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Surface electromyography in animals: A systematic review

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Abstract

The study of muscle activity using surface electromyography (sEMG) is commonly used for investigations of the neuromuscular system in man. Although sEMG has faced methodological challenges, considerable technical advances have been made in the last few decades. Similarly, the field of animal biomechanics, including sEMG, has grown despite being confronted with often complex experimental conditions. In human sEMG research, standardised protocols have been developed, however these are lacking in animal sEMG. Before standards can be proposed in this population group, the existing research in animal sEMG should be collated and evaluated. Therefore the aim of this review is to systematically identify and summarise the literature in animal sEMG focussing on (1) species, breeds, activities and muscles investigated, and (2) electrode placement and normalisation methods used. The databases PubMed, Web of Science, Scopus, and Vetmed Resource were searched systematically for sEMG studies in animals and 38 articles were included in the final review. Data on methodological quality was collected and summarised. The findings from this systematic review indicate the divergence in animal sEMG methodology and as a result, future steps required to develop standardisation in animal sEMG are proposed.

Keywords

Surface Electromyography; Animals; Muscle activity; Equine; Canine; Ruminants

1 Introduction

In humans, the study of muscle activity using surface electromyography (sEMG) is widely used for investigations of the neuromuscular system. Not only is it applied in healthy populations to assess the role and interactions of muscles during functional tasks (Cuesta-Vargas et al., 2013; Iida et al., 2012; Lee et al., 2013) and sport and exercise (Kavcic et al., 2004; Martens et al., 2015; Park et al., 2014; Serner et al., 2013), it is also used in clinical groups to understand muscle (mal-) adaptations and dysfunctions in musculoskeletal injury,

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pain and pathology (Castelein et al., 2015; Falla et al., 2014; Gardinier et al., 2012; van der Hulst et al., 2010). sEMG has made considerable technical advances in the last few decades, however, divergence in sEMG methodology between many research groups led to limitations in direct comparisons between studies. In order to standardise sEMG, the SENIAM project (Surface Electromyography for the Non-Invasive Assessment of Muscles) was established which provides guidelines for sensor placement and signal processing (Hermens et al., 1999). Furthermore, the International Society of Electromyography and Kinesiology (ISEK) has produced standards for sEMG reporting.

Although an interest in animal biomechanics has existed for centuries (van Weeren, 2012), the use of sEMG in animal populations is considerably less often reported compared to the human literature. The nature of capturing sEMG data in animals poses many challenges for researchers in this field. These are not limited to, but include, how to prepare densely hairy, woolly or greasy skin for optimal electrode adhesion whilst achieving minimal electrode-skin impedance, and where to place the electrodes. Added to this are behavioural constraints, e.g. how can I encourage the animal to perform a movement accurately and consistently? As a result, certain techniques commonly used in human sEMG data collection such as obtaining an isometric maximal voluntary contraction (MVC) for the purpose of sEMG data normalisation, are impossible in animals. Despite these challenges, the number of studies on sEMG in animals is steadily growing, with the majority of work having been carried out in equines (Garica et al., 2014; Kienapfel, 2015; St.George and Williams, 2013; Williams et al., 2014; Williams et al., 2013; Zsoldos et al., 2014). The advent of wireless sEMG in particular has been a positive step in opening the doors to research questions which would otherwise have been very difficult to obtain using a wired system in animal populations.

Although the body of knowledge in animal muscle function through the use of sEMG is growing, this area of research is plagued by the same lack of standardisation in sEMG methodology which human sEMG studies faced prior to the development of SENIAM and ISEK recommendations. Before standards in animal sEMG can be proposed however, an overview of past and present research practices in animal sEMG needs to be gained. To our knowledge, no attempts have been made to summarise the scientific literature in animal sEMG. An overview which compares the methodologies utilised in animal sEMG studies would allow aspects such as agreement or disparity in electrode placement and approaches to signal processing to be identified. It might also suggest how one major challenge, the normalisation of sEMG in animals, can be best managed.

Therefore, the aim of this review is to systematically identify and summarise the literature in animal sEMG focussing on two aspects: the first is to summarise the species, breeds, activities and muscles which have been investigated in animal sEMG studies, and the second is to identify methodological practices in animal sEMG studies based on electrode placement and normalisation approaches. Although it is not the purpose of this review to propose standardised protocols in animal sEMG, it will suggest where animal sEMG methodology is divergent and highlight the challenges that the field is facing. From there, ways in which steps can be taken to develop standardisation in animal sEMG are suggested, to bring it in line with what has been achieved in human sEMG thus far.

2 Methods

2.1 Search Strategy

A systematic literature search of sEMG studies in animals was conducted by two assessors between 12/5/15 and 9/6/15. The databases PubMed, Web of Science, Scopus, and Vetmed Resource were included. The key terms used were:

- (1) "surface electromyography" AND animal AND exercise
- (2) "surface electromyography" AND animal AND locomotion
- (3) "surface electromyography" AND animal AND gait
- (4) "surface electromyography" AND animal AND "muscle activity"
- (5) "surface electromyography" AND equine OR "surface electromyography" AND horse
- (6) "surface electromyography" AND canine OR "surface electromyography" AND dog
- (7) "surface electromyography" AND bovine OR "surface electromyography" AND cow
- (8) "surface electromyography" AND ovine OR "surface electromyography" AND sheep
- (9) "surface electromyography" AND feline OR "surface electromyography" AND cat
- (10) "surface electromyography" AND caprine OR "surface electromyography" AND goat
- (11) "surface electromyography" AND rodent OR "surface electromyography" AND rat OR "surface electromyography" AND mouse
- (12) "surface electromyography" AND bird
- (13) "surface electromyography" AND rabbit

Inclusion criteria were full publications in English from 1990 to the present of studies which included animals and surface electromyography. Publications were considered from all research disciplines (e.g. basic science, applied and clinical biomechanics, veterinary science), however only studies where muscle activity was measured during the performance of an active voluntary movement or task were included, to make the findings informative to animal biomechanics, performance and rehabilitation. This is similar to the most common applications of sEMG in humans. Observational cross sectional studies, intervention studies, and case studies were considered. Abstracts from conference proceedings, studies which evoked a muscular contraction by stimulation in either an alert or anaesthetised animal, studies in humans, primates or aquatic animals, studies which only reported sEMG at rest, and studies where either intramuscular EMG or supramuscular/subcutaneous EMG via surgical implantation were used, were excluded. Review studies on electromyography were included initially for hand searching of the reference lists. For journals where the majority of

animal sEMG studies were identified, hand searching of the 'Articles in Press' sections was performed. These journals included the Equine Veterinary Journal, Comparative Exercise Physiology, the Veterinary Journal, the American Journal of Veterinary Research, and Veterinary Surgery.

2.2 Study Selection

After the initial database search, duplicates and conference proceedings were removed. For the remaining studies, each stage of study inclusion/exclusion was performed by two assessors independently, after which study eligibility was based on consensus agreement. The first stage was assessment of the studies by title, followed by the assessment of the abstracts. Full texts of the remaining studies were retrieved and read in full to determine final study eligibility. From the final list of included studies, the reference lists were read to allow hand-searching for additional literature. In addition, forward citation was used to identify any other eligible studies. An overview of the study selection process is shown in Figure 1.

2.3 Data collection

The following data were collected from the final set of included studies: (1) Species and breed (2) Task/activity (3) Muscles analysed (4) Electrode details (4.1) Type (4.2) Size (4.3) Inter-electrode distance (4.4) Description of location given (5) Rectification (6) Signal processing and filtering (7) Normalisation (8) sEMG parameters investigated (9) Study findings. Information on skin preparation methods and motion analysis techniques used alongside sEMG data collection was also collected.

To determine methodological quality of the studies, the checklist devised by Kmet et al. (2004) was adapted to suit an animal population. This approach was similar to that adopted in a systematic review by Martens et al (2015) where the checklist by Kmet et al. (2004) was adapted to suit their study population of swimmers. The original checklist by Kmet et al. (2004) contains a 14-item list for quantitative studies and a 10-item list for qualitative studies, which can be used to assess the quality of primary research. Based on this information, the following parameters were assessed in this systematic review on animal sEMG: (1) Is the context of the study clear? (2) Is there a connection to a theoretical framework/wider body of knowledge? (3) Is the study question/objective sufficiently described? (4) Is the study design stated and appropriate? (5) Is the method of subject selection described and appropriate? (6) Are subject characteristics adequately described? (6.1) Species and breed (6.2) Age (6.3) Body mass (7) Are data collection and methods clearly described and systematic? (7.1) sEMG application (7.2) sEMG processing (7.3) sEMG normalisation (8) Is data analysis clearly described and systematic? (9) Are the results reported in sufficient detail? (10) Is some estimate of variance reported for the main results? (11) Are the conclusions supported by the results?

Each study was evaluated independently by two assessors. The following scores were given based on the degree to which specific criteria were met ("yes"=2, "partial"=1, "no"=0 or "na"=not applicable). Upon completion of the individual evaluations of the assessors, results were discussed and the final scores given based on consensus agreement. Studies of any

methodological quality were included, therefore this scoring was performed only to indicate overall methodological quality of the studies included in the review. Scoring was not used to exclude studies from the review.

3 Results

3.1 Study selection

From the initial search, 1321 titles were identified. After removing duplicates and conference proceedings, 798 studies were further evaluated. The most common reason for exclusion of studies was due to humans, rather than animals, being studied. Reasons for excluding animal studies were the use of intramuscular EMG or lack of active movements being investigated. Hand searching at the final stage of the evaluation process enabled a further 11 studies to be included. Upon completion of the evaluation process, 38 studies were eligible for inclusion in the review. A detailed summary of the number of studies included at each stage of the evaluation process is shown in Figure 1.

3.2 Synthesis of the findings

Experimental and methodological details of each of the studies included in the review are presented in Table 1, and a summary of the findings for each category is presented below:

3.2.1 Animals and breeds—The majority of studies investigated horses (28/38), including a variety of breeds but primarily Thoroughbreds and Warmblood horses. Seven studies investigated dogs, which included a range of breeds. The remaining three studies were performed in cows (n=2) and sheep (n=1).

3.2.2 Activities—Studies investigating locomotion were most common (82% of total studies included). From these, 20 studies investigated locomotion on a treadmill, with walk and trot gaits investigated in horses, dogs and sheep, and the faster gaits of canter and gallop investigated in horses only. Twelve studies investigated locomotion overground but this was in horses and dogs only. The majority of these were walking and trotting in straight lines (n=9). Additional activities investigated during overground locomotion in horses included work on a circle (lungeing) or figure of eight (n=3) and ridden exercise (n=3) including jumping. One overground locomotion study was identified in dogs stepping over cavaletti. Of the seven studies which collected sEMG data during activities other than locomotion, two investigated chewing (horses and cows), one investigated stepping during standing (cows), one investigated dynamic neck exercises (horses) and three investigated myotatic reflexes (horses), where a blunt object run over the hindquarters induces the animal to perform active trunk flexion. The motion analysis techniques which were used synchronously with sEMG data collection are listed in Table 3.

3.2.3 Muscles investigated—From all 38 studies, a total of 31 different muscles were assessed, which included muscles of the limbs, trunk, head and neck. Figure 2 depicts the frequency that each muscle was investigated in all the studies combined. The muscle most commonly investigated was the longissimus dorsi (n=15), which was reported in horses, dogs and sheep.

3.2.4 Electrode type, placement and skin preparation—In seven studies, skin preparation was not described. In the remaining 31 studies, eight reported shaving only, seven reported shaving and cleaning, whereas in 11 studies, clipping and/or shaving and cleaning was described including the product that was used to clean the skin. In a further three studies, skin was clipped, shaved, cleaned and degreased, one used cleaning and water spray only, and one study clipped, shaved and cleaned the skin after which the skin was rubbed with electrical conduction-enhancing gel.

A total of 21 studies reported the type of electrodes used, and of these the majority were Ag/AgCl electrodes (90%). Of the two studies that used different types of electrodes, one used silver bar electrodes and one used felt pads. Electrode size was reported in 16 studies with circular electrodes 30mm (n=5) or 10mm (n=4) in diameter being the most common. The remaining seven studies used a wide selection of electrode shapes and sizes, ranging from circular (range 3 - 16mm diameter) to square or rectangular (20x7mm, 50x40mm and 101x101mm). Of the 24 studies which reported inter-electrode distance, 30mm was the most frequently used (n=8) although it ranged from 10mm to 50mm. In dogs only, this ranged from 10mm to 25mm. Information regarding the location of electrode placement had been described in the majority of the studies (n=33).

3.2.5 Normalisation procedures—Although in 15 studies normalisation was not deemed necessary due to their method of sEMG processing (e.g. frequency analysis), eight studies did not apply any method of normalisation where it would have been required. In the studies where normalisation was performed, the most common method was normalization to maximal muscle activity observed during the activity of interest (n=7). However, in two of these studies, all muscles were normalised to another muscle or location rather than the accepted method of normalising muscle activity within each individual muscle. Two studies normalised to mean muscle activity, one used the range of muscle activity, and one normalised to resting sEMG. The remaining four studies used a ratio approach, of which two used a ratio calculation within the same muscle, and two used ratios between muscles or muscle groups.

3.3 Methodological quality analysis

The results of the assessed parameters are presented in Table 2. The clarity of the study context, the connection to a theoretical framework and the objective of the study were fully described in all studies. The criteria for the statement and appropriateness of the study design was only fully met in three studies and partially in two studies, and the remainder of the studies (n=33) did not state their study design. The method of subject selection was described in one study and partially in nine studies, but in the majority (n=28) of the studies, this was not described. Basic information about the subjects, such as species and breed was present in most of the studies (n=26) and partially reported in the remainder (n=12). The age of the animals was documented in most studies (n=26) but not documented in twelve studies. For body mass these values were 24 and 14 respectively. The description of sEMG application was partially described in the majority of the studies (n=28), fully described in eight studies, and not described in two studies. The description of EMG processing was partially reported in the majority of the studies (n=26), fully reported in nine studies, and not

reported in three studies. The description of sEMG normalization was fully defined in 11 studies and partially defined in three studies however it was not defined in nine studies and was not applicable in 15 studies. The majority of the studies fully described their data analysis (n=34) and four described them only partially. The results were sufficiently reported in the majority of the studies (n=31) and partially in seven studies. The estimate of variance for the main results were present in 30 studies, partially reported in three studies and not reported in five studies. The final conclusions were expressed in 37 studies but this was omitted in one study.

4 Discussion

4.1 Species, breeds and activities

The earlier work on sEMG in animals in the 1990's performed by Janssen et al. (1992) and Cheung et al. (1998) investigated horses; this included a group of Thoroughbreds and a mixed group of ponies without any further details regarding breed given. These studies were pioneering, as prior to the work by Janssen et al. (1992), assessment of muscle activity in horses had only been performed using intramuscular EMG (e.g. Tokuriki and Aoki, 1991). Numerous other sEMG studies in horses were published thereafter, the majority of these using a range of breeds in their study populations. Although these studies were crucial in providing a foundation for the understanding of muscle function in horses during locomotion and they demonstrated the feasibility of using sEMG in this species, the lack of homogeneous population groups in often small study samples may have limited the robustness of the outcomes of some studies.

It was not until 2009 that the first studies in canine sEMG were published. Lauer et al. (2009) and Lister et al. (2009) conducted studies in hounds using sEMG for the purpose of investigating rehabilitative approaches. These were followed by further canine sEMG studies, some of which were conducted in single breed study populations (e.g. Beagles by Fischer et al., 2013), although the majority used mixed breeds of usually small sample sizes.

The interest in muscle function in horses and dogs is not surprising. Horses are commonly referred to large animal veterinary practices for orthopaedic conditions and lameness, and a host of surgical and non-surgical therapies are used for rehabilitative purposes. Non-surgical therapies include physiotherapeutic exercises that target specific muscle groups. Even though such exercises are often prescribed, they are generally adapted from human rehabilitation, with little scientific evidence of their effectiveness in an equine population. Although there is a growing body of knowledge on muscle activity and function in horses from locomotion studies (ridden and unriden) in healthy, non-lame animals, only one study has investigated horses with longissimus dorsi spasm (Wakeling et al., 2006), and another study investigated the effect of lameness on muscle activity in horses (Zaneb et al., 2009). Building on this existing knowledge, efforts should be made to investigate muscle activity beyond activities of locomotion and in addition, not only include healthy horses, but also continue to assess those with lameness or neuromuscular dysfunction. Stubbs and colleagues (2011) showed that simple neck and trunk dynamic mobilisation exercises performed five times a week for three months in healthy adult horses resulted in a significant increase in multifidus size. This demonstrates that muscle changes can indeed occur in equines

following a simple physiotherapeutic exercise protocol, but changes in muscle co-activation (or synergy) over time has not been investigated in this species using sEMG. However, Zsoldos and colleagues (2014) successfully reported co-activation of neck muscles in different age groups of horses in a cross-sectional study during simple range of motion exercises of the neck, which is similar to the exercises performed in the study by Stubbs et al. (2011).

In humans, sEMG is used to investigate muscle activity in a wide range of activities, including sustained and poor postures (O'Sullivan et al. 2002, Nelson-Wong et al. 2012). Although horses may not display the same range of postures and perform the same tasks as humans do, there are many conditions the modern horse is exposed to, which from an animal husbandry or welfare perspective, may have questionable effects on muscle function, and possibly musculoskeletal health. For example, one topic highly debated at present is a training method used in equestrianism that demands hyperflexion of the neck (i.e. Rollkur). Several studies have demonstrated the effects of head and neck posture on spinal and limb kinematics and ground reaction forces in ridden and unriden horses (Rhodin et al., 2009, 2005; Weishaupt et al., 2006), however only one study to date has reported on the influence of head and neck posture on neck muscle activity (Kienapfel et al., 2015). Going forward, future work on assessment of the neuromuscular system using sEMG can provide an evidence base for (or against) equestrian practices often based on tradition alone.

Similar to horses, dogs are commonly seen in veterinary practices for orthopaedic conditions, for which physiotherapeutic approaches are used in the rehabilitation process. Canine rehabilitation also has been based largely on rehabilitation practices used in humans, again with very little evidence regarding the efficacy of these exercises on muscle function in dogs. Although muscle function in dogs has been evaluated during locomotion in healthy animals in several studies (Bockstahler et al., 2009; Breidfuss et al., 2015; Fischer et al., 2013; Lauer et al. 2009; Lister et al. 2009), only two studies used sEMG to evaluate muscle activity in lame animals (Bockstahler et al., 2012; Fischer et al., 2013). To our knowledge, no sEMG studies in dogs exist which investigate tasks other than locomotion, and this poses a wealth of opportunities for investigations in muscle function in this species. Not only can this include acquiring an evidence-base for neuromuscular rehabilitation, it can also include investigations of the biomechanical demands placed on working dogs. For example, asymmetrical pressures measured under harnesses used on guide dogs (Peham et al. 2013) could lead to development of asymmetries in muscle activity and perhaps musculoskeletal pain and dysfunction. Therefore in both horses and dogs, numerous opportunities exist to further explore motor control using sEMG.

It is only more recently that species other than horses and dogs have been evaluated using sEMG. In 2014-2015, two studies in cows (Büchel et al., 2014; Rajapaksha et al., 2014), and one in sheep (Valentin and Licka, 2015) were published. Each of these studies included only one breed. It is considerably easier however to obtain such a homogeneous study population in these species due to these animals being bred for (meat) production, unlike horses and dogs. Both the studies in cows did not investigate locomotion, unlike the other species included in this review. One study in cows investigated chewing (Büchel et al. 2014), whereas the other evaluated pelvic limb activity during stationary stepping. It may be that

there are limitations to obtaining sEMG data during locomotion in cows due to difficulties getting cows to perform this task in a cooperative manner in a similar experimental environment as those used in horse and dog studies. Some authors have been successful in quantifying bovine kinematics during walk, although this was during free locomotion in a constrained walkway (Maertens et al., 2011; van Nuffel et al., 2015, 2013; Wheeler et al., 2013), with force plates (Skjoth et al., 2013) and video analysis (Flower et al. 2005, 2007; van Hertem et al., 2014). The only study in this review which investigated sheep, analysed walk and trot locomotion on a treadmill. Based on this and previous (non-EMG) studies (Tapper et al. 2008, 2006; Valentin et al. 2014), it is evident that sheep can be trained to walk and trot on a treadmill, which might suggest that sheep may also be trained to perform other tasks which could be investigated using sEMG. Therefore there certainly appears to be scope to develop sEMG in ruminants.

Very few studies included a description of the level of training or amount of free or controlled exercise. Similar to humans, the amount of exercise and training can influence muscle outcomes, including the force-producing abilities of individuals. For example, comparing sEMG data from a group of horses kept in small paddocks that are otherwise not exercised to a group of elite dressage horses will lead to erroneous results if their levels of training are not considered. Therefore it is imperative that future sEMG studies in animals include a description of the levels of exercise and type of housing (i.e. stable or large paddock) for their particular study group.

4.2 Muscles

The limb muscles were most commonly investigated in the animal sEMG studies included in this review, in particular in horses (Colborne et al., 1998; Crook et al., 2010; Harrision et al., 2012; Hodson-Tole et al., 2006; Jansen et al., 1992; Robert et al., 2002,2001a,2001b, 2000,1999; St.George and Williams, 2013; Williams et al., 2013; Wijnberg et al., 2009; Zaneb et al., 2009) and in dogs (Bockstahler et al., 2012, 2009; Breitfuss et al., 2015; Fischer et al., 2013; Garcia et al., 2014; Lauer et al., 2009; Lister et al., 2009). It may be that these muscles are most commonly investigated due to their role in locomotion, a task frequently investigated in animal sEMG studies. It may also be that these muscles can be investigated more reliably, for example origin and insertions are more easily defined compared to the large trunk muscles which are often complex and can have considerable aponeurotic insertions. Furthermore, skin displacement tends to be less in the limbs compared to the trunk, particularly in dogs.

From the trunk muscles, the long back muscle was the most frequently assessed. This muscle is often reactive on palpation in horses with thoracolumbar pain, and this may be associated with reductions in performance and undesirable behaviour, such as bucking during ridden work. Therefore, it is not surprising that this muscle has often been the main focus in equine sEMG studies (Cottriall et al. 2008; Licka et al., 2009, 2004; Peham et al., 2001; Peham and Schobesberger 2006; Wakeling et al., 2007, 2006;). The action of this muscle during locomotion has been frequently reported, but only one study described the activity of this muscle in horses with longissimus spasm (Wakeling et al., 2006). However, further work on better understanding the functionality of this muscle in horses with back

pain is needed, as it could help improve diagnostics and therapeutic interventions for horses with thoracolumbar pain. The long back muscle in animals is analogous with that in humans, and there is a wealth of studies available on this muscle in people with low back pain. The literature on (dys)function of this and other trunk muscles in humans has included investigations into a range of activities and conditions including isometric tasks (Ekstrom et al., 2008), quasi-static tasks (Hodges et al. 2009), and dynamic tasks (Oliveira et al., 2013), whereas in horses investigations of this muscle are primarily limited to locomotion. Furthermore, advanced analysis of sEMG from multiple trunk and limb muscles has allowed assessment of muscle synergies in humans, and although such an approach has been applied previously in hind limb muscles of cats (Drew et al. 2008; Ting and Macpherson, 2005), such an approach has, as yet, not been applied in horses or dogs. However, the knowledge gained from locomotion studies in animals using sEMG has been instrumental in establishing a core understanding of many trunk and limb muscles for future studies to build upon using similar approaches used in humans. Moreover, modeling of the dog (Brown et al., 2013; Fu et al., 2010; Headrick et al., 2014) and horse limbs (Harrison et al., 2012, 2010) and spine (Grösel et al., 2010; Zsoldos et al., 2010c) is a continually developing field, and muscle parameters are crucial to improve the efficacy of such models, for which sEMG is imperative.

A further reason why the long back muscle and other trunk muscles are of interest in animals, is that knowledge of the functioning of these muscles can assist in developing a better understanding of spinal stabilisation mechanisms in quadrupeds (Valentin and Licka 2015). This has several benefits, not only to evaluate to which extent animals are suitable orthopaedic models for the human spine, but also perhaps to further develop quadrupedal robotics (Mariti et al., 2015).

4.3 Electrode type, placement and skin preparation

In the present review, most of the studies included used Ag/AgCl electrodes which were part of a wired system. However, similar to human sEMG research, wireless devices are very popular and are increasingly being used in animal studies, as indicated by several studies included in this review (e.g. Büchel et al., 2014; Garcia et al., 2014; St George et al., 2013; Valentin and Licka, 2015; Williams et al., 2014, 2013). Such wireless systems have considerably broadened the scope of sEMG applications.

Due to the art of sEMG measurements, appropriate skin preparation is crucial; in the present review these necessary steps were not always fully and clearly described. Some studies did not report skin preparation at all, whereas other reported shaving only or shaving and cleaning the skin. Others were more detailed and included a description of the solutions used for skin cleaning and degreasing. Similarly, the description of electrode placement was also frequently vague, often lacking details such as whether electrodes were placed along the muscle fibre direction. It is particularly crucial in animal sEMG studies that exact electrode locations are described, as muscles are often very large leading to potentially huge discrepancies between studies. For example, electrode placement over the biceps femoris muscle was either over the cranial aspect (n=3), caudal aspect (n=2), or not defined (n=3). Furthermore, electrodes placed over innervation zones will lead to a considerable reduction

in signal amplitude (Beck et al., 2008) and for this reason, electrodes should not be placed over these sites (Mesin et al., 2009). Innervation zones can be identified using array sEMG, a technique which is increasingly being used in humans. To our knowledge, this approach has not been used in an animal population. However, a surgically implanted 16-electrode supramuscular array EMG has been used to measure triceps brachii muscle activity during treadmill running in rats previously (Schumann et al. 2002). Although this uses an invasive approach, it nonetheless demonstrates the potential of array EMG in an animal model during a dynamic task. Building on this, using surface array methods similar to those used in humans will not only assist in the standardisation of electrode placement through the identification of innervation zones in animal muscles, it will also allow more advanced assessment of the spatial distribution patterns in muscle activation in animals.

A range of electrode sizes and shapes were used in the studies included in this review, although it was not routinely reported in all studies. The use of different shapes and sizes is not uncommon in sEMG studies, as a review by Hermens et al. (2000) on sEMG practices in humans reported a similar large variation in electrode sizes used across studies. In that review, the most commonly used electrode diameter was 10mm, and other commonly used sizes ranged from 5-8mm. Although the second most commonly used electrode diameter in this systematic review was 10mm, many studies used larger electrode sizes, i.e. the most common size was 30mm. However, electrode size has been shown to have little effect on detection depth, based on findings from a mathematical model (Fuglevand et al., 1992). The SENIAM guidelines recommend electrode sizes of 10mm when positioned along the direction of the muscle fibres for all muscles except the adductor pollicis brevis; there maximal electrode sizes are 5 and 2mm for isometric and dynamic contractions respectively. Therefore, perhaps future sEMG studies in animals should similarly adopt standard electrode sizes to improve coherence between studies, although the most suitable electrode size is influenced by muscle size and should therefore be species- and perhaps breed-specific. Resultant standardisations will allow an adequate area of muscle to be evaluated whilst reducing cross-talk.

The distance between electrodes is one of the most important factors for the amount of cross-talk from other muscles that is contained within the sEMG signal (De Luca et al., 2012). However, information on inter-electrode distance was not always presented in the studies included in this systematic review. Where this was reported, a wide range of distances were used. In horses, only one muscle (rectus abdominis) was assessed using the same inter-electrode distance as that in two other studies from different research groups (Robert et al., 2001b; Zsoldos et al., 2010b). The muscles gluteus medius and tensor fascia lata were assessed using the same inter-electrode distance in two studies (Robert et al., 2000, 1999), as was longissimus dorsi (Grösel et al., 2010; Licka et al., 2009), but this was performed by the same research groups in each case. Similarly in dogs, three muscles (biceps femoris, vastus lateralis and gluteus medius) were investigated using the same inter-electrode distance of 10mm in two studies each (Bockstahler et al., 2012, 2009; Breitfuss et al., 2015), although these studies also were all performed by the same research group. Studies from other research groups investigating those muscles in dogs used an inter-electrode distance of double the distance or more (Fischer et al., 2013; Lauer et al., 2009). In humans, the recommended inter-electrode distance using bipolar sEMG electrodes for all

trunk, upper and lower limb muscles included in the SENIAM guidelines is 20mm except for the abductor pollicis brevis muscle in the hand (SENIAM). An inter-electrode distance of 20mm may not be suitable in animal studies however, as particularly in horses, muscles are considerably larger and may experience different levels of cross talk compared to similar muscles in humans. Even though there is a lack of consensus between studies on inter-electrode distance in animal sEMG studies, a similar lack of consensus also existed in human sEMG for many muscles (Hermens et al., 2000) until recently. It is only in the last few years that further work on determining the most appropriate inter-electrode distances has been suggested, for example that based on isometric and dynamic contractions of the tibialis anterior muscle in humans (De Luca et al., 2012). Utilising a similar approach in animals to determine the most suitable inter-electrode distance for a wide range of muscles is recommended.

4.4 Normalisation procedures

In human EMG research, one of the biggest challenges is how data from muscles are normalised (Burden, 2010). There are several options available however selection of a particular method is strongly dependent on the actual study design and research question. The normalisation techniques adopted in the studies included in this systematic review were varied or in some cases not performed. One of the limitations of the nature of working with animals is that true isometric MVC measurement is not possible. However, attempts should be made to normalise sEMG data to allow meaningful conclusions to be obtained and for studies to be compared. Where normalisation was performed in the studies in this review, the most commonly reported method was to normalise to a maximum value, although this was generally a dynamic maximum rather than an isometric maximum. Normalising to a maximal value other than an MVC has also been used in human populations where obtaining an MVC may not be possible or inaccurate, for example in people with low back pain (Dankaerts et al., 2004; Nelson-Wong et al., 2013).

One of the challenges that sEMG in animals faces, is to identify the most suitable normalization methodology for different exercises and dynamic conditions. To allow the reliability of proposed sEMG normalisation measures in animals to be quantified, inter-and intra-individual variability in addition to within-and between-day variability should be evaluated in a range of animal species in the future. A similar approach has been used in humans, where reliability of different EMG normalisation methods have been reported in experimental conditions (Dankaerts et al., 2004), and have been summarised in a systematic review (Burden 2010).

4.5 Further considerations

Dynamic tasks are the preferred condition for sEMG measurements in animals, due to the difficulty in getting animals to perform an isometric task as stated earlier. A limitation of dynamic contractions is that they experience greater motion artefacts contaminating the sEMG signal, which is due to motion of the electrode relative to the muscle during the contraction (Farina 2006; De Luca et al. 2010), changes in the conductivity property of the tissues (Farina 2006) and from the electrode cable in wired systems (Reaz et al., 2006). Although this is unavoidable during data collection of dynamic contractions, signal

processing methods can be used to minimise this. For example, a corner frequency of a 20Hz high pass filter has been recommended to remove such motion artefacts in humans (De Luca et al. 2010; Clancy et al. 2002). The studies included in the present review used a wide range of signal processing methods, including low, high and band pass filtering, wavelet and Fourier analysis, integration, root mean square and moving average approaches. However, very few studies used high pass filtering similar to that recommended from the human literature to filter motion artefacts. Although there are many possibilities to process EMG signals and the research question and study methodology are imperative to selecting a suitable processing approach, future animal sEMG studies should consider the inclusion of high pass filtering to minimise signal noise from motion artefacts.

In this review, sEMG only, rather than intramuscular applications in addition, was considered as this approach is more widely used in humans. Although intramuscular EMG has been used successfully in animals (Tokuriki and Aoki, 1991, Wijnberg et al. 2002), the non-invasive nature of sEMG is of considerable benefit for many biomechanical applications. sEMG however is limited to the evaluation of superficial muscles only and is more prone to cross-talk unlike intramuscular EMG. Perhaps for these reasons, smaller quadrupeds such as cats and small dogs may be more suited to intramuscular sEMG, in particular because their skin-muscle interface is fairly mobile. However, the horse with its greater size and reduced skin mobility is probably less affected by cross-talk and motion artefacts in comparison, therefore making it very suited to sEMG of the superficial musculature.

5 Conclusions

This systematic review is the first to report on sEMG in animals. Existing literature in this field has highlighted the feasibility of the technique in species other than humans, and early work has shown the potential for future research to build upon what is currently known. However, animal sEMG is to some extent still in its infancy compared to sEMG work in humans. As such, some aspects of sEMG in animals are not yet adequately reported and a considerable lack of standardisation exists amongst studies in sEMG protocols. Future work should address this by standards being devised in animals similar to those developed for humans (SENIAM guidelines), to allow best methodological practices to be determined.

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References

- Beck TW, Housh TJ, Cramer JT, Mielke M, Hendrix R. The influence of electrode shift over the innervation zone and normalization on the electromyographic amplitude and mean power frequency versus isometric torque relationships for the vastus medialis muscle. *J Neurosci Meth.* 2008; 169(1): 100–108.
- Bockstahler B, Kraeutler C, Holler P, Kotschwar A, Vobornik A, Peham C. Pelvic Limb Kinematics and Surface Electromyography of the Vastus Lateralis, Biceps Femoris, and Gluteus Medius Muscle in Dogs with Hip Osteoarthritis. *Vet Surg.* 2012; 41(1):54–62. [PubMed: 22188303]

- Bockstahler BB, Gesky R, Mueller M, Thalhammer JG, Peham C, Podbregar I. Correlation of surface electromyography of the vastus lateralis muscle in dogs at a walk with joint kinematics and ground reaction forces. *Vet Surg.* 2009; 38(6):754–761. [PubMed: 19674419]
- Breitfuss K, Franz M, Peham C, Bockstahler B. Surface Electromyography of the Vastus Lateralis, Biceps Femoris, and Gluteus Medius Muscle in Sound Dogs During Walking and Specific Physiotherapeutic Exercises. *Vet Surg.* 2014; 44(5):588–595. [PubMed: 25328985]
- Brown NP, Bertocci GE, Marcellin-Little DJ. Development of a canine stifle computer model to evaluate cranial cruciate ligament deficiency. *J Mech Med Biol.* 2013; 13(2):1350043.
- Büchel S, Sundrum A. Evaluation of a new system for measuring feeding behavior of dairy cows. *Comput Electro Agr.* 2014; 108:12–16.
- Burden A. How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *J Electromyogr Kines.* 2010; 20(6):1023–1035.
- Castelein B, Cools A, Bostyn E, Delemarre J, Lemahieu T, Cagnie B. Analysis of scapular muscle EMG activity in patients with idiopathic neck pain: A systematic review. *J Electromyogr Kines.* 2015; 25(2):371–386.
- Cheung TK, Warren LK, Lawrence LM, Thompson KN. Electromyographic activity of the long digital extensor muscle in the exercising Thoroughbred horse. *Equine Vet J.* 1998; 30(3):251–255. [PubMed: 9622327]
- Clancy EA, Morin EL, Merletti R. Sampling, noise-reduction and amplitude estimation issues in surface electromyography. *J Electromyogr Kines.* 2002; 12(1):1–16.
- Colborne GR, Birtles DM, Cacchione IC. Electromyographic and kinematic indicators of fatigue in horses: a pilot study. *Equine Vet J.* 2001; S33:89–93.
- Cottrill S, Ritruethai P, Wakeling J. The effects of training aids on the longissimus dorsi in the equine back. *Comp Exerc Physiol.* 2008; 5(3–4):111–114.
- Crook TC, Wilson A, Hodson-Tole E. The effect of treadmill speed and gradient on equine hindlimb muscle activity. *Equine Vet J.* 2010; 42(S38):412–416. [PubMed: 20636777]
- Cuesta-Vargas AI, González-Sánchez M. Differences in Muscle Activation Patterns during Sit to Stand Task among Subjects with and without Intellectual Disability. *Biomed Res Intl.* 2013 Article ID 173148.
- Dankaerts W, O'Sullivan PB, Burnett AF, Straker LM, Danneels LA. Reliability of EMG measurements for trunk muscles during maximal and sub-maximal voluntary isometric contractions in healthy controls and CLBP patients. *J Electromyogr Kines.* 2004; 14(3):333–342.
- de Luca CJ, Kuznetsov M, Gilmore LD, Roy SH. Inter-electrode spacing of surface EMG sensors: reduction of crosstalk contamination during voluntary contractions. *J Biomech.* 2012; 45(3):555–561. [PubMed: 22169134]
- de Luca CJ, Gilmore LD, Kuznetsov M, Roy SH. Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *J Biomech.* 2010; 43(8):1573–1579. [PubMed: 20206934]
- Drew T, Kalaska J, Krouchev N. Muscle synergies during locomotion in the cat: a model for motor cortex control. *J Physiol.* 2008; 586(5):1239–1245. [PubMed: 18202098]
- Ekstrom RA, Osborn RW, Hauer PL. Surface electromyographic analysis of the low back muscles during rehabilitation exercises. *J Orthop Sport Phys.* 2008; 38(12):736–745.
- Farina D. Interpretation of the surface electromyogram in dynamic contractions. *Exerc Sport Sci Rev.* 2006; 34(3):121–127. [PubMed: 16829739]
- Falla D, Gizzi L, Tschapek M, Erlenwein J, Petzke F. Reduced task-induced variations in the distribution of activity across back muscle regions in individuals with low back pain. *Pain.* 2014; 155(5):944–953. [PubMed: 24502841]
- Fischer S, Nolte I, Schilling N. Adaptations in muscle activity to induced, short-term hindlimb lameness in trotting dogs. *PLoS One.* 2013; 8(11):e80987. [PubMed: 24236207]
- Flower FC, De Passillé AM, Weary DM, Sanderson DJ, Rushen J. Softer, higher-friction flooring improves gait of cows with and without sole ulcers. *J Dairy Sci.* 2007; 90(3):1235–1242. [PubMed: 17297100]
- Flower FC, Sanderson DJ, Weary DM. Hoof pathologies influence kinematic measures of dairy cow gait. *J Dairy Sci.* 2005; 88(9):3166–3173. [PubMed: 16107407]

- Fu YC, Torres BT, Budsberg SC. Evaluation of a three-dimensional kinematic model for canine gait analysis. *Am J Vet Res.* 2010; 71(10):1118–1122. [PubMed: 20919895]
- Fuglevand AJ, Winter DA, Patla AE, Stashuk D. Detection of motor unit action potentials with surface electrodes: influence of electrode size and spacing. *Biol Cybern.* 1992; 67(2):143–153. [PubMed: 1627684]
- Garcia TC, Sturges BK, Stover SM, Aoki K, Liang JM, Reinhardt KB, Kapatkin AS. Forelimb brachial muscle activation patterns using surface electromyography and their relationship to kinematics in normal dogs walking and trotting. *Comp Exerc Physiol.* 2014; 10(1):13–22.
- Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L. Gait and neuromuscular asymmetries after acute ACL rupture. *Med Sci Sport Exer.* 2012; 44(8):1490–1496.
- Groesel M, Zsoldos RR, Kotschwar A, Gfoehler M, Peham C. A preliminary model study of the equine back including activity of longissimus dorsi muscle. *Equine Vet J.* 2010; 42(S38):401–406.
- Harrison SM, Whitton RC, King M, Haussler KK, Kawcak CE, Stover SM, Pandy MG. Forelimb muscle activity during equine locomotion. *J Exp Biol.* 2012; 215(17):2980–2991. [PubMed: 22875767]
- Harrison SM, Whitton RC, Kawcak CE, Stover SM, Pandy MG. Relationship between muscle forces, joint loading and utilization of elastic strain energy in equine locomotion. *J Exp Biol.* 2010; 213(23):3998–4009. [PubMed: 21075941]
- Headrick JF, Zhang S, Millard RP, Rohrbach BW, Weigel JP, Millis DL. Use of an inverse dynamics method to describe the motion of the canine pelvic limb in three dimensions. *Am J Vet Res.* 2014; 75(6):544–553. [PubMed: 24866510]
- Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kines.* 2000; 10(5):361–374.
- Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg G. European recommendations for surface electromyography. *Roessingh Research and Development.* 1999; 8:13–54.
- Hodges P, van den Hoorn W, Dawson A, Cholewicki J. Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. *J Biomech.* 2009; 42(1):61–66. [PubMed: 19062020]
- Hodson-Tole E. Effects of treadmill inclination and speed on forelimb muscle activity and kinematics in the horse. *Equine and Comp Exerc Physiol.* 2006; 3(2):61–72.
- Iida Y, Kanehisa H, Inaba Y, Nakazawa K. Role of the coordinated activities of trunk and lower limb muscles during the landing-to-jump movement. *Eur J Appl Physiol.* 2012; 112(6):2223–2232. [PubMed: 21997678]
- Jansen MO, van Raaij JAGM, van den Bogert AJ, Schamhardt HC, Hartman W. Quantitative analysis of computer-averaged electromyographic profiles of intrinsic limb muscles in ponies at the walk. *Am J Vet Res.* 1992; 53(12):2343–2349. [PubMed: 1476320]
- Kavic N, Grenier S, McGill SM. Determining the stabilizing role of individual torso muscles during rehabilitation exercises. *Spine.* 2004; 29(11):1254–1265. [PubMed: 15167666]
- Kienapfel K. The effect of three different head-neck positions on the average EMG activity of three important neck muscles in the horse. *J Anim Physiol An N.* 2015; 99(1):132–138.
- Kmet LM, Lee RC, Cook LS. Standard quality assessment criteria for evaluating primary research studies from a variety of fields. *Alberta Heritage Foundation for Medical Research.* 2004
- Lauer SK, Hillman RB, Li L, Hosgood GL. Effects of treadmill inclination on electromyographic activity and hind limb kinematics in healthy hounds at a walk. *Am J Vet Res.* 2009; 70(5):658–664. [PubMed: 19405906]
- Lee AY, Kim EH, Cho YW, Kwon SO, Son SM, Ahn SH. Effects of Abdominal Hollowing During Stair Climbing on the Activations of Local Trunk Stabilizing Muscles: A Cross-Sectional Study. *Ann Rehab Med.* 2013; 37(6):804–813.
- Licka T, Frey A, Peham C. Electromyographic activity of the longissimus dorsi muscles in horses when walking on a treadmill. *Vet J.* 2009; 180(1):71–76. [PubMed: 18314362]
- Licka TF, Peham C, Frey A. Electromyographic activity of the longissimus dorsi muscles in horses during trotting on a treadmill. *Am J Vet Res.* 2004; 65(2):155–158. [PubMed: 14974571]

- Lister SA, Renberg WC, Roush JK. Efficacy of immobilization of the tarsal joint to alleviate strain on the common calcaneal tendon in dogs. *Am J Vet Res.* 2009; 70(1):134–140. [PubMed: 19119959]
- Maertens W, Vangeyte J, Baert J, Jantuan A, Mertens KC, De Campeneere S, Pluk A, Opsomer G, van Weyenberg S, van Nuffel A. Development of a real time cow gait tracking and analysing tool to assess lameness using a pressure sensitive walkway: the GAITWISE system. *Biosyst Eng.* 2011; 110(1):29–39.
- Mariti C, Muscolo GG, Peters J, Puig D, Recchiuto CT, Sighieri C, Solanas A, von Stryk O. Developing biorobotics for veterinary research into cat movements. *J Vet Behav.* 2015; 10(3):248–254.
- Martens J, Figueiredo P, Daly D. Electromyography in the four competitive swimming strokes: A systematic review. *J Electromyogr Kines.* 2015; 25(2):273–291.
- Mesin L, Merletti R, Rainoldi A. Surface EMG: the issue of electrode location. *J Electromyogr Kines.* 2009; 19(5):719–726.
- Nelson-Wong E, Alex B, Csepe D, Lancaster D, Callaghan JP. Altered muscle recruitment during extension from trunk flexion in low back pain developers. *Clin Biomech.* 2012; 27(10):994–998.
- Oliveira AS, Silva PB, Lund ME, Gizzi L, Farina D, Kersting UG. Effects of perturbations to balance on neuromechanics of fast changes in direction during locomotion. *Plos one.* 2013; 8(3):e59029. [PubMed: 23527079]
- O'Sullivan PB, Grahamslaw KM, Kendell M, Lapenskie SC, Möller NE, Richards KV. The effect of different standing and sitting postures on trunk muscle activity in a pain-free population. *Spine.* 2002; 27(11):1238–1244. [PubMed: 12045525]
- Park HJ, Oh DW, Kim SY. Effects of integrating hip movements into bridge exercises on electromyographic activities of selected trunk muscles in healthy individuals. *Manual Ther.* 2014; 19(3):246–251.
- Peaham C, Limbeck S, Galla K, Bockstahler B. Pressure distribution under three different types of harnesses used for guide dogs. *Vet J.* 2013; 198(S1):e93–e98. [PubMed: 24360734]
- Peaham C, Schobesberger H. A novel method to estimate the stiffness of the equine back. *J Biomech.* 2006; 39(15):2845–2849. [PubMed: 16288761]
- Peaham C, Frey A, Licka T, Scheidl M. Evaluation of the EMG activity of the long back muscle during induced back movements at stance. *Equine Vet J.* 2001; S33:165–168.
- Reaz MBI, Hussain MS, Mohd-Yasin F. Techniques of EMG signal analysis: detection, processing, classification and applications. *Biol proced online.* 2006; 8(1):11–35. [PubMed: 16799694]
- Rajapaksha E, Tucker CB. How do cattle respond to sloped floors? An investigation using behavior and electromyograms. *J Dairy Sci.* 2014; 97(5):2808–2815. [PubMed: 24612809]
- Rhodin M, Gomez Alvarez CG, Bystrom A, Johnston C, van Weeren PR, Roepstorff L, Weishaupt MA. The effect of different head and neck positions on the caudal back and hindlimb kinematics in the elite dressage horse at trot. *Equine Vet J.* 2009; 41(3):274–279. [PubMed: 19469235]
- Rhodin M, Johnston C, Holm KR, Wennerstrand J, Drevemo S. The influence of head and neck position on kinematics of the back in riding horses at the walk and trot. *Equine Vet J.* 2005; 37(1):7–11. [PubMed: 15651727]
- Robert C, Valette JP, Pourcelot P, Audigie F, Denoix JM. Effects of trotting speed on muscle activity and kinematics in saddlehorses. *Equine Vet J.* 2002; (S34):295–301.
- Robert C, Audigie F, Valette JP, Pourcelot P, Denoix JM. Effects of treadmill speed on the mechanics of the back in the trotting saddlehorse. *Equine Vet J.* 2001; (S33):154–159.
- Robert C, Valette JP, Denoix JM. The effects of treadmill inclination and speed on the activity of three trunk muscles in the trotting horse. *Equine Vet J.* 2001; 33(5):466–472. [PubMed: 11558741]
- Robert C, Valette JP, Denoix JM. The effects of treadmill inclination and speed on the activity of two hindlimb muscles in the trotting horse. *Equine Vet J.* 2000; 32(4):312–317. [PubMed: 10952380]
- Robert C, Valette JP, Degueurce C, Denoix JM. Correlation between surface electromyography and kinematics of the hindlimb of horses at trot on a treadmill. *Cells Tissues Organs.* 1999; 165(2):113–122. [PubMed: 10516424]
- Schumann NP, Biedermann FH, Kleine BU, Stegeman DF, Roeleveld K, Hackert R, Scholle HC. Multi-channel EMG of the M. triceps brachii in rats during treadmill locomotion. *Clin Neurophysiol.* 2002; 113(7):1142–1151. [PubMed: 12088711]

- Serner A, Jakobsen MD, Andersen LL, Hölmich P, Sundstrup E, Thorborg K. EMG evaluation of hip adduction exercises for soccer players: implications for exercise selection in prevention and treatment of groin injuries. *Brit J Sport Med.* 2014; 48(14):1108–14.
- Skjoth F, Thorup VM, do Nascimento OF, Ingvarsen KL, Rasmussen MD, Voigt M. Computerized identification and classification of stance phases as made by front or hind feet of walking cows based on 3-dimensional ground reaction forces. *Comput Electron Agr.* 2013; 90:7–13.
- George L, Williams JM. Electromyographic evaluation of approach stride, jump stride and intermediate stride in selected superficial muscles of the jumping horse: a preliminary study. *Comp Exerc Physiol.* 2013; 9(1):23–32.
- Stubbs NC, Kaiser LJ, Hauptman J, Clayton HM. Dynamic mobilisation exercises increase cross sectional area of musculus multifidus. *Equine Vet J.* 2011; 43(5):522–529. [PubMed: 21496085]
- Tapper JE, Fukushima S, Azuma H, Sutherland C, Marchuk L, Thornton GM, Ronsky JL, Zernicke R, Shrive NG, Frank CB. Dynamic in vivo three-dimensional (3D) kinematics of the anterior cruciate ligament/medial collateral ligament transected ovine stifle joint. *J Orthop Res.* 2008; 26(5):660–672. [PubMed: 18176943]
- Tapper JE, Fukushima S, Azuma H, Thornton GM, Ronsky JL, Shrive NG, Frank CB. Dynamic in vivo kinematics of the intact ovine stifle joint. *J Orthop Res.* 2006; 24(4):782–792. [PubMed: 16514638]
- Ting LH, Macpherson JM. A limited set of muscle synergies for force control during a postural task. *J Neurophysiol.* 2005; 93(1):609–613. [PubMed: 15342720]
- Tokuriki M, Ohtsuki R, Kai M, Hiraga A, Oki H, Miyahara Y, Aoki O. EMG activity of the muscles of the neck and forelimbs during different forms of locomotion. *Equine Vet J.* 1999; (S30):231–234.
- Tokuriki M, Aoki O. Neck muscles activity in horses during locomotion with and without a rider. *Equine Exerc Physiol.* 1991; 3:146–150.
- Valentin S, Licka TF. Comparative need for spinal stabilisation between quadrupedal and bipedal locomotion. *Comp Exerc Physiol.* 2015; 11(2):95–105.
- Valentin S, Essigbeck A, Wolfram I, Licka T. Kinematic parameters of sheep walking on a treadmill. *Vet J.* 2014; 202(3):657–658. [PubMed: 25457259]
- van der Hulst M, Vollenbroek-Hutten MM, Rietman JS, Hermens HJ. Lumbar and abdominal muscle activity during walking in subjects with chronic low back pain: Support of the “guarding” hypothesis? *J Electromyogr Kines.* 2010; 20(1):31–38.
- van Hertem T, Viazzi S, Steensels M, Maltz E, Antler A, Alchanatis V, Schlageter-Tello AA, Lokhorst K, Romanini ECB, Bahr C, Berckmans D, et al. Automatic lameness detection based on consecutive 3D-video recordings. *Biosyst Eng.* 2014; 119:108–116.
- van Nuffel A, Saeys W, Sonck B, Vangeyte J, Mertens KC, De Ketelaere B, van Weyenberg S. Variables of gait inconsistency outperform basic gait Variables in detecting mildly lame cows. *Livest Sci.* 2015; 177:125–131.
- van Nuffel A, Vangeyte J, Mertens KC, Pluym L, De Campeneere S, Saeys W, Opsomer G, van Weyenberg S. Exploration of measurement variation of gait variables for early lameness detection in cattle using the GAITWISE. *Livest Sci.* 2013; 156:88–95.
- van Weeren R. Equine biomechanics: From an adjunct of art to a science in its own right. *Equine Vet J.* 2012; 44(5):506–508. [PubMed: 22888771]
- Wakeling JM, Rittruechai P, Dalton S, Nankervis K. Segmental variation in the activity and function of the equine longissimus dorsi muscle during walk and trot. *Equine Comp Exerc Physiol.* 2007; 4(2):95–103.
- Wakeling JM, Barnett K, Price S, Nankervis K. Effects of manipulative therapy on the longissimus dorsi in the equine back. *Equine Comp Exerc Physiol.* 2006; 3(3):153–160.
- Weishaupt MA, Wiestner T, von Peinen K, Waldern N, Roepstorff L, van Weeren R, Meyer H, Johnston C. Effect of head and neck position on vertical ground reaction forces and interlimb coordination in the dressage horse ridden at walk and trot on a treadmill. *Equine Vet J.* 2006; 38(S36):387–392.
- Wheeler CA, White BJ, Anderson D, Amrine DE, Larson RL. Assessment of biometric tools for quantitative gait analysis in Holstein calves. *Am J Vet Res.* 2013; 74(119):1443–1449. [PubMed: 24168311]

- Wijnberg ID, Schrama SE, Elgersma AE, Maree JT, de Cocq P, Back W. Quantification of surface EMG signals to monitor the effect of a Botox treatment in six healthy ponies and two horses with stringhalt: preliminary study. *Equine Vet J.* 2009; 41(3):313–318. [PubMed: 19469243]
- Wijnberg ID, Franssen H, van der Kolk JH, Breunink HJ. Quantitative motor unit action potential analysis of skeletal muscles in the Warmblood horse. *Equine Vet J.* 2002; 34(6):556–561. [PubMed: 12357994]
- Williams JM, Johnson C, Bales R, Lloyd G, Barron L, Quest D. Analysis of Temporalis and Masseter adaptation after routine dental treatment in the horse via surface electromyography. *Comp Exerc Physiol.* 2014; 10(4):223–232.
- Williams J, Gundry P, Richards J, Protheroe L. A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. *Vet Nurs.* 2013; 4(9):566–572.
- Zaneb H, Kaufmann V, Stanek C, Peham C, Licka TF. Quantitative differences in activities of back and pelvic limb muscles during walking and trotting between chronically lame and nonlame horses. *Am J Vet Res.* 2009; 70(9):1129–1134. [PubMed: 19719429]
- Zsoldos RR, Krüger B, Licka TF. From maturity to old age: tasks of daily life require a different muscle use in horses. *Comp Exerc Physiol.* 2014; 10(2):75–88. [PubMed: 28680481]
- Zsoldos RR, Kotschwar AB, Kotschwar A, Groesel M, Licka T, Peham C. Electromyography activity of the equine splenius muscle and neck kinematics during walk and trot on the treadmill. *Equine Vet J.* 2010a; 42(S38):455–461.
- Zsoldos RR, Kotschwar A, Kotschwar AB, Rodriguez CP, Peham C, Licka T. Activity of the equine rectus abdominis and oblique external abdominal muscles measured by surface EMG during walk and trot on the treadmill. *Equine Vet J.* 2010b; 42(S38):523–529.
- Zsoldos RR, Groesel M, Kotschwar A, Kotschwar AB, Licka T, Peham C. A preliminary modelling study on the equine cervical spine with inverse kinematics at walk. *Equine Vet J.* 2010c; 42(S38): 516–522.

Figure 1.
Flow chart of the systematic literature search

Relative frequency of muscles studies in animal sEMG reaserch

Figure 2.
Frequency of reported muscles studied in animal surface electromyography studies

Table 1

Overview of all included animal surface electromyography studies. BB = Biceps, BC = Brachiocephalic, BF = Biceps femoris , BR = Brachialis , CDE = Common digital extensor, CM = Cleidomastoid, DDF = Deep digital flexor , DE = Deltoid, ECR = Extensor carpi radialis, EDL = Long digital extensor, FCR = Flexor carpi radialis, FCU = Flexor carpi ulnaris, GA = Gastrocnemius, GM = Gluteus medius, IS = Infraspinatus, LD = Longissimus dorsi, LDL = Lateral digital extensor, MA = Masseter, OE = external oblique, OI = internal oblique, OMO = Omotraversarius, RA = Rectus abdominus, SPL = Splenius, SM = semimembranosus, ST = Semitendinosus, TB = Triceps brachialis, TC = Cranial tibial, TE = Temporalis, TFL = Tensor fasciae latae , TRA = Trapezius , UL = Ulnaris lateralis , VL = Vastus lateralis.

Authors	Species and details	Task / activity	Muscles analysed	Electrode details and preparation				Rectification	Signal processing and filtering	Normalisation	sEMG parameters investigated	Study findings
				Type	Size	Inter-electrode distance	Description of location given					
(1) Bockstahler et al (2012)	10 dogs with hip OA and 7 healthy dogs (different breeds)	walking over-ground	BF, GM, VL	Ag/AgCl		1 cm	Yes	rectified	4Hz Low pass BW filter	Maximal activity, task not specified	For different motion cycle phases: max (peak), min, mean and peak occurrence	Lower min and mean sEMG of VL and BF and mean of GM during the early swing phase in lame dogs.
(2) Bockstahler et al (2009)	11 dogs (Malinois breed)	Treadmill walking	VL	Ag/AgCl	30mm diameter	1 cm	yes	rectified	4Hz Low pass BW filter	Range (max-min = 100%), task not specified	For different motion cycle phases: max (peak), min, mean, and peak occurrence	Two peaks identified (early stance and late stance) and min occurred during early swing phase. Positive correlation with GRF Significant correlations (positive or negative depending on part of the motion cycle) between VL and hip and stifle angle
(3) Breiffuss et al (2015)	10 dogs (different breeds)	Uphill, downhill walking, cavaletti	BF, GM, VL			1 cm	yes	Full-wave rectified	Low pass filtered Resampled to 100Hz		Min, Max, mean	Differences between incline and decline walking Greater VL and GM activity during cavaletti and incline walking
(4) Büchel (2014)	14 dairy cows (Holstein Friesians	chewing	MA								Signal amplitude to identify jaw movement	EMG compared to visual observation – good agreement was found
(5) Cheung et al (1998)	8 horses (Thoroughbred breed)	Treadmill walk and trot pre- and post-fatigue	EDL	Ag/AgCl	7mm	2 cm	yes		40Hz high pass RMS of 5-7 sEMG bursts in 8s of walk and trot separately	Ratio of RMS values	Mean RMS and ratios of fatigued to unfatigued	Greater activity at trot compared to walk Fatigued sEMG RMS higher than unfatigued in trained and untrained conditions at trot Ratio of fatigued to unfatigued higher for walk
(6) Colborne et al (2001)	3 horses (Thoroughbred)	Treadmill gallop	DE	Ag/AgCl	3mm	1 cm			Band pass 30-1000Hz Fast fourier analysis on 4 or 5 samples of burst activity over 3s	na	Median frequency	Reduction in median frequency over time in horse which did not change leads but when a horse changes leads, median frequency increased

Authors	Species and details	Task / activity	Muscles analysed	Electrode details and preparation				Rectification	Signal processing and filtering	Normalisation	sEMG parameters investigated	Study findings
				Type	Size	Inter-electrode distance	Description of location given					
(7) Cottrill et al. (2008)	9 horses	Lunged walk and trot	LD				yes		ECG subtracted from signal	na	Mean intensity	EMG intensity greater for LD inside of the circle Training aids, side reins and Pessoa did not increase LD activity
(8) Crook et al (2010)	6 horses (Welsh Mountain breed)	Treadmill walk and trot at 3 different gradients (0, 10, and -10%)	BF, EDL, GA, GM, VL			1.5 cm	yes		20Hz high pass BW (3rd order) 20 Hz cut-off Wavelet analysis	na	sEMG intensity	Increase in sEMG intensity with increase in speed at all gradients for BF, GA, GM, for VL on incline and decline only and EDL on horizontal and incline only. GM, BF, GL intensity higher on incline compared to horizontal walk GM and BF reduced on decline at walk compared to horizontal
(9) Fischer et al (2013)	8 adult dogs (Beagles)	Treadmill trotting	LD, TB, VL	Ag/AgCl	1.6cm diameter	2.5cm	yes		10-1000Hz band pass 20Hz high pass, low pass 300Hz, MFA (10ms window)	Mean amplitude of the sound (non-lame) condition	Timing of peak activity, activity on- and off-set, integrated sEMG for stride cycle bins	No difference in TB Reduced VL activity in the ipsilateral limb and increased in the contralateral limb during lameness Phase shift in LD with lameness
(10) Garcia et al (2014)	10 mixed breed dogs	Walk and trot overground different speeds	BB, TB		1 cm	2 cm	yes	Rectified	70-600Hz band pass with 79 point hamming window Mean off-set, RMS (0.1s window)	Resting sEMG (2s duration)	magnitude, timing, and power spectral density	Between-limb and between-speed differences found for all parameters except peak occurrence of triceps. No difference in median frequency between walk and trot for BF but higher in trot for triceps
(11) Groesel et al (2010)	10 horses (various breeds)	Induced spinal lateroflexion	LD			4 cm	yes	Rectified	Resampled using mean of 10 data points 7th order low pass BW (10Hz)	na	iEMG	Muscle shortening in model correlated to LD activity Linear relationship between Model and iEMG
(12) Harrison et al (2012)	3 Thoroughbred horses	Walk and trot overground, and walk, trot, canter on a treadmill	BR, CDE, DE, ECR, FCR, FCU, IS, LDL, TB, UL				yes		Method 1: density transformation, 20Hz high pass filtered, RMS (40ms window) Method 2: demeaned, 40Hz low pass, rectified, 10Hz high pass filtered	Mean peak centering amplitude	RMS amplitude, muscle onset / offset during swing phase and stance phase	Activity relative to stride described. Onset time similar between most muscles, but offset different. No differences between treadmill and overground in muscle timing except long head of triceps.

Authors	Species and details	Task / activity	Muscles analysed	Electrode details and preparation				Rectification	Signal processing and filtering	Normalisation	sEMG parameters investigated	Study findings
				Type	Size	Inter-electrode distance	Description of location given					
												Greater activity during canter in the majority of muscles
(13) Hodson-Tole et al (2006)	6 horses	Walk, trot, and canter on a treadmill flat and on an incline	BC, TB	Ag/AgCl	5cm wide, 4 cm long		yes		3 rd -order high pass (20Hz), wavelet analysis	na	onset/offset, mean intensity	BC highly related to max limb retraction and long head of triceps with max limb protraction. Speed and incline influence on muscle timing and intensity for TB and BC
(14) Janssen et al (1992)	5 ponies (various breeds)	Walking overground	CDE, DDE, ECR, EDL, FCR, FCU, GA, UL,	Felt pads	20x7mm	18.5mm	yes	Full wave rectified	30 Hz low-pass, 4 th order BW 5ms time lag, Zero-lag moving average (50ms)		onset/offset, peak amplitude	Activity relative to stride cycle described.
(15) Kienapfel (2014)	5 horses (warmbloods)	Walk, trot, canter with 3 head-neck positions (ridden and unriden)	BC, SPL, TRA			3cm		rectified	4 th order BW high pass 40Hz, Moving average (40 data points)		Median activity	No difference between ridden and unriden horses. Greater BC activity in the flexed position, TRA and SPL more active in the free positions at all gaits
(16) Lauter et al (2009)	8 adult dogs	Treadmill walking on the flat, incline and decline	GM, SM/BF, VL	Ag/AgCl	1cm	2cm	yes	rectified	Band pass 20-450Hz, Low pass filtered	Muscle ratios	Mean of stance and swing phase of gait cycle	No effect of incline on GM and QD muscles, but increased activity hamstrings with incline
(17) Licka et al (2009)	15 adult horses	Treadmill walking	LD			4cm	yes	rectified	5 th order low pass BW (10Hz)	Max amplitude	Amplitudes of peak 1 and peak 2, min and max	Activity relative to stride cycle described. No difference in peak amplitude between LD locations
(18) Licka et al (2004)	15 adult horses	Treadmill trotting	LD				yes	rectified	5 th order low pass BW (10Hz)	Max amplitude	Amplitudes of peak 1 and peak 2, min and max	Activity relative to stride cycle described
(19) Lister et al (2009)	6 dogs	Trotting	GA, TC				yes				Peak-to-peak amplitude	No quantitative peak-to-peak amplitude comparisons made due to high variability. Correlation between muscle activity burst and hind limb foot strike
(20) Peham and Schoberberger (2006)	15 adult horses	Induced movement at stance	LD				yes	rectified	Fourier transform (transfer function) and fitted to a filter 2 nd order polynomial	na	Transfer function coefficients	EMG data used to determine stiffness of equine spine and compared with calculated/modelled results
(21) Peham et al (2001b)	15 adult horses	Induced movement (myotatic reflex) at stance	LD				yes	rectified	7 th -order low pass BW (10Hz)	Max at T12	Max and min EMG	Differences in amplitude between locations

Authors	Species and details	Task / activity	Muscles analysed	Electrode details and preparation				Rectification	Signal processing and filtering	Normalisation	sEMG parameters investigated	Study findings
				Type	Size	Inter-electrode distance	Description of location given					
												No time shift between the locations for max activity
(22) Rajapaksha et al (2014)	16 Holstein Friesian dairy cows	Static (standing) and dynamic movement (steps)	BF, GM	Bipolar Ag/AgCl	10.1c-cm ²	3 cm	yes	na	Low pass BW (8-500 Hz) Fast Fourier transformed RMS	na	Median power frequency, median amplitude, total muscle activity	Muscle activity did not change with floor slope
(23) Robert et al (2002)	4 adult horses (3 Selle Français, 1 trotter)	Treadmill trotting at different speeds	GM, LD, RA, SPL, TB, TFL	Ag/AgCl					iEMG (1ms processing interval /10 strides)	na	Activation onset / offset, integrated EMG, Mean	Activity relative to spinal kinematics described. Muscle activity onset / offset earlier in the stride cycle with higher speeds except for TB and GM Muscle activity intensity increased with speed except for SPL
(24) Robert et al (2001a)	4 adult horses (3 Selle Français, 1 trotter)	Treadmill trotting at different speeds	LD, RA	Ag/AgCl		5cm	yes		iEMG /10 strides	na	Activation onset / offset, integrated EMG, Mean	Activity relative to spinal kinematics described. Muscle activity onset / offset earlier in the stride cycle and muscle activity intensity increased with speed
(25) Robert et al (2001b)	4 adult horses (3 Selle Français, 1 trotter)	Treadmill trotting, different speeds and inclines	LD, RA, SPL	Ag/AgCl	4mm	3cm	yes		iEMG (1ms processing interval /10 strides)	na	Activation onset / offset, integrated EMG	Activity relative to spinal kinematics described. Muscle activity onset / offset earlier in stride cycle with higher speed except for the second peak in SPL. Muscle activity intensity increased when speed increased except for SPL
(26) Robert et al (2000)	4 adult horses (3 Selle Français, 1 trotter	Treadmill trotting at different speeds and inclines	GM, TFL	Ag/AgCl		2.5cm	yes	Full-wave	iEMG /10 strides	na	Activation onset / offset, integrated EMG	Muscle activity onset/offset significantly earlier in the stride cycle when speed increased and later when inclination increased. iEMG increased with increasing speed and slope
(27) Robert et al (1999)	5 horses (4 trotters, 1 French saddlehorse)	Treadmill trotting	BF,EDL GM, ST, TFL, VL	Ag/AgCl		2.5cm	yes	Full-wave		na	Activation onset / offset, burst duration	Activity relative to stride cycle described
(28) St. George and Williams (2013)	1 horse	Jumping grid of 4 fences	GM, LD, TB	4 Silver bar			yes		5th order BW low-pass filter (10 Hz)		Mean MUAP, peak amplitude frequency (PAF) for different phases of jump	Differences for mean PAF values in left gluts between approach and jump strides, and between jump and

Authors	Species and details	Task / activity	Muscles analysed	Electrode details and preparation				Rectification	Signal processing and filtering	Normalisation	sEMG parameters investigated	Study findings
				Type	Size	Inter-electrode distance	Description of location given					
												intermediate strides in the left TB
(29) Valentin et al (2015)	15 Austrian mountain sheep (and 24 humans)	Treadmill walking and, trotting	GM, LD, OI, OE, RA				yes	Full-wave	Mean-offset 4th order BW low-pass filter (20 Hz)	Maximum of walk and trot separately	Peak EMG amplitude, phasic-ness of muscles	Differences between activity of human and sheep trunk muscles, which are muscle- and gait-specific.
(30) Wakeling et al (2007)	6 horses	Treadmill walking (incline and level) and trotting (level only)	LD	Ag/AgCl	10mm	30mm	yes		Filtering out low freq. < 24 Hz ECG subtracted from signal wavelet analysis (wavelet domain: 2-10; frequency band 24-380 Hz)	na	Muscle intensity EMG onset - offset	LD activity timing varies between muscle segments, the locomotor condition tested and spinal range of motion. Co-contraction between left and right side quantified. Unilateral activity more present in cranial segments for level walking
(31) Wakeling et al (2006)	26 horses with muscular spasm in LD	Walking a figure of eight	LD	Ag/AgCl	10mm	22mm	yes		Filtering out low freq. < 24 Hz ECG subtracted from signal wavelet analysis (wavelet domain: 2-10; frequency band 24-380 Hz)	na	Mean and median of total muscle activity intensity	Reduction in LD spasm immediately after manipulative therapy
(32) Wijnberg et al (2009)	6 healthy shetland ponies and 2 Warmbloods with stringhalt	Overground walking	EDL, LDL, VL					rectified	Integrated EMG	na	Integrated EMG,	Botox reduced EMG activity
(33) Williams et al (2014)	8 horses	chewing	MA, TE				yes	Full wave rectified	20-480 Band pass filter 4th order BW low-pass filter (10 Hz)		Mean MUAP amplitude and Mean peak amplitude	Significant changes in temporalis MUAPs but not in masseter.
(34) Williams et al (2013)	9 national hunt thoroughbred racehorses	Canter interval training + gallop	GM				yes		5th order BW low-pass filter (10 Hz)		mean MUAP, mean and median amplitude frequency	High inter- and intra-horse variability. Mean frequency not related to fitness level. No change in median frequency across training period
(35) Zaneb et al (2009)	12 lame and 12 non-lame horses	Treadmill walking and trotting	BF, GM, EDL, LD, ST	Ag/AgCl	30mm	3cm	yes	rectified	5th order BW low-pass filter(10 Hz)	ratios	mean, max, min, max-to-mean and min-to-mean activity ratios	With lameness muscle activity changes in LD, BF, GM but not in EDL
(36) Zsoldos et al. (2014)	10 horses (5 mature and 5 old)	Neural position, flexion, extension task	CM,CB, OMO, SPL	Ag/AgCl	30 mm	3 cm	yes	rectified	5th order BW low-pass filter(10 Hz), Dynamic time warping (DTW)	Relative muscle activation (RMA%)	Mean, min and max RMA%, third quartile ranges, DTW distances	Similar muscle activity across horses and age groups. Increased extensor activity in neutral position in old horses compared to mature.

Authors	Species and details	Task / activity	Muscles analysed	Electrode details and preparation				Rectification	Signal processing and filtering	Normalisation	sEMG parameters investigated	Study findings
				Type	Size	Inter-electrode distance	Description of location given					
(37) Zsoldos et al. (2010a)	6 horses	Treadmill walking and trotting	SPL	Ag/AgCl	30 mm	3 cm	yes	rectified	5th order BW low-pass filter(10 Hz)		Mean, range, min 1 and 2, max 1 and 2, occurrence of min 1 and 2 and max 1 and 2	Two maxima in both gates. Flexion-extension angle and lateral bending of neck (at C1) described with SPL activity.
(38) Zsoldos et al. (2010b)	6 horses	Treadmill walking and trotting	OEA, RA	Ag/AgCl	30 mm	3 cm	yes	rectified	5th order BW low-pass filter(10 Hz)	ratio	Mean, range, min, max Ratio (OEA/RA)	OEA and RA smaller in trot than in walk. OEA/RA ratio lower in walk than in trot.

BB Biceps, BC Brachiocephalic, BF Biceps femoris , BR Brachialis , CDE Common digital extensor, CM Cleidomastoid, DDF Deep digital flexor , DE Deltoid, ECR Extensor carpi radialis, EDL Long digital extensor, FCR Flexor carpi radialis, FCU Flexor carpi ulnaris, GA Gastrocnemius, GM Gluteus medius, IS Infrapinatus, LD Longissimus dorsi, LDL Lateral digital extensor, MA Masseter, OE external oblique abdominal, OI internal oblique abdominal, OMO Omotransversarius, RA abdominals, SPL Splenius, SM semimembranosus, ST Semitendinosus, TB Triceps, TC cranial tibial, TE Temporalis, TFL Tensor fasciae latae , TRA Trapezius , UL Ulnaris lateralis , VL Vastus lateralis

Table 2

Overview of summary assessment all animal surface electromyography studies.

Authors	Introduction			Methods						Results			Discussion (11) Conclusions		
	1) Study Context	(2) Connection	(3) Question/ objective	(4) Study design	(5) Method	(6) Subject characteristics			(7) Data collection methods			(8) Data analysis		(9) Results	(10) Some estimate of variance
						6.1. Species, Breed	6.2. Age	6.3 BM	7.1. EMG appl.	7.2. EMG proc.	7.3. EMG norm				
(1)Bockstahler et al (2012)	2	2	2	0	0	2	2	2	1	1	2	2	2	1	2
(2)Bockstahler et al (2009)	2	2	2	0	0	2	2	2	1	1	2	2	2	2	2
(3) Breitfuss et al. (2015)	2	2	2	2	0	2	2	2	1	1	0	2	2	2	2
(4) Büchel (2014)	2	2	2	2	1	2	0	0	0	0	0	1	1	2	2
(5) Cheung et al (1998)	2	2	2	0	0	2	2	2	2	2	1	2	2	2	2
(6) Colborne et al (2001)	2	2	2	0	0	2	2	0	1	2	na	2	1	0	2
(6) Cottriall et al. (2008)	2	2	2	0	0	1	2	0	1	0	na	1	1	1	2
(7) Crook et al (2010)	2	2	2	0	0	2	0	2	1	2	na	2	1	1	2
(8) Fischer et al (2013)	2	2	2	0	1	2	2	2	1	1	2	2	2	2	2
(9) Garcia et al (2014)	2	2	2	0	0	2	0	2	1	2	1	2	2	2	2
(10) Groesel et al (2010)	2	2	2	0	0	1	2	2	1	1	na	2	1	0	2
(11) Harrison et al (2012)	2	2	2	0	0	2	2	2	1	2	2	2	2	2	2
(12) Hodson-Tole et al (2006)	2	2	2	0	0	1	0	2	1	2	na	2	2	2	2
(13) Janssen et al (1992)	2	2	2	0	0	1	0	2	2	2	0	2	2	2	2
(14) Kienapfel (2014)	2	2	2	0	0	1	2	0	1	1	0	1	1	2	2
(15) Lauer et al (2009)	2	2	2	2	0	1	0	0	2	1	1	2	2	2	2
(16) Lieka et al (2009)	2	2	2	0	1	2	2	2	1	1	2	2	2	2	2
(17) Lieka et al (2004)	2	2	2	0	1	2	2	2	1	1	2	2	2	2	2
(18) Lister et al (2009)	2	2	2	0	0	1	0	2	1	0	0	1	1	0	0
(19) Peham and Schobesberger (2006)	2	2	2	0	0	1	2	2	1	1	na	2	2	2	2
(20) Peham et al (2001b)	2	2	2	0	0	1	2	2	1	1	1	2	2	2	2
(22) Rajapaksha et al (2014)	2	2	2	1	0	2	0	2	2	2	na	2	2	2	2
(23) Robert et al (2002)	2	2	2	0	0	2	0	0	1	1	na	2	2	2	2
(24) Robert et al (2001a)	2	2	2	0	0	2	2	2	1	1	na	2	2	2	2
(25) Robert et al (2001b)	2	2	2	0	0	2	0	0	1	1	na	2	2	2	2
(26) Robert et al (2000)	2	2	2	0	0	2	2	2	1	1	na	2	2	2	2
(27) Robert et al (1999)	2	2	2	0	0	2	0	0	1	1	na	2	2	2	2
(28) St. George and Williams (2013)	2	2	2	1	0	2	2	0	1	1	0	2	2	0	2

Authors	Introduction			Methods							Results		Discussion (11) Conclusions		
	1) Study Context	(2) Connection	(3) Question/ objective	(4) Study design	(5) Method	(6) Subject characteristics			(7) Data collection methods			(8) Data analysis		(9) Results	(10) Some estimate of variance
						6.1. Species, Breed	6.2. Age	6.3 BM	7.1. EMG appl.	7.2. EMG proc.	7.3. EMG norm				
(29) Valentin et al (2015)	2	2	2	0	0	2	2	2	1	1	2	2	2	2	
(30) Wakeling et al (2007)	2	2	2	0	0	1	2	0	1	1	na	2	2	2	
(31) Wakeling et al (2006)	2	2	2	0	1	1	2	0	1	1	na	2	2	2	
(32) Wijnberg et al (2009)	2	2	2	0	1	2	2	2	0	1	na	2	2	2	
(33) Williams et al (2014)	2	2	2	0	1	1	2	0	1	2	0	2	2	2	
(34) Williams et al (2013)	2	2	2	0	1	2	0	0	1	1	0	2	2	2	
(35) Zaneb et al (2009)	2	2	2	0	1	2	2	0	2	1	2	2	2	2	
(36) Zsoldos et al. (2014)	2	2	2	0	0	2	2	2	2	1	2	2	2	2	
(37) Zsoldos et al. (2010a)	2	2	2	0	0	2	2	2	2	1	0	2	2	2	
(38) Zsoldos et al. (2010b)	2	2	2	0	2	2	2	2	2	1	1	2	2	2	
	38/38	36/38	38/38	33/38	27/38	35/38	38/38	38/38	38/38	38/38	38/38	38/38	38/38	38/38	

Table 3

	Authors	Kinematics – Optical motion capture system	Video cameras	Force plates	Accelerometers	Others
1	Bockstahler et al. (2012)	10 cameras		4 force plates		
2	Bockstahler et al. (2009)		4 cameras	4 force plates		
3	Breitfuss et al. (2015)	10 cameras		4 force plates		
4	Büchel (2014)				1 accelerometer	
5	Cheung et al. (1998)					
6	Colborne et al. (2001)	2 cameras				
7	Cottrill et al. (2008)				1 accelerometer	GPS
8	Crook et al. (2010)	8 cameras			1 accelerometer	
9	Fischer et al. (2013)			1 force plate		
10	Garcia et al. (2014)	8 cameras		2 force plates		5 infrared beam timing gates
11	Groesel et al. (2010)	10 cameras				SIMM, OpenSim
12	Harrison et al. (2012)	8 cameras				force measuring horseshoe
13	Hodson-Tole et al. (2006)	cameras (number unspecified)				
14	Janssen et al. (1992)				1 accelerometer	
15	Kienapfel (2014)				1 accelerometer	
16	Lauer et al. (2009)					electrogoniometers
17	Licka et al. (2009)	6 cameras				
18	Licka et al. (2004)	6 cameras				
19	Lister et al. (2009)			1 force plate		
20	Peham and Schobesberger (2006)	6 cameras				
21	Peham et al. (2001b)	6 cameras				
22	Rajapaksha et al. (2014)		4 video cameras			onset data loggers
23	Robert et al. (2002)		2 video cameras		2 accelerometers	
24	Robert et al. (2001a)		2 video cameras		2 accelerometers	

	Authors	Kinematics – Optical motion capture system	Video cameras	Force plates	Accelerometers	Others
25	Robert et al. (2001b)				2 accelerometers	
26	Robert et al. (2000)				1 accelerometer	
27	Robert et al. (1999)		2 video cameras		1 accelerometer	
28	St. George and Williams (2013)		1 video camera			
29	Valentin et al. (2015)	10 cameras				
30	Wakeling et al. (2007)				1 accelerometer	fibre-optic goniometer
31	Wakeling et al. (2006)					
32	Wijnberg et al. (2009)	6 cameras	1 video camera			
33	Williams et al. (2014)					
34	Williams et al. (2013)					
35	Zaneb et al. (2009)	10 cameras				
36	Zsoldos et al. (2014)	10 cameras				
37	Zsoldos et al. (2010a)	10 cameras				
38	Zsoldos et al. (2010b)	10 cameras				