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Muscle Activity in Sprinting: A Review

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Abstract

The use of electromyography (EMG) is widely recognised as a valuable tool for enhancing the understanding of performance drivers and potential injury risk in sprinting. The timings of muscle activations relative to running gait cycle phases and the technology used to obtain muscle activation data during sprinting are of particular interest to scientists and coaches. This review examined, the main muscles being analysed by surface EMG (sEMG), their activations and timing, and the technologies used to gather sEMG during sprinting. Electronic databases were searched using 'Electromyography' OR 'EMG' AND 'running' OR 'sprinting'. Based on inclusion criteria, 18 articles were selected for review. While sEMG is widely used in biomechanics, relatively few studies have used sEMG in sprinting due to system constraints. The results demonstrated a focus on the leg muscles, with over 70% of the muscles analysed in the upper leg. This is consistent with the use of tethered and data logging EMG systems and many sprints being performed on treadmills. Through the recent advances in wireless EMG technology an increase in the studies on high velocity movements such as sprinting is expected and this should allow practitioners to perform the analysis in an ecologically valid environment.

Keywords – Gait/Locomotion, Running, EMG, Track Events, Injury

Introduction

In sports biomechanics, EMG analysis provides important information on muscle activity which may be useful in optimising performance or reducing the likelihood of sports injuries (Ditroilo et al., 2011; Nummela, Rusko, & Mero, 1994; Paul & Wood, 2002). This is crucial for athletes such as sprinters, since the likelihood of injury increases with running speed (Higashihara, Ono, Kubota, Okuwaki & Fukubayashi, 2010; Schache, Dorn, Blanch, Brown & Pandy, 2012; Yu et al., 2008). Sports performance monitoring for injury prevention is very important for athletes and their coaches as potentially the risk of injury may be increased with an increase in speed and due to muscle fatigue. Identification of the specific effects of fatigue on muscle activation may provide important insights about specific injury mechanisms in sprinting (Thelen, Chumanov, Best, Swanson, & Heiderscheit, 2005; Yu et al., 2008). Utilising EMG to provide information on muscle activity can be useful in examining changes across increases in speed or muscle fatigue. Many features of the EMG signal have been associated with fatigue or speed, especially the amplitude of the EMG signal. Of particular importance are the average EMG (AEMG) which calculates the average amplitude of the rectified EMG signal and the integrated EMG (iEMG) which calculates the total accumulated activity of the muscle. An increase in either the AEMG or iEMG has been reported to be associated with an increase in muscular fatigue (Nummela, Vuorimaa & Rusko, 1992; Nummela et al., 1994), while also having a positive association with increasing running speeds (Chumanov, Heiderscheit & Thelen, 2007; Higashihara et al., 2010).

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While many studies have examined applications of EMG in gait, relatively few have examined muscle activity in sprinting. This could be due to the many challenges associated with gathering accurate EMG data in sprinting. The demands of sprinting require EMG data to be acquired in an unobtrusive way, therefore the EMG sensor design needs to minimise encumbrances on the athlete during sprinting. Any change in the way in which an athlete normally performs a sprint could result in unreliable data being gathered. To reduce discomfort and avoid invasive procedures, the majority of dynamic movements are analysed using sEMG. With advances in technology, sEMG measurements have evolved from tethered systems to data loggers (wireless telemetry) and more recently, to fully wireless systems. For the analysis of sprinting, wireless systems are particularly useful since they do not constrain the movement and facilitate ecologically valid data capture, such as the athlete sprinting on a track rather than on a treadmill in a laboratory setting (Baur, Hirschmuller, Muller, Gollhofer, & Mayer, 2007; Savelberg, Vorstenbosch, Kamman, van de Weijer, & Schambardt, 1998; Van Caekenberghe, Segers, Willems, et al., 2013).

To advance technical knowledge of coaches and athletes, there is a need to understand muscle activations sequences and timing in sprinting, and wireless EMG data could augment understanding of sprinting together with the existing kinematics and kinetic analyses of sprinting derived from many studies. Since the muscles generate the forces required for running there is a particular need to gain knowledge of the timings and sequencing of muscle activity in unrestricted sprinting across the phases of the running gait cycle. With the advent of wireless technology, an increase in studies using sEMG in overground sprinting is expected. Therefore a review of existing knowledge of EMG in sprinting is necessary to determine the patterns of muscle activations during sprinting as it is vitally important to understand the muscles involved and how they act to produce an effective sprint running action since a full understanding of the biomechanics of sprinting requires analysis of movement, force generation and muscle action. A review of sEMG technologies and their applications in sprint analysis is also important and could highlight how the current knowledge base can be used most effectively in new sEMG studies of sprinting to identify specific areas for future research. Consequently, the primary aim of this study was to examine the various muscles analysed during sprinting highlighting where the focus has been, which muscles are important for sprinting in terms of sequencing and timings of activations and the changes in muscle activity levels as a function of running speed. The secondary aim was to understand the various technologies used for sEMG in sprinting, to identify the key features of these systems and examine their relative merits and limitations in the analysis of sprinting.

Methods

This review was limited to articles where sEMG data was collected on participants performing maximal sprint trials. Sprinting was defined as any distance up to and including 400 m, with only the maximal velocity part of sprinting being included in analysis (speeds above 7 m/s). Scopus, ScienceDirect, and Web of Science were searched to identify studies which utilised surface Electromyography in sprinting. The following keywords/combinations were used in searches: (1) 'Electromyography' OR 'EMG' AND (2) 'running' OR 'sprinting'. After the initial search results returned over 1200 citations the advanced search option was used. The inclusion criteria was defined as (1) articles written in English, (2) the source types were journals with books and conference proceedings being excluded, (3) the articles were published in the period from January 2000 to December 2014 and (4) the paper type was an article (review papers were excluded). A final search of 'surface EMG' was

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performed on the results and this identified 418 articles. The titles of the articles were subsequently reviewed with the inclusion criteria: (1) surface EMG measurements were acquired, (2) sprinting was performed and, (3) participants were human. Duplicates acquired from multiple databases were also excluded and this identified 36 articles. The reference lists of these articles were examined to identify any important articles not found in the previous search (28 extra articles were identified) and finally the full papers were examined of all remaining articles. Articles needed to include surface EMG measurements on participants while they were performing maximal sprints, those which did not meet the inclusion criteria were excluded. Articles on the sprint start were excluded because these articles focused only the start and acceleration phases and therefore the athletes would not have been sprinting at maximum velocity. On completion of this process, a total of 18 articles were identified which met all inclusion criteria. Additional databases such as Google Scholar, PubMed and Research Gate were examined under the same search criteria. The first 50 results were examined and no new papers satisfying the above criteria were found. A flow chart outlining selection and exclusion of articles is provided in Figure 1.

The key phases of the running gait cycle, adapted from (Novacheck, 1998; Nummela, et al., 1994; Pinniger, Steele, & Groeller, 2000; Yu et al., 2008) are defined as follows for this study (see Figure 2):

1. The Early Stance (Braking) Phase: This phase begins as the foot makes initial contact (IC) and ends at the mid-stance phase, estimated at 0 – 15% of the cycle.
2. The Late Stance (Propulsion) Phase: This phase begins at the mid-stance phase and ends at the toe off (TO), estimated at 15 – 30% of the cycle.
3. The Early & Middle Swing (Recovery) Phase: This phase begins at TO and ends roughly two thirds of the way through the swing phase, estimated at 30 – 77% of the cycle.
4. The Late Swing (Pre-activation) Phase: This phase begins roughly two thirds of the way through the swing phase and ends at the IC, estimated at 77 – 100% of the cycle.

The 18 articles were examined under two headings: (1) Muscle activations and timings in sprinting and (2) EMG systems and specifications. The muscles activation timings were compared across the key phases of running gait as defined above. The review papers were analysed to compare and contrast the timings (Chumanov et al., 2007; Higashihara et al., 2010; Kuitunen, Komi, & Kyröläinen, 2002; Kyröläinen, Avela, & Komi, 2005; Mero & Komi, 1987; Pinniger et al., 2000; Thelen et al., 2005; Yu et al, 2008), EMG timings from the review paper on the biomechanics of running (Novacheck, 1998) were also included to provide more detailed results on timings of muscle activation. Ensemble means of the muscle activation timings were derived and these were used to create a prolife of the phasic muscle activity across the running gait cycle. Muscle groups included in the profile were based on the muscle groups where clear data was given in the papers reviewed and only muscles which had timings across the entire gait cycle were included.

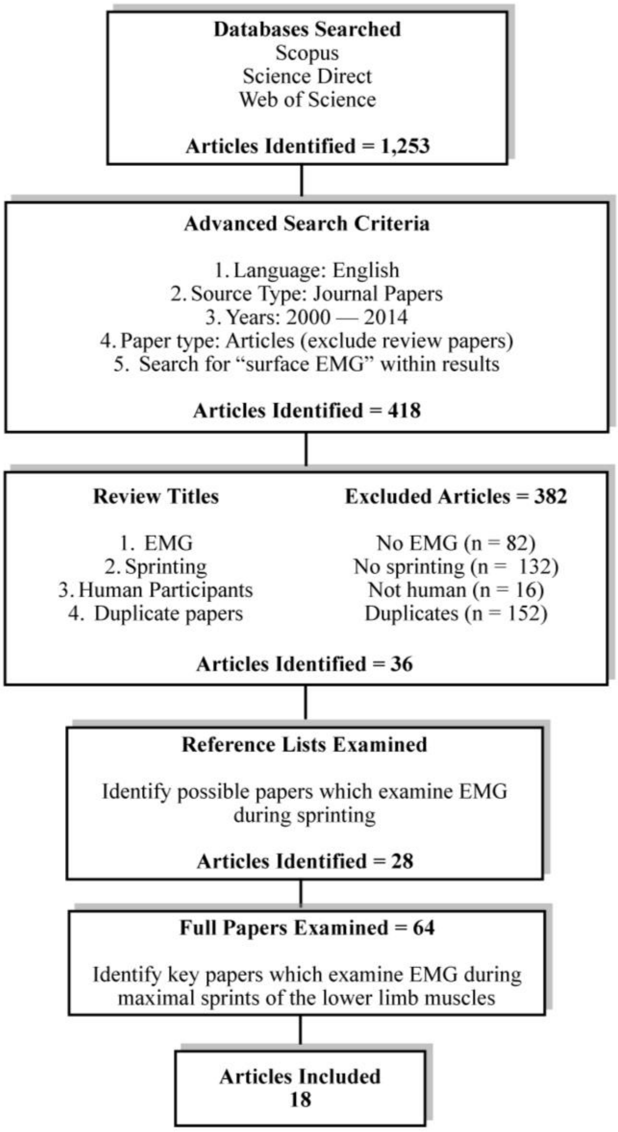

Figure 1. Flow chart outlining the inclusion criteria for articles reviewed

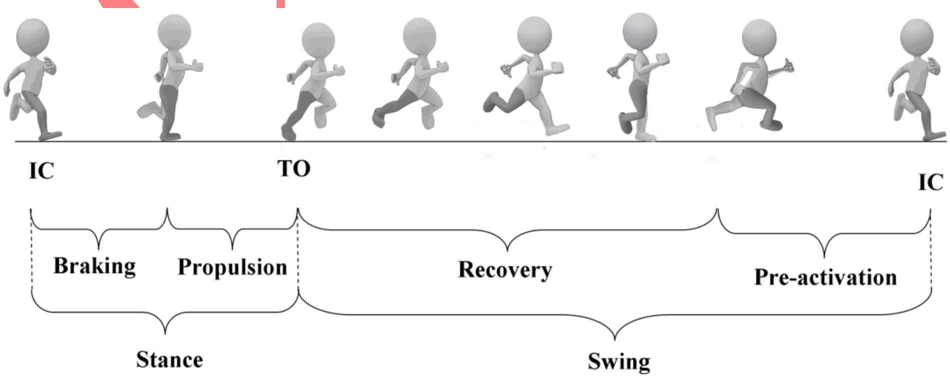

Figure 2. The key phases of the running gait cycle

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Results

Study design and sample

Within the 18 selected articles, 204 participants (73 sprinters, 47 distance runners, 26 recreational runners, 12 footballers and 46 mixed sports or unknown) were tested with 11 ±5 participants per study. On average 5 ±3 trials of EMG data gathered during sprinting were performed by each participant in each study, with a total of 60 ±55 sprinting trials completed by all the participants in each study. A total of 1107 trials were therefore examined over all studies. The mean maximum sprint velocity across all articles was 8.50 ± 0.89 m/s. Table 1 provides a complete summary of these data. Further information on the purpose and outcomes of each of the studies is summarised in Table 2.

Table 1. Participant information from the selected 18 review papers

	Number of participants per study			Number of trials per participant	Total number of trials per study	Sprint speed (m/s)	Participants sport
	Male	Female	Total				
Albertus-Kajee et al.(2011)			12*	2	24	NS[1]	Middle distance
Ball & Scurr (2011)	16		16	3	48	NS[1]	Recreational
Ball & Scurr (2008)	16		16	3	48	NS[1]	NS[1]
Bartlett et al.(2013)	5	5	10	5	50	NS[1]	Recreational
Chumanov et al.(2007)			5*	5	25	NS[1]	NS[1]
Higashihara et al.(2010)	8		8	4	32	8.50 ±0.14	Sprinters
Kuitunen et al.(2002)	10		10	4	40	9.73	Sprinters
Kyröläinen et al.(2005)	17		17	3	51	8.50 ±0.57	Middle distance
Mastalerz et al.(2012)	4		4	4	16	NS[1]	Sprinters
Mero & Komi (1987)	11	8	19	10	190	10.16 ±0.15 9.78 ±0.42 8.77 ±0.30	Sprinters
Nummela et al.(1992)	6		6	5	30	8.17 ±0.31	Sprinters
Nummela et al.(1994)	10		10	6	60	9.23 ±0.59	Sprinters
Nummela et al.(2008)	18		18	5	90	7.61 ±0.44	Middle distance
Pinniger et al.(2000)	12		12	16	192	NS[1]	Footballers
Schache et al.(2012)	5	2	7	1	7	8.95 ±0.70	Sprinters
Slawinski et al.(2008)	1	8	9	1	9	7.56 ±0.41	Sprinters
Thelen et al.(2005)	5		5	5	25	NS[1]	NS[1]
Yu et al.(2008)	20		20	7	140	7.77 ±0.11	Mixed
	164	23					
	287		204	89	1077	8.50 ±0.89	

*Gender of participants not disclosed.
[1]Not specified (NS) by the authors.

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Table 2. Study information from the selected 18 review papers

	Participant EMG characteristics	Purpose of study	Sprint trial description	Outcome measures	Results of study
Albertus-Kajee et al.(2011)	EMG of right leg	Normalisation methods	(3 Days) 2 x 20m max sprint: 140m indoor track*	RMS and peak EMG	Sprint and MVC most repeatable methods
Ball & Scurr (2011)	EMG of dominant leg	Normalisation methods for 20m sprint	(3 Days) 3 x 20m max sprint: indoor sports hall*	RMS & peak EMG	Normalise to peak in sprint or squat jump
Ball & Scurr (2008)	Unilateral EMG measures	Reliability and standardisation of normalisation methods	(3 Days) 3 x 20m max sprint: indoor sports hall*	RMS and peak EMG	Sprint and squat jump methods
Bartlett et al.(2013)	EMG of right leg	Activity of gluteal muscles in walk, run, sprint & climb	5 x 30m max sprint:30m runway*	RMS & peak EMG	Gluteal activity changes with increased speed
Chumanov et al.(2007)	EMG of right leg	Effects of speed on hamstring muscle mechanics	80%, 85%, 90%, 95% & 100% of max velocity: treadmill	Linear Envelope	Increase in peak hamstring activity with increase in speed
Higashihara et al.(2010)	Unilateral EMG measures	Hamstring muscle activity at different running speeds	50%, 75%, 85% & 95% of max velocity: high speed treadmill	RMS & peak time of maximum activity	Significant difference in activation patterns as speed increases
Kuitunen et al.(2002)	EMG of right leg muscles	Examine ankle and knee joint stiffness during sprinting	70% - 100% (4 sprints) of max velocity, accelerate to photocells (10m apart)	Smoothed EMG (15 point average) & Average EMG	Ankle stiffness remained constant, knee joint stiffness increased with running speed
Kyröläinen et al.(2005)	Unilateral EMG measures	Changes in muscle activations as speed increases	5 submaximal sprints & 3 x 30m max: 200m indoor track*	Average EMG	Increase in activity of all muscles with increase in speed
Mastalerz et al.(2012)	EMG of right & left legs	Represent fatigue in EMG profile across different run intensities	4 x 400m (90s, 70s, 60s & max): tartan athletics track	MPF & FFT	Greater fatigue in left leg compared to right
Mero & Komi (1987)	Unilateral EMG measures	Find relationship between EMG and contact forces in sprinting	2 runs x 5 speeds: indoor hall*	iEMG & peak EMG	Peak activity was shown in all muscles except the RF at braking phase of ipsi-lateral contact
Nummela et al.(1992)	EMG of right leg	Neural activation changes across speed in 400m sprint (iEMG)	(2 Days) 20m max sprint & 400m & 200m (Day 1) & 100m & 300m (Day 2): indoor running track (flying start for all runs)*	iEMG	Fatigue in 400m running is mainly due to skeletal muscles rather than the central nervous system
Nummela et al.(1994)	EMG of right leg	EMG activities in fatigued and non-fatigued sprinting	(2 Days) 20m max sprint (40m flying start) & 400m time trial (Day 1) & 3/4 submaximal 20m (Day 2): outdoor running track	Average EMG	The increased neural activation was due to muscular fatigue

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Nummela et al.(2008)	EMG of right leg	Fatigue induced changes	3-5x 20m max sprints (15m running start): indoor running track*	Average EMG	Fatigue in 5km running at maximum effort was related to sprint performance
Pinniger et al.(2000)	Unilateral EMG measures	Effects of hamstring fatigue induced by maximum effort during maximum sprint	3 x 40m max sprint (non-fatigued); 10 maximal 40m sprints hamstring fatigue task; 3 x40m max sprint (fatigued)*	Linear Envelope	Increased duration of hamstring activity and earlier offset of RF during swing phase
Schache et al.(2012)	Unilateral EMG measures	Differences in each hamstring muscle during sprint	20m sprint: 110m indoor synthetic running track	Average EMG	Peak musculotendon force and strain for the hamstrings occurred around the same time as terminal swing, this may be when hamstrings are at greatest risk of injury
Slawinski et al.(2008)	Unilateral EMG measures	Muscle activity during inclined and level training	300m max sprint: indoor/outdoor running track*	RMS & iEMG	A lower velocity in the inclined sprinting results in a decrease in hamstring activity
Thelen et al.(2005)	Unilateral EMG measures	Mechanics of hamstring during swing phase of sprinting	80% - 100% of max velocity: treadmill	Linear Envelope	Increase in excitation of BF at 70 – 80% of running gait cycle until the end of the swing phase
Yu et al.(2008)	EMG of dominant leg	Mechanics of hamstring muscle strain injuries during overground sprinting	7 sprint trails with a 10m run up to calibration zone	Linear envelope across running gait cycle	Hamstrings were active during entire running cycle, maximum activations occurred during the early stance phase and late swing phase.

*Partial study information; only the maximum sprint trials are accounted for

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Muscle activations and timings in sprinting

Muscles analysed

The results demonstrated a focus on the hamstrings and quadriceps muscle groups in the papers reviewed (see Table 3). 14 of the 18 articles analysed the biceps femoris (BF), seven analysed the medial hamstrings. 12 of the 18 articles analysed the rectus femoris (RF), 10 analysed the vastus lateralis (VL) and five analysed the vastus medialis (VM). Two of the 18 articles analysed the gastrocnemius (GA), however 10 specifically analysed the medial gastrocnemius (MG) and three analysed the lateral gastrocnemius (LG). Of the 18 articles, five analysed the gluteus maximus (GMAX) and one analysed the gluteus medialis (GMED). Four of the 18 articles analysed the soleus (SOL) and the tibialis anterior (TA). 77 muscles were analysed in total across all the articles reviewed. Of these, 35% of the 77 muscles analysed were quadriceps; 27% were hamstrings, 25% were calves, 8% were gluteal muscles and 5% were TA. Over 70% of the 77 muscles analysed were the upper leg muscles with less than 30% of those analysed being from the lower leg muscles.

Table 3. Muscles studied during sprinting using sEMG

Muscles	Biceps Femoris (BF)	Gastrocnemius (GA)	Gluteus Maximus (GMAX)	Gluteus Medius (GMED)	Medial Hamstrings (MH) – ST & SM	Lateral Gastrocnemius (LG)	Medial Gastrocnemius (MG)	Rectus Femoris (RF)	Soleus (SOL)	Tibialis Anterior (TA)	Vastus Lateralis (VL)	Vastus Medialis (VM)
Bartlett et al.(2013)			•	•								
Mastalerz et al.(2012)	•							•				
Schache et al.(2012)					•							
Albertus-Kajee et al.(2011)	•					•	•	•			•	•
Ball & Scurr (2011, 2008)						•	•		•			
Higashihara et al.(2010)	•				•							
Nummela et al.(2008, 1994, 1992)	•						•	•			•	•
Slawinski et al.(2008)	•	•	•		•			•	•	•	•	
Yu et al.(2008)	•				•							
Chumanov et al.(2007)	•				•		•	•			•	
Kyröläinen et al.(2005)	•	•	•					•		•	•	
Thelen et al.(2005)	•				•			•			•	
Kuitunen et al.(2002)	•		•				•	•	•	•		•
Pinniger et al.(2000)	•				•		•	•			•	
Mero & Komi (1987)	•		•				•	•		•	•	

Muscles activation timings

The muscle activation timings of the lower limbs are presented in Figure 3. The periods of muscle activity were identified using the timings gathered from the review papers which gave timing details (Chumanov et al., 2007; Higashihara et al., 2010; Kuitunen et al., 2002;

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Kyröläinen et al., 2005; Mero & Komi, 1987; Pinniger et al., 2000; Thelen et al., 2005; Yu et al, 2008) and the biomechanics of running paper by Novacheck (1998).

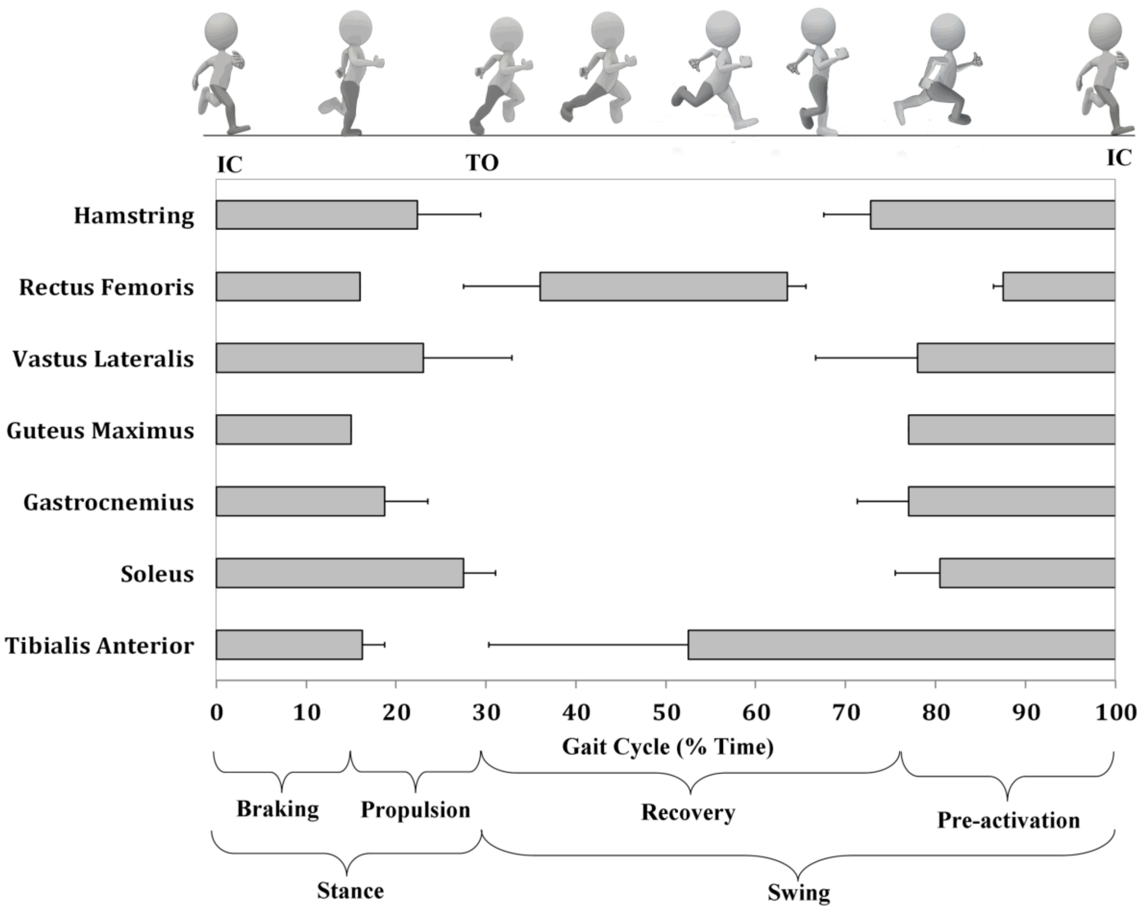

Figure 3. The muscle activation timings of the lower limbs during sprinting across the gait cycle as a percentage of time. Timings gathered from Chumanov et al. (2007), Higashihara et al. (2010), Kuitunen et al. (2002), Kyröläinen et al. (2005), Mero and Komi (1987), Novacheck (1998), Pinniger et al. (2000), Thelen et al. (2005), and Yu et al. (2008). The light grey areas represent periods where there is muscle activity. The error bars in the plot represent the SD of the mean onset and termination times which were gathered.

Muscle activation timings in the stance phase

Figure 3 shows that the hamstrings were active through the stance phase (Higashihara et al., 2010; Pinniger et al., 2000; Yu et al, 2008). An earlier peak activation of the BF than the ST during the stance phase was found (Higashihara et al., 2010). The quadriceps muscle group were also active in the stance phase, which was consistent with Pinniger et al. (2000). Peak activity of the gluteus maximus (GMAX) was found at foot strike, with activity in the early stance phase (Bartlett, Sumner, Ellis, & Kram, 2013; Kyröläinen et al., 2005). It can also be observed in Figure 3 that the GA was active in stance phase (Kuitunen et al, 2002; Kyröläinen et al., 2005; Mero & Komi, 1987; Pinniger et al., 2000) and the SOL was active in the braking (early stance) phase, with the peak activity occurring after the initial contact (Kuitunen et al, 2002). The TA also produced activity in the early stance phase in Figure 3 (Kuitunen et al., 2002; Kyröläinen et al., 2005; Mero & Komi, 1987).

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Muscle activation timings in the swing phase

Figure 3 also shows the hamstrings are active in the late swing phase (Chumanov et al., 2007; Higashihara et al., 2010; Pinniger et al., 2000; Thelen et al., 2005; Yu et al, 2008). It can be observed from Figure 3 that the RF had two clear bursts of activity, one in the early swing phase and a second in late swing phase. The VL was also active in the late swing phase (Pinniger et al.; 2000). Muscle activity was observed in the GMAX in the late swing phase (Kyröläinen et al.; 2005) and as outlined in Figure 3 the GA and the SOL were active in the pre-activation (late swing) phase (Kuitunen et al, 2002; Kyröläinen et al., 2005; Mero & Komi, 1987). Figure 3 showed activity beginning in the mid-swing phase for the TA (Kuitunen et al., 2002; Kyröläinen et al., 2005; Mero & Komi, 1987).

Muscle activity levels

Seven articles found increases in muscle activity with increases in speed (Albertus-Kajee, Tucker, Derman, Lamberts & Lambert, 2011; Bartlett et al., 2013; Higashihara et al., 2010; Kuitunen et al., 2002; Kyröläinen et al., 2005; Mastalerz, Gwarek, Sadowski, & Szczepanski, 2012; Nummela et al., 1994). The maximum activations of the BF and semimembranosus (SM) were found in the late swing and early stance phases, with the activation in the late swing phase being two to three times greater than the late stance and early swing (Yu et al, 2008). Similarly, Kuitunen et al. (2002) found the highest EMG activity of the BF in the pre-activation (late swing) phase. The ST showed greater activity than the BF during the mid-swing phase, with the earlier peak activation of the ST than the BF during the late swing phase (Higashihara et al., 2010). In an inclined sprint, the root mean square (RMS) of the BF and ST was decreased compared to level sprinting during the early stance phase (Slawinski et al., 2008). Slawinski et al. (2008) found the RMS of the VL and the SOL was also lower in inclined sprinting compared to level sprinting. Ball and Scurr (2011) showed higher RMS EMG in Medial Gastrocnemius (MG) and SOL compared to Lateral Gastrocnemius (LG). Mastalerz et al. (2012) found greater fatigue in the left BF to the right BF on bend running.

EMG systems and specifications

The range of EMG systems used within the studies included in the review is described in Table 4. Of the 18 articles reviewed, 14 used telemetry (of which four were also data logging systems), two used data logging and two used wired systems. Four of the articles mentioned the use of transmitter devices attached to the participants back, either strapped (Albertus-Kajee et al.,2011; Pinniger et al. 2000) or attached to a belt (Nummela, et al., 1992; Nummela, et al., 1994; Nummela, et al., 2008). Two articles mention taping cables back to avoid motion artefacts (Higashihara et al., 2010; Thelen et al., 2005). Similar specifications were seen between each of the systems used (see Table 5). Typically a 12 – 16 bit Analog to Digital Converter, and a gain of 500 – 1000 was used. The most common sampling frequency was 1000 Hz. The bandwidth was generally from 10 to 500 Hz and the input impedance was set below 100 MΩ. Five articles also mentioned the use of a ground or reference electrode attached to the wrist (Ball & Scurr, 2008; Ball & Scurr 2011; Thelen et al., 2005) or the tibia (Pinniger et al., 2000; Schache et al., 2012; Yu et al., 2008).

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Table 4. The frequency of use of the EMG systems from the 18 review papers

EMG system	Bangoli-16 DelSys	Biometrics Datalog EMG System	Glonner Biomes 2000	ME3000 Mega Electronics	ME6000 Mega Electronics	Telemyo EMG System Noraxon	Medinik AB (IC-600-G)
Bartlett et al.(2013)						•	
Mastalerz et al.(2012)				•			
Schache et al.(2012)						•	
Albertus-Kajee et al.(2011)						•	
Ball & Scurr (2011, 2008)		•					
Higashihara et al.(2010)					•		
Nummela et al.(2008, 1994, 1992)			•				•
Slawinski et al.(2008)					•		
Yu et al.(2008)						•	
Chumanov et al.(2007)	•						
Kyröläinen et al.(2005)				•			
Thelen et al.(2005)	•						
Kuitunen et al.(2002)			•				
Pinniger et al.(2000)						•	
Mero & Komi (1987)							•

Table 5. Specifications of Electromyography systems reviewed

EMG devices specifications	Sampling Rate	Analog to Digital Converter (ADC)	Common Mode Rejection Ratio (CMRR)	Input Impedance	Gain	Bandwidth (BW)
Bartlett et al.(2013)	1 kHz	16-bit	>100 dB	>100 MΩ	1700	
Mastalerz et al.(2012)	1 kHz	14-bit	>130 dB		1000	2 - 500 Hz
Schache et al.(2012)	1.5 kHz	16-bit	>100 dB	>100 MΩ	500	
Albertus-Kajee et al.(2011)	2 kHz	16-bit	>100 dB	>100 MΩ	1000	10 - 500 Hz
Ball et al.(2011, 2008)	1 kHz		>96 dB @ 60 Hz	> 100 MΩ	1000	20 - 450 Hz
Higashihara et al.(2010)	2 kHz	16-bit				50 - 500 Hz
Nummela et al.(2008, 1994, 1992)	1 kHz				1000	
Slawinski et al.(2008)	1 k Hz				375	8 -500 Hz
Yu et al.(2008)	2.4 kHz	16-bit	>100 dB	>100 MΩ	1000	10- 800 Hz
Chumanov et al.(2007)	2 kHz	12-bit	> 84 dB @ 60 Hz	> 100 MΩ		20 - 450 Hz
Kyröläinen et al.(2005)	1 kHz				500	0-360 Hz
Thelen et al.(2005)	2 kHz	12-bit	> 84 dB @ 60 Hz	> 100 MΩ		20 - 450 Hz
Kuitunen et al.(2002)	833 Hz					
Pinniger et al.(2000)	1 kHz	16-bit	>100 dB	>100 MΩ	1000	0 - 340 Hz
Mero et al.(1987)	1 kHz				1000	

Discussion & Implications

The primary aim of this study was to examine the various muscles analysed during sprinting, highlighting where the focus has been, which muscles were important for sprinting in sequencing and timings of activations and the changes in muscle activity levels as a function of running speed. Analysis of the hamstring muscle mechanics and fatigue during sprinting were two of the most common themes emerging from this review. This focus on hamstring muscle sEMG in many of the studies reviewed is reasonable given the important role that the hamstrings play in generating forward ground reaction forces during the propulsive part of stance in sprinting. This muscle group is also the most commonly injured during sprinting (Chumanov et al., 2007; Thelen et al., 2005) which emphasises the importance of evaluating the hamstring muscle activity during sprinting. Yu et al., (2008) examined the kinematics and activations of the hamstrings during over-ground sprinting using sEMG wireless telemetry. Differences in running biomechanics and onset times of muscle activations have been observed between treadmill and overground running (Baur et al., 2007; Wank et al., 1998), since treadmills have limited ecological validity and therefore analysis of over-ground sprinting is more appropriate and valid (Van Caekenberghe, Segers, Willems, et al., 2013).

Higashihara et al. (2010) and Schache et al. (2012) analysed the BF and ST and compared their muscle activity over trials of increased running speed, a potentially greater risk of hamstring strain as sprint speed increased was proposed, however it must be noted that although the authors suggest an increased risk it was not directly observed or measured. Understanding the specific muscle activations of the hamstring and gluteal muscle groups is useful for coaches and practitioners as this knowledge may provide vital insights on injury risk factors and muscle loadings during the various phases of the sprint action. Hamstring strain injuries are likely to occur at the muscle belly during the late swing phase (Best, McElhaney, Garrett, & Myers, 1995; Yu et al., 2008). Yu et al. (2008) observed that the peak eccentric contraction speeds of the hamstring muscle were significantly greater during the late swing phase than the late stance phase, which could explain why 90% of hamstring strain injuries occur in the muscle belly (Askling, Tengvar, Saartok, & Thorstensson, 2007; Koulouris, Connell, Brukner, & Schneider-Kolsky, 2007). Early identification of injury risks in athletes will highlight the possibility of muscle imbalances or incorrect running biomechanics. This in turn, may help prevent the risk of a more serious injury or reoccurrence due to non-optimal running biomechanics or training methods.

The effects of fatigue on muscle activation can also provide vital insights about specific injuries during sprinting (Thelen et al., 2005; Yu et al., 2008). These studies noted that there was increased muscle activation due to muscle fatigue in submaximal conditions. Fatigue in the muscles was also correlated with an increase in the duration of the muscle activation, an increase in the AEMG or an increase in the iEMG. For coaches and practitioners, there is a need for early recognition of the onset of fatigue levels that may precede injury and therefore place an athlete at risk. Recognising the onset of fatigue through EMG monitoring during sprinting may be helpful in providing early warnings of elevated injury risk.

Pinniger et al. (2000) noted that in a fatigued sprint, the duration of the muscle activation in the ST muscle increased significantly with an earlier onset and a later termination of the activation. Similarly, there was a difference in the RF in the fatigued condition: the first burst of activity terminated significantly earlier and the second burst turned on significantly earlier (Pinniger et al., 2000). Pinniger et al. (2000) also observed that fatigue measured during the 20 m sprint and during the maximum voluntary contraction (MVC) measurement was not related to the fatigue which caused the decrease in velocity during the endurance task.

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Longer, endurance sprints, such as the 400 m, were performed in some studies to consider the effects of fatigue (Mastalerz et al., 2012; Nummela et al., 1994; Nummela et al., 1992; Slawinski et al., 2008). These studies observed that EMG activity increased as the sprint progressed. Increased contact times in the latter half of the run could be as a result of the increasing number of slow-twitch fibres involved as the fast-twitch fibres fatigued (Nummela et al., 1992). The left limb had a greater fatigue compared to the right limb due to a considerable load on the BF of the inner leg, which could be caused from the curve on the track (Mastalerz et al., 2012). Understanding the differences in fatigue between long and short sprinters is very important to allow coaches observe the signs of fatigue in their athletes during speed or endurance specific training session.

Several studies observed changes in the EMG data across various running speeds, which showed that the activity of the muscles increased with an increase in speed (Nummela et al., 1994; Kuitunen et al., 2002; Bartlett et al., 2013; Mastalerz et al., 2012; Albertus-Kajee et al., 2011; Kyröläinen et al., 2005; Higashihara et al., 2010). Nummela et al. (1994) observed a significant difference in the RF in the braking (early stance) phase; this was most likely due to the important role the RF plays in tolerating impact loads. Kuitunen et al. (2002) examined a variety of speeds as a percentage of maximum speed which showed that there was an increase in muscle activation of the plantar flexors (TA) and the knee extensors (RF) in the pre-activation (late swing) phase as the speed increased, the VM showed earlier peak activation in the late swing phase in higher speeds and there was significant differences found in the BF with increased speeds. Another study found a large increase in EMG amplitude in sprinting compared to the walking condition, the RMS mean normalised to walking showed a significant difference of four to seven times greater during sprinting (Bartlett et al., 2013). The greatest changes in muscle activity were found in the BF and RF as speed increased (Albertus-Kajee et al., 2011). Kyröläinen et al. (2005) found that the MVC is not a good indicator of the activation potential, since some muscles recorded amplitudes greater than the MVC recorded.

The timings of muscle activations provide important insight into the functions the muscles perform throughout the gait running cycle. Figure 3 shows that during the braking (early stance) phase, agonistic and antagonistic muscles co-contract to facilitate stabilisation. It can be observed from Figure 3 that there are temporal overlaps of muscle activity in agonist and antagonist groups. For example, the calves and the hamstrings in the braking (early stance) phase contract simultaneously with the TA and RF respectively. During the flight phase when the knee is in a flexed position there is minimal activity observed in the hamstrings and the calves. Figure 3 shows RF is active in the early swing phase and contracts eccentrically for hip extension and knee flexion. There is no activation of the RF during the concentric contraction in the forward flexion of the thigh, however in the late swing phase there is activation in the RF as the leg extends in preparation for the ground contact (see Figure 3). Mero and Komi (1987) concluded that the RF had a more important role as a hip flexor than a knee extensor. The TA is also active earlier in the swing phase to keep the foot in a dorsiflexed position throughout mid swing to late swing phase. It is then activating in preparation for the ground contact when it takes on a stabilisation role alongside the calves muscle group in the braking phase. All of the muscle groups shown are active in the late swing phase in preparation for ground contact and then in the early stance phase in a stabilisation role.

The secondary aim was to understand the various technologies used for sEMG in sprinting, to identify the key features of these systems and examine their relative merits and limitations in

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the analysis of sprinting. Examinations of EMG systems and their specifications in sprinting show that the main issues were with the data transmission rather than the specification of the acquisition features. System specifications were very similar across the devices, with data acquisition and analysis steps performed to similar standards. Many of the systems used were data logger technologies, which required long wires when evaluating sEMG on distal body segments were required. The quadriceps and hamstring muscles are prime movers in sprinting. Logically the majority of papers analysed these muscles, however the convenience in measuring the upper leg muscles (see Table 3) may have also been a factor resulting in these muscles being the most analysed in sprinting, results show over 70% of the muscles analysed were the upper leg muscles. Less emphasis has been placed on the analysis of the lower leg muscles. Less than 30% of those analysed were the lower leg muscles which may be due to technology constraints. Longer wires would cause increased noise artefact or movement encumbrance if the data logger was mounted on the distal segment. Clearly, there is a bias on the muscles analysed which may be a consideration due to the limitations of devices. The use of fully wireless sEMG systems could facilitate the effective analysis of a wider range of muscles used in sprinting (Howard, Conway & Harrison, 2016).

There appears to be a historic trend which dominates sEMG measurements. Several studies in this review reported the use of a tethered sEMG system for analysing gait and running performance. However, these studies all involved the athlete running or walking on a treadmill (Chumanov et al., 2007; Higashihara et al., 2010; Thelen et al., 2005). Very few treadmills allow athletes to reach maximum sprint speed and this limits the ecological validity of treadmill running since sprinting or jogging on a treadmill is not identical with overground sprinting or jogging (Baur et al., 2007; Van Caekenberghe, Segers, Willems, et al., 2013; Wank et al., 1998). There may also be potential changes in the muscle activation timings and magnitudes as motorised treadmills also contribute to hip extension, as the belt moves the foot of the participant backwards (Van Caekenberghe, Segers, Aerts, Willems, & De Clercq, 2013). As a result a tethered sEMG system is likely to cause the athlete to moderate the way they run due to the fact sprints need to be performed on a treadmill. The use of data loggers and telemetry also required the participants to wear a transceiver pack connected via wires to the electrodes while sprinting which could cause changes in the sprint movement pattern.

For coaches, monitoring sports performance it is important that the results accurately reflect the activity in an ecologically valid environment. Technologies were initially quite bulky and limited the amount of data that could be captured. The majority of sampling rates of the systems in the papers reviewed were 1 kHz which is an appropriate sampling rate (SENIAM). More recently higher sampling rates are being used (Albertus-Kajee et al., 2011; Higashihara et al., 2010; Schache et al., 2012; Thelen et al., 2005; Yu et al., 2008). The issues associated with tethered systems highlight the need for wireless based sEMG devices. The system selected for analysis of sprinting needs to ensure many of the same specifications necessary for any other application, while also allowing real time data streaming. By exploiting wireless technology the data gathering process will be simplified for the practitioner (Howard et al., 2016). Advances in technology have facilitated smaller wireless devices which can sample at higher rates and stream large data sets wirelessly across a long distance. Companies have invested in low power wireless technology with a huge emphasis on wearable wireless sensor technologies. Technologies from other sectors can be easily transferred into the area of sports performance and sprinting aiding the analysis of sprint performance for both the coach and practitioner.

Conclusion

This review presented information on muscle activations during maximal sprinting such as timings and activity levels across the running gait cycle. The composite of muscle activity timings across the running gait cycle provides a summary of timings from previous research and could aid future researchers. It is important that more research is done in the area of injury prevention utilising data from muscle activations during sprinting, allowing a greater insight into the causes of injury and the times at which athletes are at a greater risk. This will aid coaches and facilitate more analysis in the area of sports performance for practitioners. This review also highlights the current technologies used in the analysis of sEMG in sprinting and will provide a useful reference for future studies. Due to the limitations of sEMG devices, there are relatively few articles on sprinting using sEMG. EMG systems used throughout these studies tended to be tethered or data logging systems giving a bias to the muscles analysed and the way in which sprints were performed. There is a need to utilise wireless technology to facilitate the analysis of all lower limb muscles during sprinting and allow practitioners to perform the analysis in an ecological valid environment.

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