables was based on reasoned criteria for inclusion. These criteria were supported by the bivariate correlations together with physiological and mechanical knowledge from the literature on the response time sequence (Figure 1). The correlation analysis identified variables that should be eliminated from the regression equations to avoid collinearities. Thus, when SSRT was the dependent variable, suitable independent variables were signal processing time, elastic charge time and force development time. For the regression analysis, Brosnan et al. (2016) SSRT false start limits were used ($♂ = 115$ ms; $♀ = 119$ ms), based on preliminary results of response times and correlation analyses (Table 2).

**Results**

**Heel-lift variables**

Time intervals for heel-lift experiment variables are displayed in Table 1.

![Table 1 near here]
Elastic charge time accounted for 94.0% and force development time 6.0% of EMD. The signal processing time represented approximately 64.0% of heel-lift response time and EMD accounted for the remaining 36.0% (with elastic charge time accounting for 33.7%, and force development time accounting for 2.3% of the response time).

**Sprint start response times**

The mean SSRT was 146.0 ± 15.5 ms using Brosnan et al. (2016) SSRT limits and 142.4 ± 17.7 ms using existing IAAF SSRT limits. The results comparing false start detection criteria (Table 2) indicated a mean difference between false start detection criteria of 3.6 ms. SSRT values and the number of false starts during the testing session are documented in Table 2. Using Brosnan et al. (2016) SSRT limits, nine further false starts were documented in addition to the detected false starts in accordance with IAAF limits. As IAAF equipment and limits were used during the testing procedure, only three false starts were determined during testing.

The mean time intervals for heel-lift response time were longer than SSRT with a mean difference between measures of 44.4 ms using Brosnan et al. (2016) SSRT limits and 48.0 ms using IAAF SSRT limits.

**Correlation analysis heel-lift variables and sprint start response times**

Table 3 outlines the correlational analysis between SSRT and heel-lift experiment variables for the nineteen elite sprinters. For the correlation analysis, revised mean SSRT in accordance with
Brosnan et al. (2016) limits are reported. This revised response time threshold was calculated as the SSRT above which 99% of the observed SSRTs (from World and European Championship SSRT data from 1999 to 2014) lay, and provides a more rigorous method of ensuring false starts are not included in the analysis (Brosnan et al. 2016). The justification for the selection of these limits instead of IAAF limits is reported in Table 2, with 9 additional false starts documented when using Brosnan et al. (2016) limits.

A scatterplot matrix including simple linear regression lines was used to illustrate the Pearson correlations between SSRT and each response time component (elastic charge time, force development time and signal processing time) (Figure 6). There were significant moderate correlations between SSRT and EMD \( (r = 0.527, p < 0.05) \), elastic charge time \( (r = 0.545, p < 0.05) \), and force development time \( (r = 0.460, p < 0.05) \). No significant relationships were observed between heel-lift response time and SSRT \( (r = 0.395, p = 0.095) \), and signal processing time and SSRT \( (r = 0.030, p = 0.904) \).

Regression analysis heel-lift variables and sprint start response times

Revised mean SSRT in accordance with Brosnan et al. (2016) limits were used for the multiple regression analysis also. Results of the multiple regression analysis demonstrated a participants SSRT could be best predicted from the heel-lift variables (signal processing time, force development time, and elastic charge time) with the following regression equation:
(1) \[ SSRT = 0.426 \times \text{elastic charge time} + 2.706 \times \text{force development time} \]

\[ - 0.073 \times \text{signal processing time} + 0.117 \]

The average residual difference between the predicted SSRT and the measured SSRT using this equation was 10 ms (Figure 7). The heel-lift variables elastic charge time, force development time and signal processing time together accounted for approximately 37\% of the variance in a participants SSRT \((r^2 = 0.372)\).

Discussion and implications

The purpose of this study was: (1) to examine mechanical delays in the triceps surae muscle of sprinters during a heel-lift experiment; (2) to investigate the relationship between mechanical delays and simulated competition SSRT. It was hypothesised that EMD was an element of the response time and therefore would influence an athlete’s SSRT. The results provide evidence that EMD may account for part of the variance in SSRT and that some athletes may gain a performance advantage due to a reduction in this mechanical delay. The relationship between mechanical delays and SSRT was reinforced by the regression analysis. Based on the results of the regression analysis, EMD (force development time and elastic charge time) and signal processing time appeared to have a cumulative effect on the prediction of SSRT. The heel-lift variables entered into the regression equation predicted an athlete’s SSRT to within 10 ms on average. However, there were limitations of note in the measurement of EMD. The heel-lift experiment measured EMD in a low-level muscle activation state, whereas a sprinter’s muscles
are pre-tensed in the ‘set’ position of the sprint start, increasing the musculotendinous stiffness (McNair, Wood, & Marshall, 1992; Sinkjaer, Toft, Andreassen, & Hornemann, 1988). Thus, moderate levels of pretension during the sprint start ‘set’ phase which is absent in the muscles during the heel-lift experiment, may explain why EMD only produced a moderate correlation with SSRT. This difference in the contraction state of the musculotendinous unit reduces the ecological validity of the measure. While this study has provided results suggesting heel-lift variables can predict SSRT within 10 ms of the actual SSRT, a more ecologically valid measure of SSRT delays is needed to validate this relationship. Thus, a measure of EMD in the blocks during the sprint start is required to determine the relative contribution mechanical delays have on a sprinters’ starting performance.

Prior to an athlete producing a SSRT, an established sequence of physiological and mechanical response delays occurs (Figure 1). Research from Komi et al. (2009) proposed EMD as an element in this delay sequence and estimated it to constitute approximately 5-10 ms of the response time process. In addition, limited evidence of mechanical delays during the SSRT was provided by Pain and Hibbs (2007). This current study builds on these results and provides an indication that a relationship exists between EMD obtained in a simple heel lift procedure and an athlete’s SSRT ($r = 0.572, p < 0.05$). As a result, the additive effects of signal processing time, force development time and elastic charge time accounted for 37% of the variability in an athlete’s SSRT. In particular, elastic charge time appeared to be more indicative of the mechanical delay relationship with an athlete’s SSRT ($r = 0.545, p < 0.05$) when compared to the force development time ($r = 0.460, p < 0.05$). The potential mechanism for this may be explained by examining the mechanical factors that influence the EMD time. EMD has been proposed as a measure of the time taken to stretch the series elastic component of the muscle-tendon unit (Cavanagh & Komi, 1979). Waugh et al. (2013) demonstrated that Achilles tendon stiffness accounted for 68% of the variance in voluntary EMD times of the
gastrocnemius muscle. This suggests that tendon stiffness is a significant contributor to the EMD time in a muscle. Since elastic charge time is the time interval between the onset of muscle tension and movement of the connected joint, it is plausible that elastic charge time could be a surrogate measure of the stiffness of the tendon and aponeurosis (Winter & Brookes, 1991; Clegg & Harrison, 2005). The stronger predictive value of elastic charge time on SSRT could be indicative of a relationship between tendon stiffness and an athlete’s starting performance. However, this proposed relationship is yet to be established experimentally.

Longer mechanical delay times are reported in the current study (Table 1) when compared to previous research that has addressed the concept of mechanical delays as an element of SSRT. Komi et al. (2009) hypothesised EMD values in the region of 5-10 ms, and Pain and Hibbs (2007) measured two sprinters pseudo-motor time (non-muscle specific EMD) during the sprint start and produced average values of 17, 17, and 25 ms (normal, preloaded and relaxed). Pseudo-motor time was calculated as the delay between individual muscle activity increase and increased force from the set position. This delay period is comparable to force development time in the current study, however force development time is muscle specific. The varying methodological approach in defining EMD and pseudo-motor time probably explains the differences in values between the current study and previous research. Previous sprint start research has defined and quantified EMD and pseudo-motor time to the onset of force (Komi et al., 2009; Pain & Hibbs., 2007), while this study measured EMD to the onset of movement. When measuring EMD to the movement response in the sprint start, it would be expected that longer mechanical delay values would be produced compared with Pain and Hibbs (2007) pseudo-motor time values, since the movement response would also include the elastic charge time. The advantage of measuring EMD to the movement response is that it provides an indication of the compliance of an athlete’s musculotendinous structures by determining the elastic charge time. This information could be useful for coaches if research confirms the
relationship between elastic charge time and tendon stiffness. Additionally, including a measure of movement initiation is more representative of an athlete’s SSRT. The IAAF quantify SSRT as the time taken to exceed a predefined force or acceleration threshold on the starting-blocks (International Association of Athletics Federations [IAAF], 2015). Technically, SSRT from IAAF equipment should not include any movement response. However, the threshold-based approach employed in IAAF-approved starting block systems explains the tendency for the SSRT to be detected during the elastic charge time period (force onset to movement). The IAAF thresholds do not account for strength and rate of force development differences between athletes and this leads to a delayed SSRT detection in weaker athletes, which may include part of the movement response (Lipps et al., 2011). An improved detection algorithm to determine the initial rise in block force, after the start signal, standardised in all IAAF-approved starting block systems would enable SSRT to be detected without including any part of the movement component.

The present study has provided an initial indication of the impact of EMD on sprint start performance. However, it is crucial to note the importance of examining the EMD relationship with SSRT. At present, there is a level of ambiguity surrounding the IAAF 100 ms ruling for false start disqualification at athletic competitions (Brosnan et al., 2016). Several studies have suggested that SSRT’s shorter than 100 ms are possible (Brown, Kenwell, Maraj, & Collins, 2008; Komi et al., 2009; Pain & Hibbs, 2007). Response times as low as 85 ms were proposed by Pain and Hibbs (2007), with Komi et al. (2009) suggesting SSRT values even below 80 ms. However, despite the growing evidence questioning the validity of the 100 ms rule, it still remains as a criterion for disqualification. Additionally, the inadequacy of the IAAF 100 ms ruling when using the IAAF-approved starting block systems is quite clear. Using Brosnan et al. (2016) revised SSRT limits, it was demonstrated that the number of false starts increased considerably (Table 2), confirming the inadequacy of current 100ms rule. Further research
mapping out the kinetic sequence of events during the sprint start is required to directly address
the validity of the IAAF 100 ms false start ruling. Measurement of the EMD component and
exactly how it contributes to an athlete’s SSRT is important for understanding the sequence of
events that occur during the sprint start. The onset of muscle activation is the initial
neuromuscular parameter to trigger the movement of the joint (and force production). Thus, the
order of muscle activations and the resulting kinetic changes are important in uncovering the
ongoing problems in the current false start criteria (Komi et al., 2009).

Until SSRT, EMD and tendon stiffness are simultaneously measured during the sprint
start, the true influence of mechanical delays and morphological properties of the plantarflexors
on sprint start performance cannot be confirmed. Such research could potentially confirm initial
suggestions of an EMD-SSRT relationship and also determine the optimal level of pretension
required to produce the most effective SSRT. Determination of EMD would require precise
measures of EMG onset using high frequency wireless technology, block force onset using
force transducers and initiation of heel movement using high speed motion capture techniques
to determine EMD components during a sprint start. The attachment of an ultrasound probe
over the junction of the Achilles tendon and the medial gastrocnemius muscle fibres could
facilitate the determination of tendon and aponeurosis elongation during the sprint start
movement and in combination with block force measures, this would allow a measure of tendon
stiffness in-vivo during the sprint start.

Conclusion

With few studies addressing the response delay sequence during the sprint start, the findings
from this study provide novel information on the influence of mechanical delays on SSRT
which may be useful for scientists, coaches and ultimately sprint athletes. Initial results suggest
EMD is part of the response time process and that certain athletes may gain a performance
advantage due to reduced EMD. The combined influences of signal processing time, force
development time and elastic charge time accounted for a significant proportion of the
variability in an athlete’s SSRT (37%), and on average predicted an athlete’s SSRT to within
10 ms. Interestingly, elastic charge time appeared more important than force development time
in predicting an athlete’s SSRT, potentially related to the stiffness of an athlete’s Achilles
tendon. Increased levels of musculotendinous stiffness may provide athletes with this reduction
in SSRT. A simultaneous measure of tendon stiffness, EMD and SSRT during the sprint start
is required. This research is necessary to confirm initial suggestions of an EMD-SSRT
relationship and also to determine the optimal level of pretension required to produce the
quickest SSRT. Additionally, it will ensure the ecological validity of the relationship between
mechanical delays and SSRT. Research as such could contribute toward sequencing the
response delays that occur during the sprint start and the ongoing debate surrounding the current
IAAF 100 ms ruling.

Disclosure statement

No potential conflict of interest was reported by the authors

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References


Dapena, J. (2005). *The ‘loud gun’ starting system currently used at the Olympic Games does not work properly*. Retrieved from Educacio Fisica website:


### Table 1. Time period of the heel-lift experiment variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heel-lift response time</td>
<td>190.4 ± 24.0</td>
</tr>
<tr>
<td>Signal processing time</td>
<td>122.1 ± 14.8</td>
</tr>
<tr>
<td>Electromechanical delay</td>
<td>68.3 ± 15.8</td>
</tr>
<tr>
<td>Elastic charge time</td>
<td>64.2 ± 15.0</td>
</tr>
<tr>
<td>Force development time</td>
<td>4.1 ± 1.8</td>
</tr>
</tbody>
</table>
Table 2. Sprint start response time data using Brosnan et al. (2016) proposed limits and existing IAAF limits.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Brosnan et al. (2016) limits</th>
<th>IAAF limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprint start response time (ms)</td>
<td>146.0 ± 15.5</td>
<td>142.4 ± 17.7</td>
</tr>
<tr>
<td>No. false starts</td>
<td>12</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 3. Correlation analysis of heel-lift variables and sprint start response time (using Brosnan et al. (2016) proposed limits).

<table>
<thead>
<tr>
<th>Variable</th>
<th>SSRT</th>
<th>HLRT</th>
<th>SPT</th>
<th>EMD</th>
<th>ECT</th>
<th>FDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSRT</td>
<td>r</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>r²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLRT</td>
<td>r</td>
<td>0.395</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>-0.220,0.770</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>r²</td>
<td>0.156</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPT</td>
<td>r</td>
<td>0.030</td>
<td>0.768**</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>-0.452,0.520</td>
<td>0.534,0.921</td>
<td>1,1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CI</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>r²</td>
<td>0.001</td>
<td>0.590</td>
<td>1</td>
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<tr>
<td>EMD</td>
<td>r</td>
<td>0.572*</td>
<td>0.804**</td>
<td>0.230</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.060,0.876</td>
<td>0.555,0.944</td>
<td>-0.255,0.727</td>
<td>1,1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CI</td>
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<td></td>
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<tr>
<td></td>
<td>r²</td>
<td>0.327</td>
<td>0.640</td>
<td>0.053</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ECT</td>
<td>r</td>
<td>0.545*</td>
<td>0.804**</td>
<td>0.243</td>
<td>0.994**</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.025,0.865</td>
<td>0.574,0.946</td>
<td>-0.243,0.737</td>
<td>0.984,0.999</td>
<td>1,1</td>
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<tr>
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<td>CI</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>r²</td>
<td>0.297</td>
<td>0.646</td>
<td>0.059</td>
<td>0.988</td>
<td>1</td>
</tr>
<tr>
<td>FDT</td>
<td>r</td>
<td>0.460*</td>
<td>0.300</td>
<td>-0.012</td>
<td>0.467*</td>
<td>0.370</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.017,0.702</td>
<td>-0.226,0.685</td>
<td>-0.495,0.502</td>
<td>0.121,0.747</td>
<td>-0.012,0.712</td>
</tr>
<tr>
<td></td>
<td>CI</td>
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<td></td>
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<tr>
<td></td>
<td>r²</td>
<td>0.212</td>
<td>0.090</td>
<td>0.0001</td>
<td>0.218</td>
<td>0.137</td>
</tr>
</tbody>
</table>

**p < 0.01; *p < 0.05. SSRT: sprint start response time, HLRT: heel-raise response time, SPT: signal processing time, EMD: electromechanical delay, ECT: elastic charge time, FDT: force development time, 95% CI: 95% confidence interval, r: Pearson correlation coefficient, r²: coefficient of determination
Figure captions list

**Figure 1.** The sequence of events and subsequent delays occurring during the sprint start.

**Figure 2.** The (a) heel-lift experimental rig, (b) attachment of electrodes on the participant’s leg during the stationary phase (90° knee flexion), and (c) following the auditory signal (plantar flexion).

**Figure 3.** Lab Chart 8 visual output from a heel-lift experiment trial. Electronic start (auditory) signal and force plate output are represented on the same channel (Channel 1). Soleus EMG output (Channel 2) and heel-lift response time (Channel 3) are also represented. The x-axis represents time (s) with the y-axis representing signal output (mV or V). Arrows represent the onset of the M-wave (EMG/force).

**Figure 4.** Placement of Starting Module on IAAF-approved starting blocks

**Figure 5.** TimeTronics False Start III Pro output example. The x-axis represents time and the y-axis represents an arbitrary unit that shows motion from the blocks as an increase in value. Horizontal lines ‘sensitivity’ and ‘offset’ are individualised to each athlete.

**Figure 6.** Scatterplot matrix: main diagonal shows histograms of variables used in the regression modelling stage with superimposed density curve; upper triangular part shows the Pearson product-moment correlation coefficient between pairs of variables, **p < 0.01; *p < 0.05;** lower triangular part shows scatterplots of variables with superimposed simple linear regression lines.
Figure 7. Scatter plot of predicted sprint start response time values against residuals.