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Sprint starts and the minimum auditory reaction time

Matthew T. G. Pain[1] & Angela Hibbs[2]

[1]School of Sport and Exercise Sciences, Loughborough University, UK
[2]English Institute of Sport, Loughborough University, UK

Abstract

The simple auditory reaction time is one of the fastest reaction times and is thought to be rarely less than 100 ms·. The International Association of Athletics Federations, IAAF, currently bases the false start criterion in a sprint on this assumed auditory reaction time of 100 ms. However, there is evidence, anecdotal and from reflex research, that simple auditory reaction times of less than 100 ms can be achieved. Reaction time in nine athletes performing sprint starts in four conditions was measured using starting blocks instrumented with piezoelectric force transducers in each footplate that were synchronised with the starting signal. Only three conditions were used to calculate reaction times. The pre-motor and pseudo motor time for two athletes were also measured across thirteen muscles using surface EMG synchronised with the rest of the system. Five of the athletes had mean reaction times of less than 100 ms in at least one condition and 20% of all starts in the first two conditions had a reaction time of less than 100 ms. The results demonstrate that the neuromuscular-physiological component of simple auditory reaction times can be under 85 ms and that EMG latencies can be under 60 ms.

Keywords: neurophysiology, reflex, athletics

Introduction

The International Association of Athletics Federations, IAAF, currently bases the false start criterion in a sprint on an assumed auditory reaction time of 100 ms (IAAF, 2003). One of the of the approved IAAF starting system suppliers, Omega (2006), state that “The rules of the IAAF fix the minimum time of physiological reaction at 100 milliseconds.” whilst describing how their system works. In the research literature this 100 ms value is claimed to be the minimum physiological simple auditory reaction time possible, as determined by a number of empirical studies, e.g. Thompson et al. (1992), Mero, A. and Komi, P.V. (1990). The 100 ms limit for auditory reaction time with specific examples and references to sprint starts appears in at least one motor function text book (Schmidt and Lee, 1999) where it is used to argue against possible faster reaction times. Until 1990 the false start criterion was 120 ms, based on these same studies. In the past, enforcement of rules based on the 100 ms limit has led to contentious results, news headlines and ongoing media debates, one of the most notable being Linford Christie’s protests at the 1996 Olympic 100 m final.

Dapena (2005) and Julin and Dapena (2003) have shown that the starting systems may or may not take into account the different times needed for the sound of the start signal to reach different athletes. This can have a large effect on measured reaction times as each metre the sound has to travel takes approximately 3 ms, depending on environmental conditions. Removing this component by having the start signal travel electronically to speakers behind the athletes has been tried in different formats with varying degrees of success (Dapena, 2005). IAAF approved starting systems by Seiko, Lynx System Developers and Omega all use different transducers and threshold detection mechanisms. Seiko uses force transducers in the blocks and in the past used a 20 kg threshold above baseline in the set position to determine the start. More recently they have moved to using steepest rise of the curve. Lynx System Developers uses an accelerometer in a unit attached by velcro straps to the back of the starting block rail and an unpublished threshold value to determine the start. Omega uses a closure system where the athlete's push off closes a sliding switch. This can lead to different delays in the detection of an external measurement parameter once the reaction has started. Depending on the system specifications the same reaction would yield different reaction times. This problem of system dependence on measuring parameters that do not constitute components of the neuromuscular-physiological reaction time is present to varying degrees in all reaction time research. Claiming what the minimum reaction time is should really be specific to the equipment and methodology used. Thus, it may be that the value of 100 ms used by the IAAF is correct for the varied systems used if it is meant to include the equipment response time as well. However it would be better to be able to distinguish what each component of the chain is contributing to the overall measurement of reaction time, especially when one of the components can vary independently of the athlete.

In the sprint start it appears non neuromuscular-physiological components of the reaction time could have a significant effect on the measured reaction time using the current systems. The question of system set up, measurement parameter choice and thresholds needs to be addressed by the governing body for consistency, but the statement that the minimum reaction time based on physiological grounds is 100 ms needs to be addressed scientifically. Considering that the majority of reaction time work is not sport specific, the following section deals with theoretical and experimental considerations when determining reaction times.

Reaction times are widely used to evaluate neuromuscular-physiological responses in such diverse areas as medicine (Muller et al., 2004) and impairment detection (Roehrs et al., 2003) through to environmental safety (Philipova, 1998, Haas and Edworthy, 2003) and sports (Guissard and Duchateau, 1990). Reaction time is dependent on several factors: arrival of the stimulus at the sensory organ, conversion by the sensory organ to a neural signal, neural transmissions and processing, muscular activation, soft tissue compliance, and the selection of an external measurement parameter. Each of these factors has an associated processing time that contributes to the overall reaction time. The simple auditory reaction time is one of the fastest reaction times and is thought to be rarely less than 100 ms (Thompson et al., 1992). This widely accepted minimum auditory reaction time of 100 ms is used as an independent measure in its own right and also as the baseline for evaluating the further processing delays that arise with more complex auditory reaction time measurements.

These empirical studies are dominated by reaction time measurements obtained from pressing keys with fingers in response to stimuli. These measures of reaction time include the movement time of the finger and the movement of the key. A further factor that can contribute to longer reaction time measures is that although these are simple and practised motions, the fingers and hands are designed for complex motions and perform fine motor functions that do not have high concentric contraction velocities. It is possible that other movements that have grosser motor functions that have been shown to be modulated by reflex actions would exhibit quicker reactions times, especially if all movement times were removed.

There is evidence that simple auditory reaction times of less than 100 ms can be achieved. Most reflex actions give rise to movement responses in less than 100 ms and in some cases have been seen to modulate voluntary motor actions, such as using the startle reflex to initiate rising onto the toes (Rothwell and Valls-Solé, 2002). In these experiments components of EMG onset seen in the soleus occurred in 60 ms.

We believe that the actual neuromuscular-physiological component of the simple auditory reaction time can be less than 100 ms. The current supposed limit for simple auditory reaction time is based on empirical data that include time for stages that are not wholly dependent on the neuromuscular-physiology of the athletes. These are the arrival of the stimulus at the sensory organ and the detection of an external measurement parameter. The former can be calculated and with improvements in sensing technology and pattern recognition (Pain, 2003) the latter can be reduced.

Including 3 ms for the start signal to travel one metre to the athlete, the lowest likely pre-motor time, using times consistent with those seen in the startle reflex, is 63 ms. The time for the signal to reach the brainstem from the ear accounts for up to 10 ms of this time (Kemp et al. 1937). From the reticular formation of the brainstem, through the reticulospinal tract to the spinal cord and to the muscles accounts for the other 50 ms from signal to EMG onset. The minimum motor time would be the time required to change the tension within the muscle itself as the neural signal travelled along the t-tubules and increased calcium ion concentration within the muscle fibres and this is around 10 ms (Basmajian, 1978, Winter and Brooks, 1991, Corcos et al., 1992). Including series elastic stretch gives a total electromechanical delay of 15 to 20 ms (Perry, 1999, Muraoka et al. 2004). Thus reaction times could be as low as 73 ms but are more likely to be between 78 and 83 ms. The reaction time measurements reported for this study are from signal initiation to detection of force. This includes the 3 ms for the sound to travel one metre to the subject. Certain athletes maintain that they are not guessing when they react in under 100 ms during a sprint start. Perhaps they are correct.

The aim of this study was to determine the minimum neuromuscular-physiological component of auditory reaction time during sprint starts.

Methods

Nine athletes, (age, 23 $\pm$ 3 yrs; mass, 72 $\pm$ 12 kg; height, 1.77 $\pm$ 0.07 m) who had given informed consent in accordance with the university's ethical advisory committee procedures took part in this study. The athletes were sprinters or ex-sprinters who had competed at various levels from county to international standard and were familiar with the use of starting blocks. After warm up and familiarization each athlete performed ten maximum intensity starts in each of four different conditions with the condition order randomised. Subjects were allowed to perform at their own pace and choose how much of a run off they needed to perform a maximal start with the advanced knowledge that they were going to be performing up to 50 starts. As with race starts the time between set and the start signal was chosen randomly by the starter in a window of three to four seconds duration, that started approximately one second after the subject was in the set position following the set command.

These conditions were: normal condition, the athletes' preferred method; preloaded condition, where athletes had to exert a greater force backwards into the blocks in the set position; relaxed condition, where the minimal force required to hold a set position was used; guess condition, normal start but the athlete was allowed, but not required, to guess when the start signal would come. In the first three conditions, if either the athlete or one of two investigators, thought they had guessed negative feedback was given and the trial repeated. The first three conditions allowed us to examine effects of mechanical stiffness on reaction time and the fourth condition was used to account for possible guessing of when the start would be. Only the first three conditions were used to evaluate actual reaction times.

Force in each footplate of a standard set of starting blocks was measured with piezoelectric force transducers (PCB Piezotronics ICP quartz force sensor model 208C03). Force was recorded at 2000 Hz onto a Toshiba laptop computer. An electronic hooter was used to give the audible start signal as well as send a 500 ms square wave that dropped from five volts to zero volts to the laptop to synchronise force measurement and the start signal. This was controlled using a remote control switch so that the starter would be out of sight and not disturb the athlete in the set position. All data, including EMG, were recorded through the same 16 bit National Instruments DAQ Card (A1-16-XE-50). The hooter was placed one metre from the athlete's head when the athlete was in the set position.

Custom software (Pain, 2003) identified the reaction time for each leg. Data from the set to the gun firing were used to establish a zero baseline. The force data were then low pass filtered at a number of cut off frequencies from 50Hz to 150Hz. These data were then double differentiated. An algorithm then identified any periods where there was an increasing force for greater than a prescribed time and extrapolated back to determine the onset of this continuously increasing force. The different results from each filtered version of a single trial were then used to converge on a single optimum solution whilst providing secondary options for the researcher to observe.

The accuracy of this method was tested in a number of ways. Simulated force traces were developed that consisted of a baseline component and a rising force component. Random noise of 1% and 5% was also added to each simulated signal before testing the detection software on them. This allowed the accuracy of onset to be calculated, as the real onset was known. The custom software was compared against a variety of techniques for determining the start of the rise including threshold detection, human observation, discrete and continuous wavelet analysis during this validation procedure. The custom software was more accurate than threshold detection and discrete wavelet analysis. It had similar accuracy to human observation, and was slightly less accurate than the continuous wavelet analysis. However, it was fully automatic, whilst human observation and the continuous wavelet analysis were not. The time determined by the custom software was visually checked. In 90% of the trials the operator agreed with the automatic identification and in the other 10% the operator believed the reaction time was equal to one of the alternatives presented by the software and this alternate value was used. The reaction time for a trial was the quickest reaction time from either leg. Further reaction time measures of a sample of trials from the 9 subjects were calculated using a simple threshold criterion to see what delay this introduced for their sprint starts.

Two athletes performed three further starts in each condition. These were recorded at 500 Hz using a Phantom 4.1 digital video camera. The video was used to determine time of initial movement onset to give further comparison reaction times. EMG of thirteen muscles was recorded at 2000 Hz using high impedance differential electrodes (Biovision). The muscles were: tibialis anterior, gastrocnemius, rectus femoris, biceps femoris, vastus medialis, gluteus maximus of each leg and the right anterior deltoid. The pre-motor time was defined as ‘start signal to onset of EMG’. The onset of EMG was determined by visual inspection with the researcher deciding when the signal had changed from the baseline level during the set position. Given that only the net force from each leg could be determined it was not possible to calculate the electromechanical delay or the true motor time of each muscle. Pseudo motor time was defined as ‘onset of EMG to onset of increased force’.

Results

Five of the athletes had mean reaction times of less than 100 ms in one of the non-guess conditions (Table 1) and 20% of all starts in the first two conditions had a reaction time of less than 100 ms. The examination of individual athlete results indicated a clear difference between the distribution of reaction times between the first three conditions and the guess condition. Looking at the fastest reacting subject, Figure 1, it is unlikely that the distribution of starts below 100 ms in the normal condition is due to guessing. Removing the two fastest reaction times from subject 8’s normal trials, which were almost certainly guesses, still gives a mean reaction time of 87 ms and a standard deviation of 4 ms. Figure 2 shows the distribution of starts for the four other subjects who had mean reaction times below 100 ms in one of the conditions. These results would indicate that subject 8 was not unique and that subjects 7 and 9 had a distinct group of starts under 100 ms. Subjects 1 and 2 could be argued to have starts of just over 100 ms with their average brought down below 100 ms by either false starts or a small number of quick starts. Four of the athletes had their quickest non-guess reaction times in the preloaded condition and the other five in the normal condition, where some amount of preloading is still present. None of the athletes had their quickest reaction time in the relaxed condition. Comparing the average reaction time for an athlete’s quickest condition to the average reaction time in the relaxed condition across all athletes gave an average increase in reaction time of 39%.

Table1. Mean reaction times in each of the four conditions (standard deviations in parentheses).

	Reaction time in each condition (ms)				
Athlete	Normal	Preloaded	Relaxed	Guess*	Rejected starts
1	112 (19)	95 (22)	188 (63)	-5 (114)	2
2	97 (17)	108 (19)	104 (29)	65 (82)	2
3	122 (21)	147 (38)	199 (22)	85 (77)	1
4	119 (20)	111 (19)	122 (12)	120 (13)	0
5	106 (16)	135 (25)	158 (31)	104 (124)	3
6	113 (11)	101 (20)	123 (12)	69 (64)	2
7	107 (21)	95 (18)	150 (28)	88 (77)	3
8	82 (17)	96 (10)	95 (12)	22 (78)	7**
9	94 (12)	104 (19)	123 (13)	82 (63)	2

*The guess condition reaction times do not indicate actual reaction times and are presented to show the large difference in distribution patterns when actual reaction times are compared with those including guesses.

**Four of these were during the first five attempts, where the athlete claimed he could hear something clicking. The remote control for the starter was moved further away. After this, the remaining false starts were scattered among the 30 good trials.

Raw data for the rear leg of a trial from Athlete 8 are presented in Figure 3. The mean motor and pre-motor times for the non-guess conditions are presented in Table 2 for subjects 8 and 9.

The time between the end of the pre-motor period in the average muscle and the beginning of increased force on the blocks for the normal, the preloaded and the relaxed conditions was, 17 ms, 17 ms and 25 ms, respectively, which means the relaxed condition has a pseudo motor time only 8 ms (47%) longer in the relaxed condition than in the loaded conditions. This was slightly less than 10% of the total reaction time of the quickest subject. This suggests that the level of muscular-tendinous stiffness can alter the measured reaction time by an amount that could be useful in competition. Pre-motor times for both the relaxed and preloaded condition were on average 37-40% longer than in the normal condition and in the case of individual muscles up to 50% longer.

Using a simple threshold of force detection increased the measure of reaction time by 26 ms on average. Using high speed video at 500 Hz to determine onset of first visible movement increased the measure of reaction time by 60 ms on average.

Discussion

These experimental results indicate that the neuromuscular-physiological component of simple auditory reaction times can be under 85 ms, which falls just above the range of hypothetical reaction times proposed in the introduction. The question that must now be addressed is, are those legitimate reaction times or guesses? It is unlikely that the distribution of starts below 100 ms in the normal condition in Figure 1 is due to guessing as the start gun is fired randomly in a three second window after the set. Athlete 8 would have needed to guess 8 times to an accuracy of 12 ms in 3000 to obtain this distribution. If the two starts with reaction times in the 50-60 ms range are counted as false starts that got through this may strengthen the argument that the other 8 are genuine quick reactions as the presumed false starts sit 20 ms away from the majority with no other times in between. Athlete 8 had a problematic start to the testing where he produced four definite false starts during the first five attempts. During this period the subject claimed he could hear something clicking. The remote control for the starter was moved further away from the subject. After this the remaining false starts were scattered among the 30 good trials.

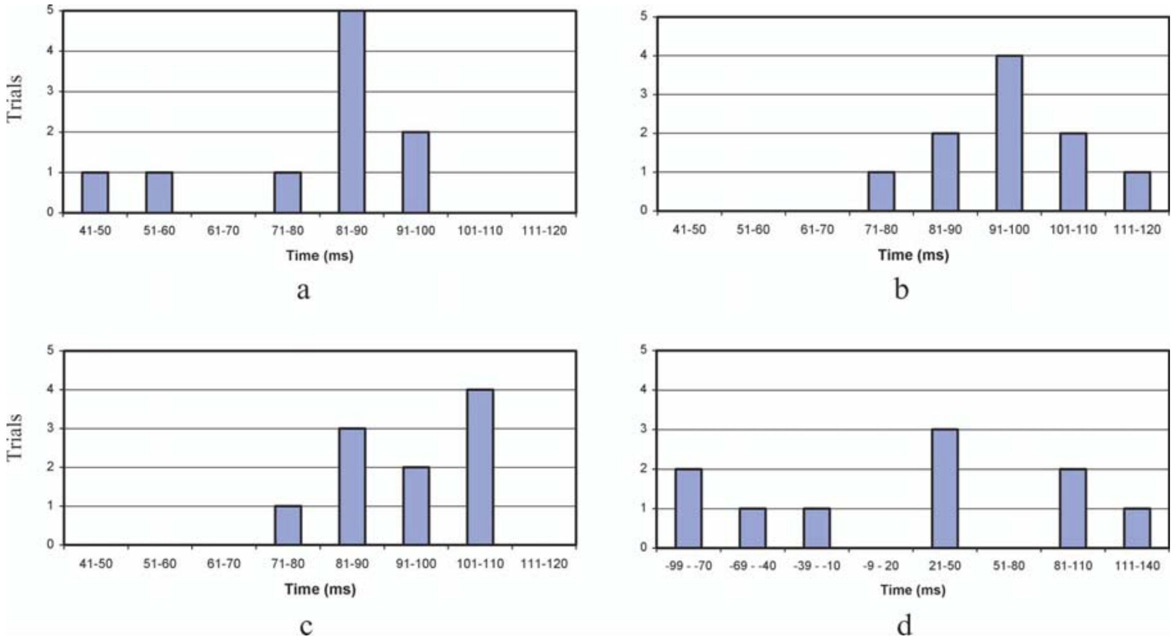

Figure 1. Reaction times for Athlete 8 across the four conditions: (a) normal condition, (b) preloaded condition, (c) relaxed condition, and (d) guess condition. The distributions in (a), (b) and (c) appear to be normal as would be expected in measuring a reaction, whereas that in (d) appears to be random. As the distribution in (d) includes times before the gun was fired, it would be consistent with guessing when to start.

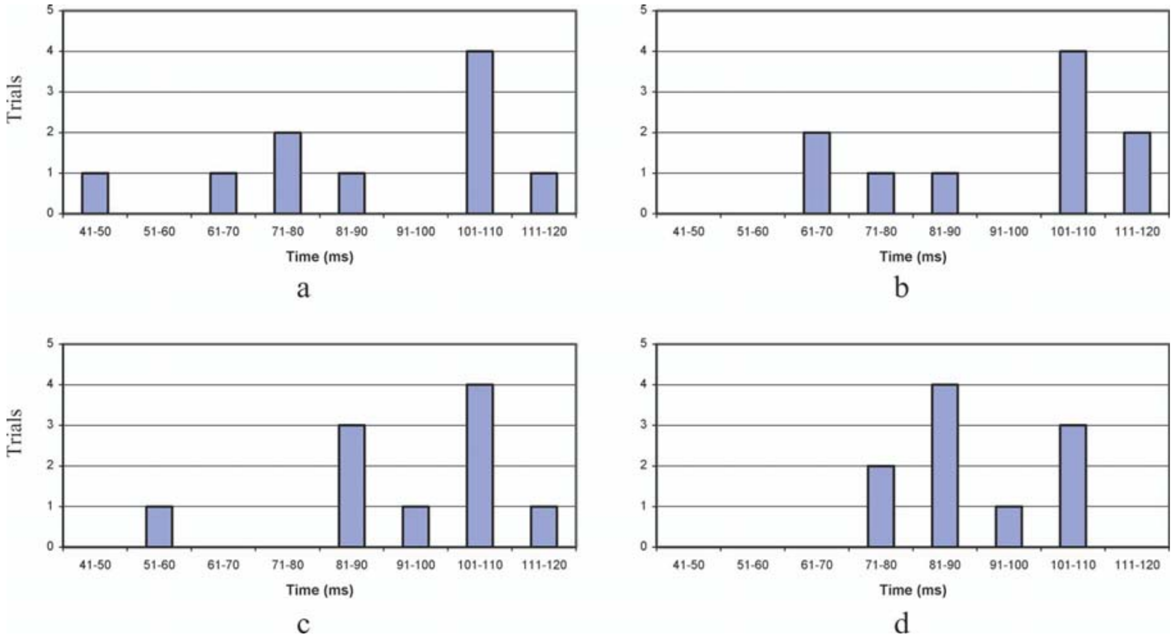

Figure 2. Reaction times for four athletes from the condition in which they had the lowest average reaction time. (a) Participant 1, preloaded condition; (b) Participant 2, normal condition; (c) Participant 7, preloaded condition; (d) Participant 9, normal condition.

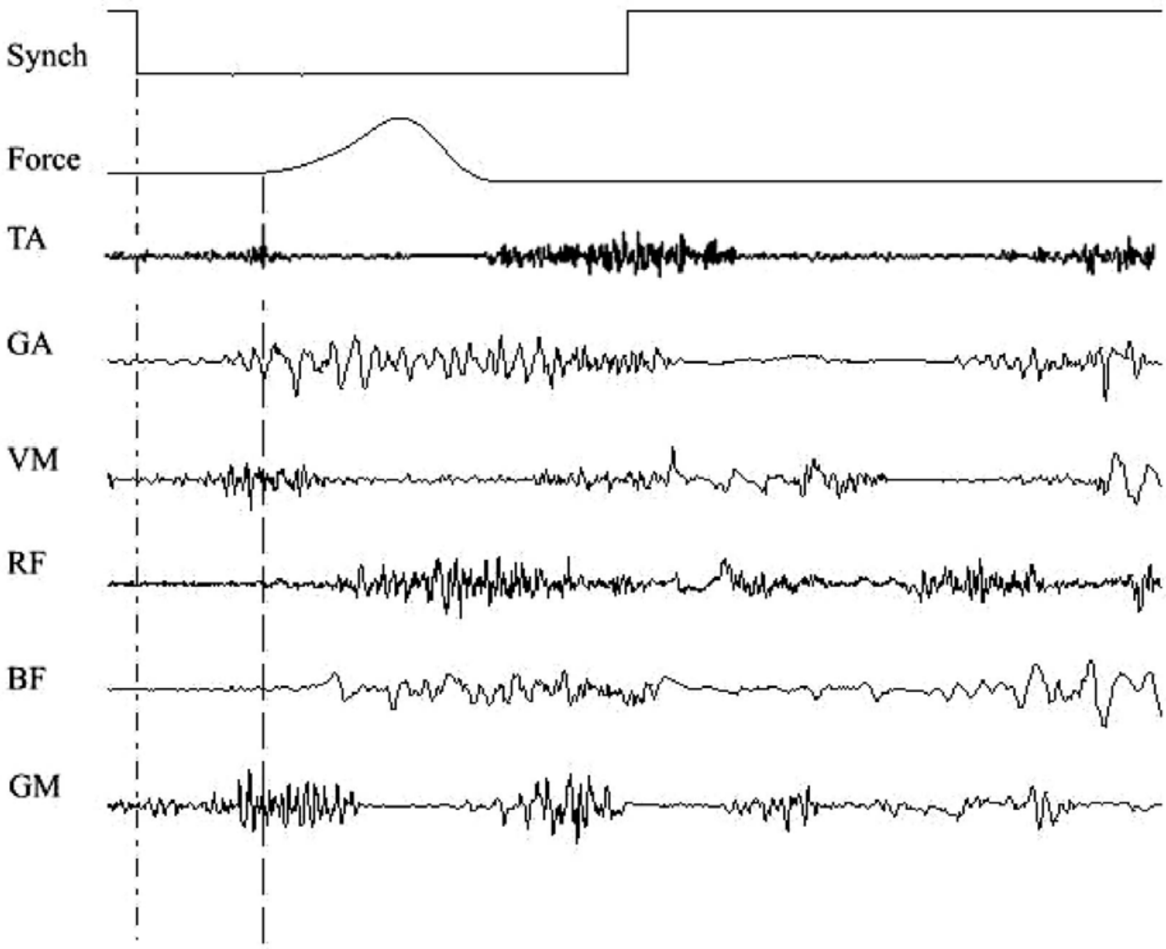

Figure 3. Electromyograms of six muscles of the rear leg of Athlete 8 during a trial in the normal condition together with the force trace from the rear foot and the start signal. The duration of the square wave is 500 ms. The dashed line is the start of force production and the dotdashed line is the start signal. TA = tibialis anterior, GA = gastrocnemius, VM = vastus medialis, RF = rectus femoris, BF = biceps femoris, GM = gluteus maximus.

In the guess condition in Figure 1d the distribution is close to what you would expect from a random distribution achieved by guessing. In the other conditions in Figure 1 and in Figure 2 the dispersion of the reaction times in much smaller than in the guess condition and is consistent with reacting to the start signal with varying degrees of success. Although it is not possible to definitely state if an individual start involved a real reaction in under 100 ms or was guessed, the evidence indicates that many of the starts with reaction times under 100 ms must have been legitimate reactions. The fact that the modal empirical reaction time values were just above the theoretical values would suggest that the theoretical values are probably a legitimate indicator of the minimum auditory reaction time. There is no reason to believe that the subject with the fastest reaction time in this study is at the limit of human ability. A greater number of subjects, especially of elite athletes, may produce a distribution of reaction times that include quicker reaction times. These results do not mean that the subjects with reaction times below 100 ms would achieve reaction times below 100 ms if they were tested using IAAF approved systems but the neuromuscular-physiological component of simple auditory reaction times can be well under 100 ms.

By pretensioning the muscular-tendinous system the system stiffness is increased and the average motor time decreased slightly. However excessively tensioning the system may not further aid reaction time as the muscles need to perform a sequenced pattern of activations. This may be especially significant where two-joint muscles such as rectus femoris, biceps femoris or gastrocnemius are involved. They cause flexion at one joint and extension at another and the net effect is dependent on muscle moment arm and body configuration. There is also the possibility that in highly loaded muscles where the resistance is rapidly removed the unloading reflex (Latash, 1998) may occur, reducing voluntary activation levels. Although the unloading reflex will not be directly affected by sound, some of the loading is produced by pushing forwards with the arms against the ground. If this loading force decreases faster than the leg force can increase, as the arms stop pushing against the ground to allow forward motion, the legs will become less loaded. Examining the EMG results showed no unloading reflex was present in either athlete. It seems that an optimal level of pretension is required for the fastest reaction time, although these results do not indicate what it is or if it will have a major direct effect on the total reaction time.

The pre-motor times of around 65 ms in most of the muscles of the rear leg in the normal condition are comparable with the latencies seen in the startle reflex (Rothwell and Valls-Solé, 2002) and with the pre-motor times of the gastrocnemius in a previous work (Mero and Komi, 1990). Whether these EMG latencies are due solely to a pure startle reflex or to a modulated startle reflex or a reaction independent of the startle reflex was not determined here. However given the habituation to the task and the noise level of less than 100 dB it is unlikely that the repeated trials elicited a classical startle reflex. It has been shown that performing reaction time tasks reduces habituation rate for visual tasks (Valls-Solé et al., 1997) but this has not been shown for auditory tasks. In terms of a limit set in sport, such as the IAAF limit, it would be irrelevant whether the action is initiated by a pure reflex response or other mechanism.

Table2. Mean pre-motor and pseudo-motor times (ms) for participants 8 and 9.

Condition	Muscle	Pre-motor time Front	Pre-motor time Rear	Pseudo-motor time Front	Pseudo-motor time Rear
	TA	79	64	11	17
	GA	86	66	4	15
	VM	55	60	36	21
	RF	56	59	34	22
	BF	77	74	13	7
	GM	74	67	16	14
	D	65		15	
Preloaded	TA	81	89	34	23
	GA	113	97	2	15
	VM	89	98	26	14
	RF	92	92	23	20
	BF	107	105	8	7
	GM	101	104	14	8
	D	73		32	
Relaxed	TA	88	85	36	29
	GA	119	101	5	12
	VM	85	85	39	29
	RF	90	84	34	29
	BF	106	100	18	13
	GM	105	85	19	28
	D	77		35	

Abbreviations: TA = tibialis anterior, GA = gastrocnemius, VM = vastus medialis, RF = rectus femoris, BF = biceps femoris, GM = gluteus maximus, D = deltoid.

The fact that the pre-motor times for both the relaxed and preloaded condition for these two subjects were on average almost 40% longer than in the normal condition was surprising. These delays were seen in the muscles of the extensor chain and it could be that postural stability of the lumbar region and pelvis was destabilised by changing the start technique. Studies have shown (De Wolf, 1998) an interaction between reaction-time movements and the timing and magnitude of anticipatory postural adjustment (APA) profiles. The set position taken up by the athlete is a preparatory position in anticipation of the dynamics of the start. If the set position does not have the correct postural stabilization for the start dynamics, further APA would have had to adjust the core stabilising muscles to avoid injury. It could be that the similarity of pre-motor times in the relaxed and preloaded conditions arise from APAs.

The detection systems currently used for the automatic determination of false starts have what would be considered in research terms high detection thresholds. The purpose of this study was not to determine the reliability or accuracy of the current approved systems but to determine the neuromuscular-physiological minimum auditory reaction time. If the IAAF wish false start regulations to remain higher than the minimum neuromuscular-physiological component of reaction time due to added time for the sound to travel to the athletes, or the system to measure a suitably high rise in the parameter it is detecting then obviously that is the IAAF's prerogative. However these results demonstrate that the neuromuscular-physiological component of simple auditory reaction times can be under 100 ms, probably under 85 ms, and that EMG latencies can have values of about 65 ms.

References

Basmajian, J.V. (1978). *Muscles Alive 4th edn.* Williams and Wilkins, Baltimore, Maryland.

Corcos, D.M., Gottlieb, G.L., Latash, M.L., Almeida, G.L. and Agarwal, G.C. (1992). Electromechanical delay: an experimental artifact. *Journal of Electromyography and Kinesiology,* 2, 59-68.

Dapena, J. (2005). The "loud gun" starting system currently used at the Olympic games does not work properly. http://www.trackandfieldnews.com/features/2005/start-problem.html

De Wolf, D., Slijper, H. and Latash, M.L. Anticipatory postural adjustments during self-paced and reaction time movements. *Experimental Brain Research* 121, 7-19 (1998).

Guissard, N. and Duchateau, J. (1990). Electromyography of the sprint start. *Journal of Human Movement Studies,* 18, 97-106.

Haas, E. C. and Edworthy, J. (2003). *The Ergonomics of Sound*. Human Factors and Ergonomics Society, Santa Monica.

IAAF. (2003). Technical rules for international competitions. http://www.iaaf.org/newsfiles/23484.pdf

Julin, L. and Dapena, J. (2003) Sprinters at the 1996 Atlanta Olympic Games did not hear the starter's gun through the loudspeakers in the starting blocks. *New Studies in Athletics* 18, 23-27.

Kemp, E.H., Coppeé, G.E. and Robinson, E.H. (1937). Electric response of the brain stem to unilateral auditory stimulation. *American Journal of Physiology*, 120, 304.

Latash, M.L. (1998). *Neurophysiological Basis of Movement*. Human Kinetics, Champaign, Illinois.

Mero, A. and Komi, P.V. (1990). Reaction time and electromyographic activity during a sprint start. *European Journal of Applied Physiology and Occupational Physiology,* 61, 73-80.

Muller, T., Benz, S., Bornke, C. and Przuntek H. (2004). Differential response in choice reaction time following apomorphine based on prior dopaminergic treatment. ***Acta Neurologica Scandinavica***, 109, 348-354.

Muraoka, T., Muramatsu, T., Fukunaga, T. and Kanehisa, H. J. (2004). Influence of tendon slack on electromechanical delay in the human medial gastrocnemius in vivo. *Applied Physiology*, 96, 540-544.

Omega, (2006). Athletics. http://www.omegawatches.com/index.php?id=322

Pain, M.T.G. (2003). Identifying reaction times in sprint starts: a comparison of wavelet analysis and custom algorithms, *International Journal of Computer Science in Sport*, 2, 129-131.

Perry, J. (1999). *The Contribution of Dynamic Electromyography to Gait Analysis*. Department of Veterans Affairs. http://www.vard.org/mono/gait/perry.htm

Philipova, D. (1998). Auditory event related potentials and reaction time during decompression from hyperbaric trimix conditions. *Aviation Space and Environmental Medicine*, 69, 545-50.

Roehrs, T., Burduvali, E., Bonahoom, A., Drake, C. and Roth, T. (2003). Ethanol and sleep loss: a "dose" comparison of impairing effects. *Sleep*, 26, 981-5.

Rothwell, J.C. and Valls-Solé, J. (2002). The startle reflex, voluntary movement, and the reticulospinal tract. In *Progress in Motor Control, Volume Two Structure-Function Relations in Voluntary Movements* (edited by M.L. Latash) 13-23 Human Kinetics, Champaign, Illinois.

Schmidt, R.A. and Lee, T.D. (1999). *Motor Control and Learning 3rd edn.* Human Kinetics, Champaign, Illinois.

Thompson, P.D., Colebatch, J.G., Brown, P., Rothwell, J.C., Day, B.L., Obeso, J.A., and Marsden, C.D. (1992). Voluntary stimulus-sensitive jerks and and jumps mimicking myoclonus or pathological startle syndromes. *Movement Disorders,* 7, 257-262.

Valls-Solé, J., Valldeoriola, F., Tolosa, E., and Nobbe, F. (1997). Habituation of the auditory startle reaction is reduced during preparation for execution of a motor task in normal human subjects. *Brain Research.* 751, 155.

Winter, E.M. and Brooks, F.B. (1991). Electromechanical response-times and muscle elasticity in men and women. *European Journal of Applied Physiology and Occupational Physiology,* 63, 124-128.