

The biomechanical construction of the horse's body and activity patterns of three important muscles of the trunk in the walk, trot and canter

K. Kienapfel¹  | H. Preuschoft² | A. Wulf³ | H. Wagner³

¹Department of Animal Ecology, Evolution and Biodiversity, Ruhr University Bochum, Bochum, Germany

²Anatomical Institute, Ruhr University Bochum, Bochum, Germany

³Institute of Sport and Exercise Science, University of Münster, Münster, Germany

Correspondence

K. Kienapfel, Department of Animal Ecology, Evolution and Biodiversity, Ruhr University Bochum, Bochum, Germany.
Email: Kathrin.Kienapfel@rub.de

Summary

The activity patterns of trunk muscles are commonly neglected, in spite of their importance for maintaining body shape. Analysis of the biomechanics of the trunk under static conditions has led to predictions of the activity patterns. These hypotheses are tested experimentally by surface electromyography (EMG). Five horses, with and without a rider, were examined in the walk, trot and canter. Footfall was synchronised with EMG by an accelerometer. Averages of ten consecutive cycles were calculated and compared by statistical methods. The start and stop times of the muscle activities of 5–10 undisturbed EMG plots were determined and the averages and standard deviations calculated. In walking, muscle activities are minor. Electromyography (EMG) activity was increased in the m. rectus during the three-limb support. When the bending moments assume their greatest values, for example while the horses' mass is accelerated upward (two times earth acceleration) in the diagonal support phases in trot and canter the m. rectus, connecting the sternum with the pubic bone is most active. The m. obl. externus is most active when the torsional and bending moments are greatest during the same support phases, but not bilaterally, because the forces exerted on one side by the (recorded) m. obl. externus are transmitted on the other side by the (not recorded) m. obl. internus. While the hindlegs touch the ground in the trot and canter, ground reaction forces tend to flex the hip joint and the lumbar spine. Therefore, the vertebral column needs to be stabilised by the ipsilateral m. longissimus dorsi, which in fact can be observed. As a whole, our EMG data confirm exactly what has been predicted by theoretical analysis.

KEYWORDS

bow and string theory, dressage, electromyography, finite elements

1 | INTRODUCTION

The construction of the body stem (that is head, neck, trunk and tail) in quadrupedal animals can be explained with a theoretical consideration. This can be called the "beam-theory," which has been developed from the older and commonly known "bow-string theory." In spite of being more popular, the latter explains not more than the trunk alone. The beam theory has been developed on the basis of mechanical

theory (Kummer, 1959; Preuschoft, 1976; Preuschoft & Fritz, 1977; Preuschoft, Witzel, Hohn, Schulte, & Distler, 2007; Slijper, 1946). Although the theoretical approach is well-established in engineering sciences and since several years confirmed by Finite Element Systems Analysis (Witzel, Mannhardt, Goessling, de Michaelis, & Preuschoft, 2011), it has not been tested experimentally. Because the beam theory implies predictions concerning muscle activities, an experimental approach is possible by means of the electromyography (EMG)

method, which allows controlling of the activity of muscles in real time. Unfortunately, the exerted force cannot be determined. According to several authors (Konrad, 2011; Larson, 1995; Stern, Wells, Vangor, & Fleagle, 1977), it can be expected that muscle activities are most pronounced while muscles exert most force, that means: during locomotion.

In the case of trunk muscles, the necessary excursions are minimal during standing, so that necessary forces may be exerted by connective tissue, such as ligaments (head and neck), strong fasciae (abdomen) or aponeuroses (lumbar region). These ("passive") structures may well be responsible for the maintenance of body posture, particularly at rest under static conditions, when tension-resistant structures must not change their lengths. During locomotion, however, muscles have to assume different lengths by active contractions, which exists only for short periods of time, alternating with short periods of lesser activity in a motion cycle. This can be documented by EMG that is why we put most emphasis on gaits, rather than statics.

The body stem of a quadruped can be compared to a heavy beam on two supports. This beam is exposed to shearing forces and bending stresses under its own weight. As illustrated by Preuschoft and Fritz (1977), the anterior cantilever (=head and neck) is bent downward, so producing compression at its lower margin and tension on the upper. Between the supports, the trunk tends to sag ventrally downwards, so that compressing forces occur along the upper margin and tension at the lower. This distribution of internal forces is in agreement with the arrangement of the compression-resistant skeleton (vertebral column and sternum, pelvis, (Preuschoft & Fritz, 1977)) and the tension-producing musculature (neck, cranial thoracic dorsal musculature and several shoulder muscles, as detailed in Kienapfel (2014)). Aside from the muscles, there exist very strong strands of connective tissue, which can take over at least part of the tensile forces, and are claimed by several researchers (Gellman & Bertram, 2002; Nickel, Schummer, Seiferle, & Frewein, 2004; Slijper, 1946; Zschokke, 1892) to do so.

During locomotion, maintaining body shape becomes more demanding than at rest, because the mass of the body is accelerated upwards. According to Preuschoft (1985) and Witte, Lesch, Preuschoft, and Loitsch (1995a,b), the accelerations in the gaits trot and canter commonly are two times earth acceleration. This means that the weight force, which must be countered, is twice as much as at rest. In addition, the body is supported on all four, three, two extremities or even one limb alone. There occur even phases without any ground contact, while the body is floating freely. Because of these phases of aerial floating, the reaction forces between ground and the body vary considerably. In the take-off phase for a jump, horses produce accelerations of 2.5 g, during landing after a jump 3.7 g (as calculated in (Preuschoft & Fritz, 1977)). In smaller mammals, especially adapted to leaping, the accelerations may well reach more than 10 times earth acceleration (Demes & Gunther, 1989; Gunther, Ishida, Kumakura, & Nakano, 1991).

The occurring shearing forces reach their maximum at the shoulder and decline towards the hindlimb support, changing their sign at about thoracal/lumbar region. Shearing forces are in a firm mathematical relationship to bending moments. A structure, well suited for sustaining

shearing forces are the ribs plus the intercostal muscles (Preuschoft et al., 2007).

As soon as only one limb is lifted from the ground (for example to place it forward and so initiate locomotion), torsional moments occur inside the trunk (that is that part of the body stem between anterior and posterior limbs (Preuschoft et al., 2007; Preuschoft, Hohn, Distler, Witzel, & Sick, 2005)). To sustain torsional moments inside the trunk, there exist well-suited structures: ribs for compressive forces and the oblique muscles of the body wall (Mm. obliquus externus and internus, intercostales) for tensile forces. Torsional moments concentrate near the periphery of the twisted part and therefore the peripheral arrangement of the ribs as well as of the oblique muscles fits perfectly to the theoretical expectations. A close-up (still theoretical) analysis of these structures shows exact agreement between theoretical demands and morphology in various animals (Hohn, Preuschoft, Witzel, & Distler, 2013; Preuschoft & Klein, 2013; Preuschoft et al., 2005, 2007).

We concentrated our efforts on horses, which are typical cursorial mammals. The locomotor modes and EMG activities of these animals are known in detail. They are used to being handled by humans and so can easily be induced to perform all necessary actions for a study. Their gaits are rhythmic, the cycles reliably uniform and not influenced or disturbed in normal conditions by humans, that is riders or researchers (common experience among riders; own results) and in addition, horses are available in numbers sufficient for proving the relevance of the experiments. They are well suited to serve as models to stand for all cursorial mammals. Because we wanted to examine the gait patterns in practical riding, the horses were examined on track and not on a treadmill.

The patterns of muscle activity have been studied repeatedly. In most cases, the interest of the authors was fixed on muscles of the limbs. This has resulted in a fairly complete overview of muscle actions during several performances of a variety of vertebrates. Rare, however, are studies designed to obtaining empirical proves to verify the balance of forces inside the more or less horizontally orientated body stem (Carrier, 1990, 1993; Ritter, 1996; Ritter, Nassar, Fife, & Carrier, 2001; Schilling & Carrier, 2009).

The knowledge of the regular muscle activity patterns of the trunk evidently promises an understanding of the biomechanical construction of a quadrupedal animal's body. It also will give useful answers to questions concerning training techniques, or to identify pain.

Muscles lying near the surface so that they provide the required information are the m. longissimus dorsi as most obvious muscle of the topline, the m. rectus abdominis as straight muscle of the belly and the m. obliquus externus as diagonal abdominal muscle.

The activity of the m. longissimus dorsi is known in the walk and trot (Cottrill, Rituechai, & Wakeling, 2009; Licka, 2001; Licka, Frey, & Peham, 2009; Robert, Audigie, Valette, Pourcelot, & Denoix, 2001; Robert, Valette, & Denoix, 2000; von Scheven, 2010). Just one study mentions one peak activity in the canter (Robert et al., 2000), but no further information was provided.

The m. rectus abdominis was mentioned in the same study in the canter with one peak activity, but again with no further information

about the stage of movement. In the walk and trot, its activity is documented by the studies of several authors (Robert, Valette, & Denoix, 2001; Robert et al., 2000; Zsoldos, Kotschwar, Rodriguez, Peham, & Licka, 2010). The *m. obliquus externus* was also part of the latter study and investigated in the walk and the trot.

In a heavy beam, which is supported like body stem of horse on anterior and posterior limbs, we can expect tensile forces—that is muscle activity—along the ventral side of the belly as well as along the dorsal side of the anterior thorax and proximal neck. The latter has indeed been found in an earlier study (Kienapfel, 2014). If the same beam is supported near its rear (caudal) end by a forwardly inclined leg, with ground contact underneath its belly, tensile forces will occur at the posterior back and rear margin of the beam. The forces will occur only for short periods of time in each motion cycle. If we imagine the beam on stilts replaced by a horse's body, a forwardly placed hindlimb needs to be balanced in the hip joint by muscles. Some of these muscles (hamstrings, ischiofemoral part of *m. gluteus*) pull the ischium downwards and so lead to an upward movement of the iliosacral junction plus posterior lumbar vertebrae. Such a flexion must be blocked, at least controlled, by muscles: *mm. gluteus medius*, *iliocostalis* and *longissimus*. Diagonal support of the "beam" on a frontlimb and its contralateral hindlimb leads to a twisting of the "beam"—or trunk—between the supporting limbs. Twisting implies tensile forces between the supporting diagonal limbs, which can be produced by the oblique muscles of the trunk wall.

Therefore, the correctness and reliability of our theoretical approach would be confirmed if three hypotheses turn out to be correct:

- (i) The straight ventral muscles of the trunk have to be activated in the phases of support, when the greatest forces are acting downwards
- (ii) The dorsal/epaxial muscles of the trunk (*m. longissimus dorsi*) are activated during the stance phase of the ipsilateral hindleg.
- (iii) Torsional stresses lead to an activation of the oblique abdominal muscles in the phases of diagonal support. More precisely, the *m. obliquus abdominis externus* (which alone can be controlled by surface electrodes) of one side should be active during support on the ipsilateral fore- and contralateral hindlimb.

2 | MATERIALS AND METHODS

2.1 | Ethics statement

This type of non-invasive research is approved under the German animal protection act and does not require a study-specific permission. The horses were handled by their usual riders without adding stressors or pain to the animals.

2.2 | Methods

The measurements were taken from five warmblood geldings without backpain or lameness according to their professional trainers. Their height at withers varied between 1.68 and 1.74 m and their ages were

between 9 and 16 years. The horses were used for training of riders on basic to advanced levels.

The measurements were done in a Longe hall (diameter 20 m).

For measuring muscle activation, bipolar self-adhesive electrodes were fixed on the shaved and cleaned skin. Two bipolar electrodes (2,000 Hz) were positioned 3 cm apart in the direction of muscle fibres on the muscle bellies. The *m. obliquus externus* was measured bilaterally at the level of the 16th rib. Electrodes on the *m. longissimus dorsi* were placed as far cranial as possible on the saddled horse with the saddle not touching the electrodes. This was approximately on top of L3–L4. The reference electrode was placed on the highest point of the pelvis, which is not covered by musculature. The EMG signals were filtered with a Butterworth fourth-order highpass (40 Hz) and then rectified. Thereafter, the data were smoothed by moving average procedure (window 40 data points) for each horse and condition. Movements were synchronised by recording accelerations along the left foreleg. The accelerometer was fixed to the metacarpal by a bandage. The locomotor cycles were identified in close analogy to (Falaturi, 2001) using the maximum peaks of the accelerometer data as triggers.

We recorded 1–3 cycles in each gait in the Longe hall and collected data for ten or more clear rhythmic strides in a row in the desired position. First, the program was performed under a rider and then without. The ten consecutive cycles were chosen for each run on the basis of the videotapes. Selection was based on correct rhythm, maintenance of constant speed and relaxed head-neck position. Averages were calculated separately per horse and experimental run.

For the searching of divergences between the muscles on both sides, with and without a rider and on both sides, statistical analyses were performed. The on- and off-times of the muscle activities were determined and mean values and standard variations calculated. Because no clear on- and off-data of activity in the case of the *m. obliquus externus* could be discerned, only the maximum activities were used for the calculations of mean value and standard variation.

2.3 | Statistical analyses

To evaluate differences between the muscles of both sides, with and without a rider, and left versus right turns, the data were tested with the Kolmogorov–Smirnov test for a Gaussian distribution. Equality of the variances was tested by the Levene's test. If there were differences, they were located with the Mann–Witney (independent data, e.g., comparison between both sides, with and without a rider), if the data did not show a Gaussian distribution. If the data were distributed symmetrically according to Gauss, the Student's *t* test was performed. Every test was taken for dependent variables. Significance level was considered to be at $p \leq .05$.

For the graphs of the activity patterns, five typical EMG plots (each being the mean value of 10 cycles) for every horse were overlain, and for each time unit, the median line showing the activity was drawn by hand.

The accelerometer plot was synchronised with the footfall pattern of Preuschhof and Günther (1994), the length of the stride cycle

was the same in both figures, so that it could be adapted without further changes. "Adapting" here means shifting the data along the time axis until the footfall patterns matched with the accelerometer data.

3 | RESULTS

The activities of all three trunk muscles become significantly greater ($p < .01$) from walk over trot to canter—so in canter the activity was the greatest. No significant differences occurred between the muscles of the left and the right side or between moving on the left and right rein. In the walk, the mm. longissimus dorsi and rectus abdominis

show significantly more activity with a rider than without ($p < .05$). Neither in the trot nor in the canter such differences could be found. In the faster gaits trot and canter, which include phases of aerial suspension, and therefore higher ground reaction forces, all EMG activities are more marked than in the walk (Figure 1a,b).

In walking, the m. obliquus externus is active while one of the frontlimbs and the contralateral hindlimb support the trunk.

The m. longissimus dorsi shows no clear activities in the walk. The m. rectus abdominis is active two times in each cycle, as soon as one of the forehooves is touching the ground. Its activity ends in a later stage of the stance phase of the forehoof. While the forehoof is in contact with the ground and the m. rectus abdominis is active, body weight is supported by three limbs, two fore and one hind.

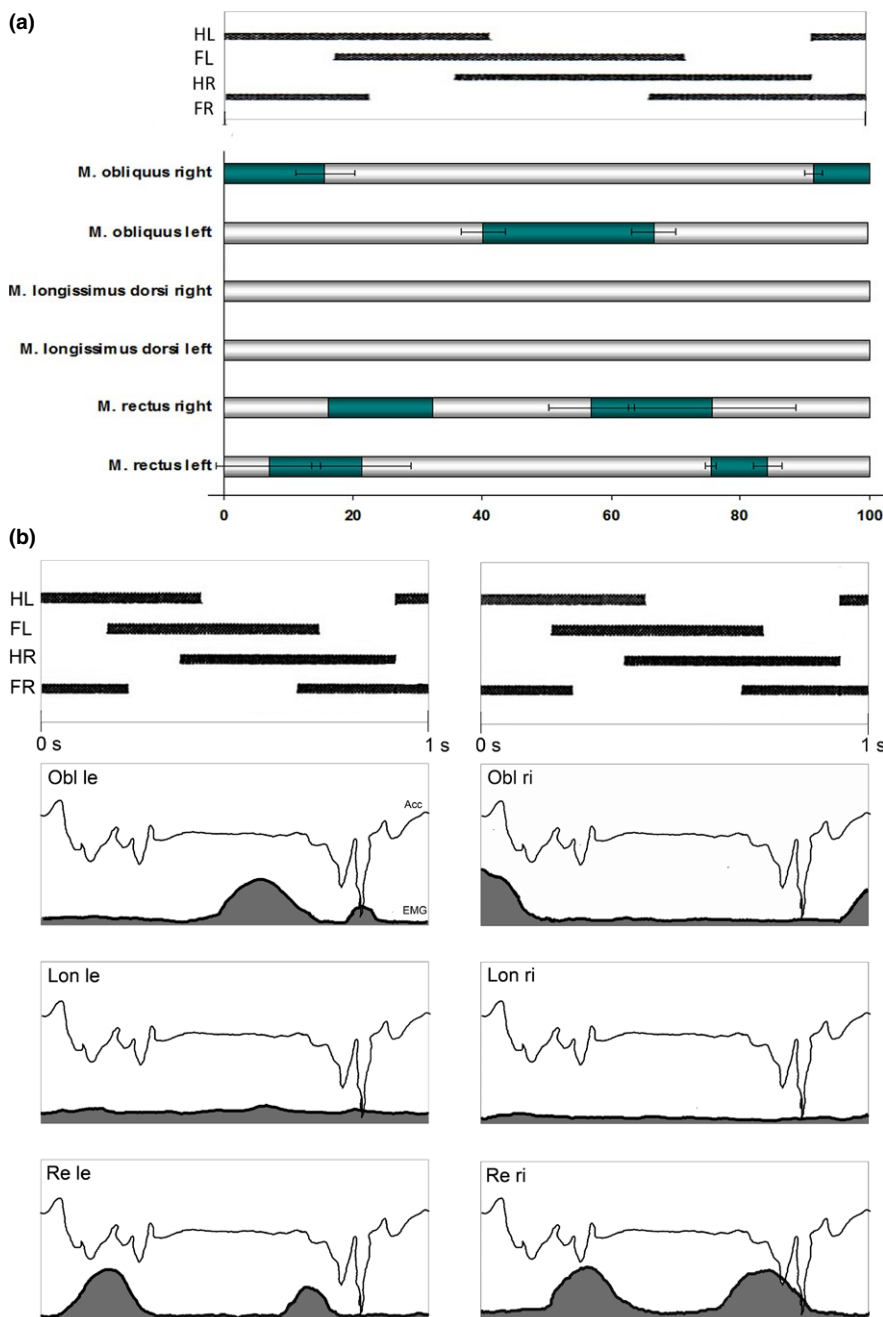


FIGURE 1 (a) Walk. Mean activity phases as green segments of the solid columns. The horizontal axis is divided in % of the cycle duration. Standard deviations \pm SD are shown as narrow bars. At the top, the footfall is displayed. One cycle in the walk had a mean duration of 1 s. The m. longissimus dorsi showed no measurable activity during the walk. For the m. obliquus externus, only the maximum peaks are considered. (b) Walk. On top, the footfall sequence is displayed. The bold lines are the median electromyography (EMG) signals from five horses over ten cycles per horse. The thin line represents the accelerometer at front left metapodium, being identical in all diagrams and allows connecting the EMG data with footfall sequence. Obl. le/ri: m. obliquus externus left and right, Lon le/re: m. longissimus left and right, Re le/re: m. rectus abdominis left and right. HR, hind right; HL, hind left; FR, front right; FL, front left

In the trot (Figure 2a,b) the activity of the *m. obliquus externus* has three to five peaks of activity throughout each cycle, with one high and several lower spikes. The main peak of the left *m. obliquus externus* occurs during the stance phase of LF and RH. The right *m. obliquus externus* has its main peak during the diagonal stance phase RF and LH. This muscle obviously is active at the stance phase of the ipsilateral fore- and contralateral hindlimb.

The main activity of the *m. longissimus dorsi* takes place from the middle of the swing phase until shortly after touchdown of the ipsilateral hindleg with an additional low peak at liftoff. The *m. rectus* shows

two peaks from the beginning to the middle of each diagonal stance phase of both fore- and the contralateral hindhoof.

In the canter (Figures 3a,b, 4a,b), the *m. obliquus externus* of the leading side shows one high peak of activity shortly after the touch-down of the leading foreleg (for example the left foreleg in the left lead canter) until the middle of its stance phase (including the three-leg support of the leading front, the trailing front and leading hind). The contralateral obliquus has three peaks of activity: a low one at ground contact of the trailing hindleg, the big peak in the middle of the three-leg support phase (HL, HR, FL in right lead and HR, HL, FR

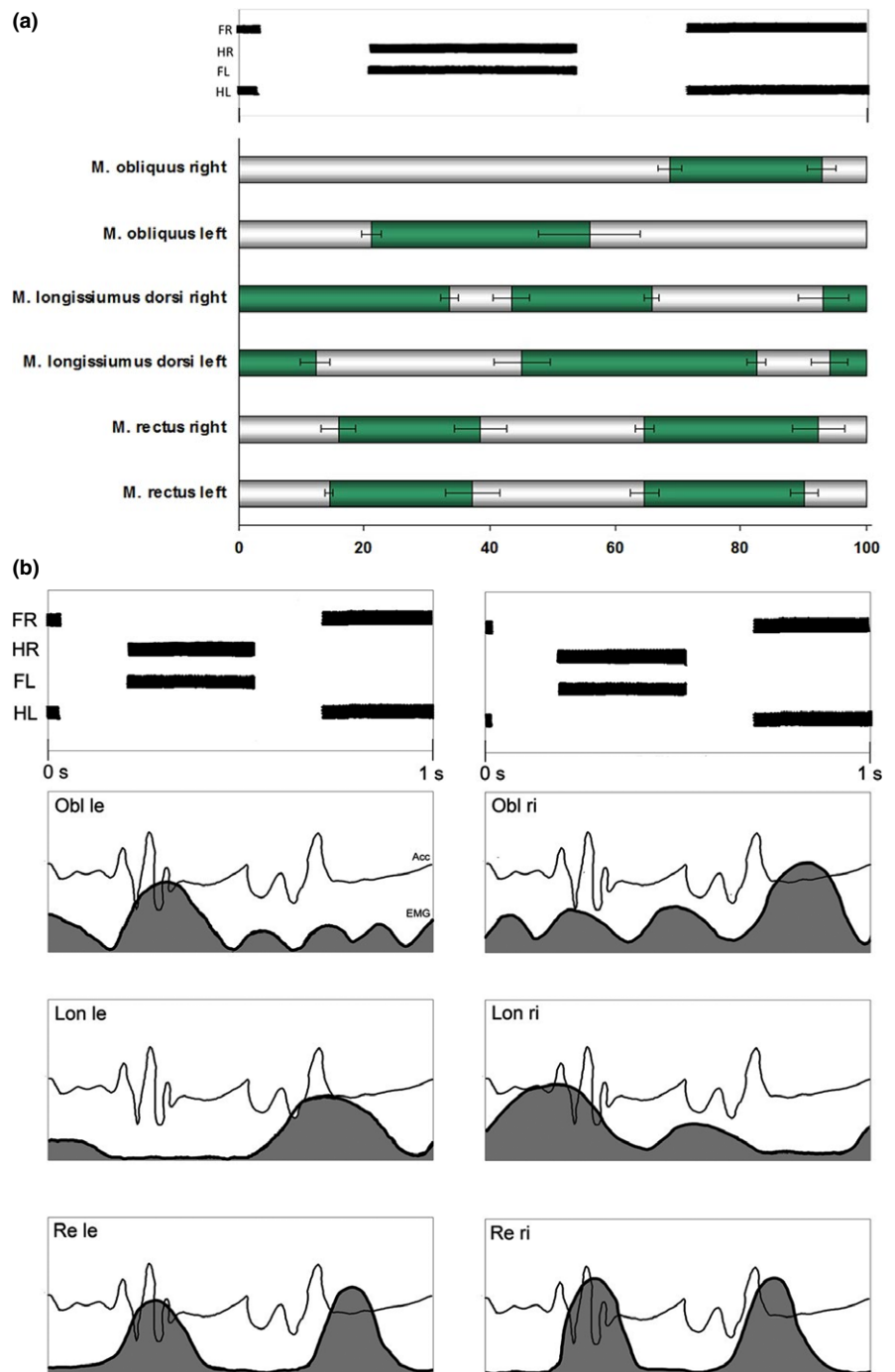


FIGURE 2 (a) Trot. Mean activity marked green, \pm SD by narrow bars. The horizontal axis is divided in % of the cycle duration. On top, the footfall is displayed. Each full cycle in trot had a mean duration of 0.8 s, or a frequency of ca. 85/min, like in Preuschoft (1987). For the *m. obliquus externus*, only the highest peaks are shown. (b) Trot. Footfall on top. Each cycle of the trot had a mean duration of 1 s. Conventions as in Figure 1. HR, hind right; HL, hind left; FR, front right; FL, front left

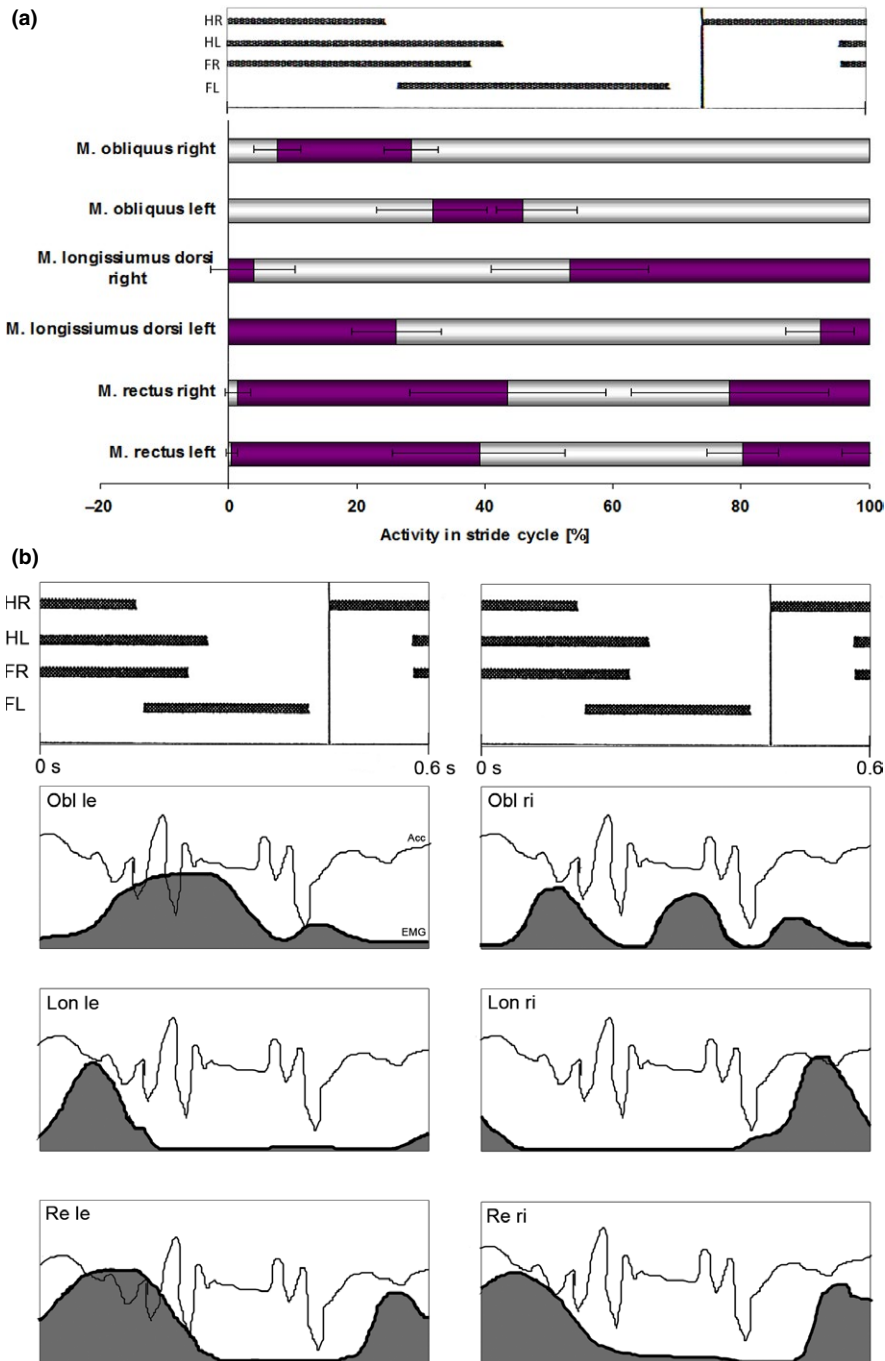


FIGURE 3 (a) Canter left lead. Mean activity phases are marked pink, \pm SD shown by narrow bars. The horizontal axis is divided in % of the cycle duration. On top, the footfall sequence is displayed. One cycle in the canter had a mean duration of 0.6 s. For the m. obliquus, only the maximum peaks are displayed. (b) Canter left lead. At the top, the footfall is displayed. One stride cycle in canter had a mean duration of 0.6 s. Conventions as in Figure 1. HR, hind right; HL, hind left; FR, front right; FL, front left

in left lead) and another low one in the middle of the stance phase of the leading foreleg. The maximum peaks are shown in Figure 3a. The m. longissimus dorsi is active shortly before touchdown of the ipsilateral hindleg until the middle of the stance phase, no matter if it is the leading or trailing.

The m. rectus abdominis is active on both sides shortly after touchdown of the trailing hindleg until the end of the diagonal stance phase. The m. obliquus externus shows most activity always slightly after the peak activity of the m. rectus abdominis in the diagonal stance phase of the trot as well as in the three-leg support in the canter, while most weight is supported by the diagonal.

4 | DISCUSSION

To make the most important point first, our present study provides data obtained during true locomotion. A comparison with the literature, however, shows that the differences between our results and those obtained from the treadmill are minor. Most EMG data in the literature (except Robert, Valette, Pourcelot, Audigie, & Denoix, 2002) who recorded muscle activities in two horses under natural conditions) were not taken at track but on the treadmill. This artificial condition, which is not the one to which horses are adapted by evolution, provides data which theoretically may well diverge from normal

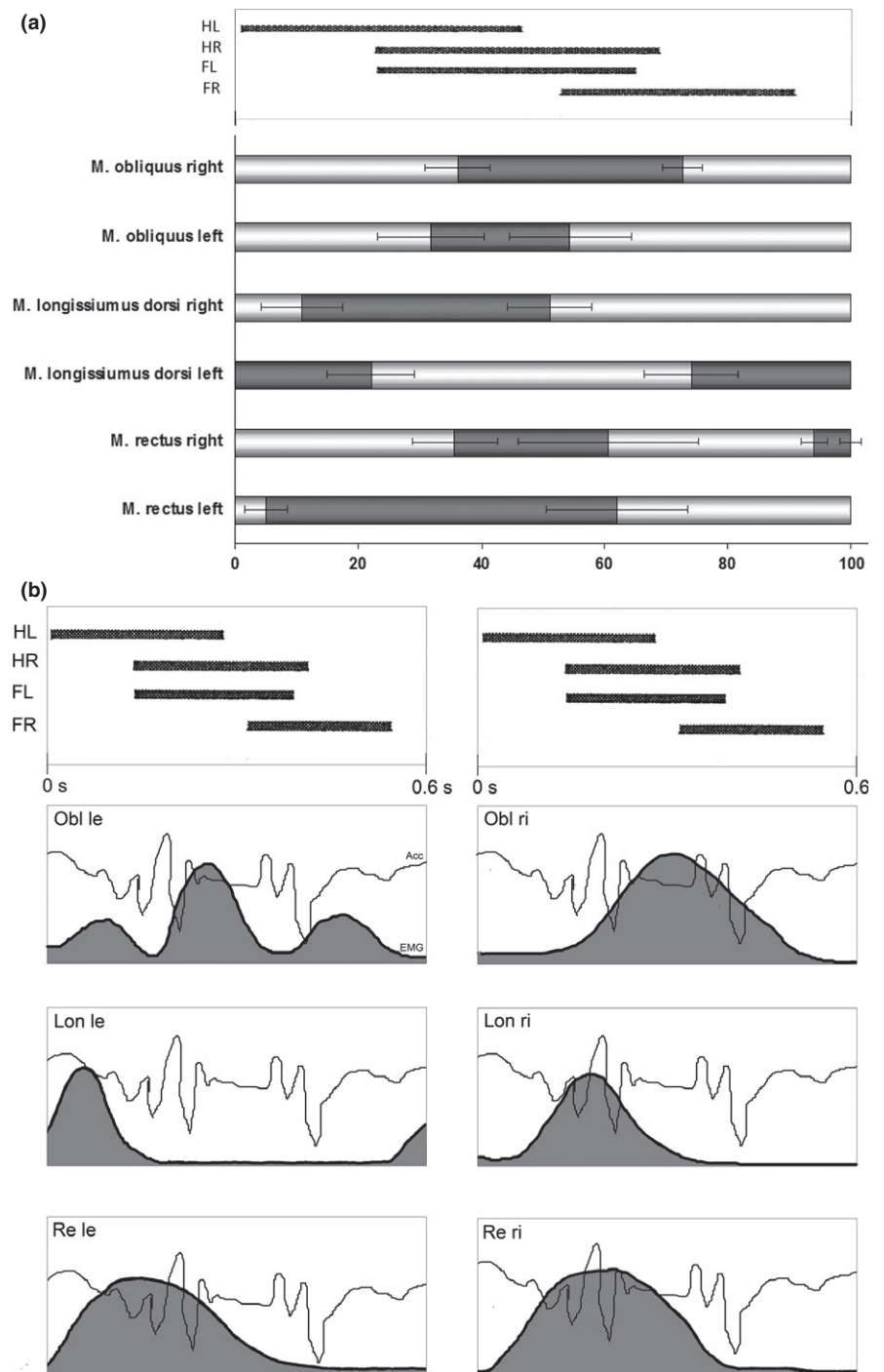


FIGURE 4 (a) Canter right lead. Mean activity phases are marked dark grey, \pm SD indicated by narrow bars. The horizontal axis is divided in % of the cycle duration. On top, the footfall pattern is displayed. Each cycle in the canter had a mean duration of 0.6 s. For the m. obliquus, only the maximum peaks are shown. (b) Canter right lead. At the top, the footfall is displayed. One cycle in canter had a mean duration of 0.6 s. Conventions as in Figure 1. HR, hind right; HL, hind left; FR, front right; FL, front left

conditions outside on the grounds or even in a riding hall. On the treadmill, the horse cannot move on its individually preferred speed or stride lengths, has no feedback by the progress it is making in the chosen gait, and does not need to balance the uneven, permanently changing conditions of the soil in overground locomotion. According to own, unpublished data, ground reaction forces may vary on rough grounds by $\pm 40\%$ of the average values. Differences between these two conditions occur especially in the lumbar regions of the back (Álvarez, Rhodin, Byström, Back, & Weeren, 2009). Using a treadmill has advantages such as constant environment, speed and ground

conditions; therefore, experiments promise to better repeatability (Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999). The same authors admit, on the other hand, that testing on track, especially with the aim to study locomotion, is closer to natural conditions.

According to Milner-Brown and Stein (1975), it should be possible to create an approximately linear relationship between EMG signal and force as long as the recording is confined to one muscle and the electrodes are not moved. Larson (Larson, 1995) also used two stages of EMG activity as benchmark for muscle force, low and high activity, following in this point Stern et al. (1977). The pattern of muscle

activities can be understood best, if their fit to the major exchange of forces between horse and ground is taken into consideration.

In the trot, ground contact (and that means a possibility to exert forces from the ground on the horse's body) exists alone during the phases of diagonal support. In the canter, the "diagonal" in fact represents a phase of three-legged support, during which first the leading hindlimb, second the trailing hind and contralateral forelimb (diagonal stance) and third the other forelimb are on the ground. According to Preuschoft and Fritz (1977), the greatest accelerations upward coincide with the support on the diagonal limbs. If the horse is in the support phase of trot and canter, and most of the weight carried by the diagonal, the bending moments should reach their highest values (Preuschoft, 1987): The weights of all heavy segments between the supporting limbs, thorax and abdomen (together about 70% of total body mass) are moving downwards at exactly this time (Preuschoft, 1987). We must expect those muscles, which keep the trunk in balance against weight, to be highly active. This is indeed the case, the *m. rectus abdominis* is always active during the diagonal stance phase of the trot, as well as during the stance phase in the canter, which is dominated by the "diagonal."

The activities of *m. rectus abdominis* are in complete agreement with the literature (Robert, Audigie, et al., 2001; Robert, Valette, et al., 2001; Robert et al., 2002; Zsoldos et al., 2010) with two activity peaks in trot and one in canter, as well as the timing of the activity phases.

As Zsoldos et al. (2010) noted as well, the *m. obliquus externus* shows a high variability in the walk and in the trot. The authors supposed this could be due to the assumed respiratory function (Nickel et al., 2004). If the inconsistent activity in the trot would indeed be caused by breathing (Ainsworth et al., 1997; Bramble & Carrier, 1983), its activity in the canter (where breathing and locomotion are coupled according to Bramble and Carrier (1983) and Ainsworth et al. (1997)) should be more pronounced and steadier. As this is not the case, another reason seems to be responsible. The skin muscle *m. cutaneous trunci*, for example, was suspected by Nickel et al. (2004) to play a role in motion. As its fibres have the same direction as the *m. obliquus externus*, it could indeed interfere with the *obliquus* signal. Maybe there is also some crosstalk from the *m. obliquus internus* and the *m. rectus abdominis*, which makes the signal so variable. In spite of all these problems, the main activity of the *m. obliquus abdominis externus* coincides consistently with support on diagonal limbs.

In fact, the diagonal support requires a tension-resistant tie between the stance limbs. This is provided by the *obliquus internus* of the ipsilateral side of the hindlimb and the *m. obliquus externus* of the contralateral side. To avoid a dislocation of the *linea alba*, the tensile force of the deep oblique must be passed on to the superficial oblique of the contralateral side. Our superficial electrodes did not allow controlling the *m. obliquus internus* but the *m. obliquus externus* of the contralateral side was in fact active. This is in full agreement with Deban, Schilling, and Carrier (2012) on dogs.

The *m. longissimus dorsi* has a maximum activity before and while the ipsilateral hindleg is on the ground (that means, while weight is borne by this limb) and a lower peak at liftoff in trot but not in canter.

Carrying load on the anteverted hindlimb requires a contraction of the very strong extensors of the hip joint, namely *mm. glutei* and

the hamstrings. Following the theory, the *m. gluteus* should be active (not studied in this paper, but in Robert, Valette, Degueurced, & Denoix, 1999) as well as the *m. longissimus*, which is indeed the case for both muscles (Robert et al., 1999). These muscles not only extend the hip joint they also lift the cranial part of the pelvis, the ilium. To compensate the resulting torque at the iliosacral joint and between the lowermost lumbar segments, a contraction of the dorsal musculature is required. Regarding this point, we are in full agreement with the results obtained by Schilling and Carrier (Schilling & Carrier, 2009) on dogs.

The most powerful flexor of the hip joint used for initiating the foreswing of the hindlimb is the *m. psoas*, located ventral to the vertebral bodies of the lumbar section. It seems logical that this contraction of the *psoas* leads to a flexion of the lumbar segments which must be counteracted by the extensor—the *m. longissimus dorsi*. This would result in the minor peak of activity observed at liftoff of the ipsilateral hindlimb. In the canter, such a stabilising counteraction is not necessary, because both hindlegs are swung forward together and the most posterior segments of the trunk are flexed ventrally (Loitsch, 1993). This ventral flexion is followed by an extension (or dorsiflexion) of the trunk. That movement seems to be induced by elastic recoil of muscles and their tendons and has been interpreted biomechanically by Witte et al. (1995a) as a means to accelerate the foreswing of the hindlimbs. If the hindleg is touching the ground and weight is shifted on this limb, the vertebral column needs to be stabilised against the ventral flexing moment of the hamstrings and other extensors of the hip joint. Studies of Licka (2001), Licka et al. (2009), Robert, Audigie, et al. (2001), Robert et al. (2000), von Scheven (2010); Cottrill et al. (2009) confirm that in walk and trot, the activity of the *longissimus* is connected with the ipsilateral hindleg. Licka (2001) reported two maxima per cycle in the trot like we have observed in most cases of our study, but they described the activity to occur a bit later in the motion cycle than we can report.

Former investigations have shown that in the phase of forelimb support, the dorsal neck muscles (*m. splenius*, anterior part of *m. trapezius*) are active (Kienapfel, 2014).

The most conflicting among our results is the missing of a clear-cut activity of the *m. longissimus dorsi* in the walk. A contraction of this muscle is evident from palpation behind the saddle by the rider. Simple observation shows that the perceived contraction of the dorsal muscle coincides with the stance phase of the ipsilateral hindlimb. Licka et al. (2009) observed EMG activities of the *m. longissimus dorsi* in the walk, which we did not find at all. The reason could be the divergent location of the electrodes. We placed the electrodes at the level of L2/L3 because of the saddle (which is for riding), whereas Licka (2001) found a lower activity at this level in comparison with more cranial regions of the *m. longissimus dorsi*. Our results of the *m. longissimus dorsi* concerning the peaks of the trot match well with the timing observed by Robert et al. (2000) and Cottrill et al. (2009). von Scheven (2010) reported one to four inconsistent activity bursts of this muscle.

In canter, we found the expected burst per cycle of the *m. longissimus* and constant activity patterns in all measured horses. Wakeling, Ritruetchai, Dalton, and Nankervis (2007) found differences between

the left and right rein, with the inner muscle side giving higher EMG activities than the outer side. We could not detect such differences, but this could be due to the big circle diameter of 20 m, where the horses do not need to bend markedly, and because this effect was detected in the more cranial part of the longissimus dorsi.

If a rider is mounted on a horse, he is adding his weight on top of the weight of the segments between the supporting legs. This is reflected in more muscle activity in walking with a rider in comparison with walking without. A horse with normal height has a weight of approximately 500 kg, a rider plus saddle hardly less the 80 kg. In more rapid movements, up to two times earth accelerations (see Introduction) are leading to a multiplication of the weight force, in this case yielding 1,000 kg. Therefore, much more muscle force is needed in the trotting and cantering horse without the rider than in the walk even with. The difference between muscle force required with and without the rider is too minimal in relation to the muscle force required anyway for stabilising the trunk.

The anterior cantilever of the "beam," which is the neck plus head, is flexed downwards. Its bending moments will assume their greatest values, if the neck is stretched or if acceleration forces are transmitted through the forelimbs, especially in the canter. Both require increased muscle activities, which indeed have been observed by Kienapfel (2015).

5 | CONCLUSION

As expected from a theoretical analysis, in which the body stem of a horse is compared to a heavy beam, the m. rectus is active at those phases of the stride cycle, in which the bending moments assume their greatest values, namely the diagonal stance phases in trot and gallop. The m. obliquus externus is active, while torsional forces are acting on the body, because the highest upward accelerating forces are supported by the diagonal limbs. The m. longissimus dorsi is always active at touchdown of the ipsilateral hindleg; its biomechanical function is the stopping of the trunk movement and stabilisation of the trunk.

This means that the theoretical predictions based on the beam theory are confirmed.

ACKNOWLEDGEMENTS

We have to thank hugely the Westfälische Reit- und Fahrshule and especially Martin Plewa and Bianca Schwarzer for giving their horses and rider. Also, we have to thank Bernhard Glenszczyk for the great help with the little pilot test for this study. At last we have to thank Jan Soeren Koch for help in statistical questions and Hans-Gert Kienapfel for taking the video tapes.

ORCID

K. Kienapfel  <http://orcid.org/0000-0001-5123-0242>

REFERENCES

- Ainsworth, D., Smith, C., Eicker, S., Ducharme, N., Henderson, K., Snedden, K., & Dempsey, J. (1997). Pulmonary-locomotory interactions in exercising dogs and horses. *Respiration Physiology*, 110, 287–294. [https://doi.org/10.1016/S0034-5687\(97\)00094-7](https://doi.org/10.1016/S0034-5687(97)00094-7)
- Álvarez, C., Rhodin, M., Byström, A., Back, W., & Weeren, P. R. (2009). Back kinematics of healthy trotting horses during treadmill versus over ground locomotion. *Equine Veterinary Journal*, 41, 297–300. <https://doi.org/10.2746/042516409X397370>
- Bramble, D., & Carrier, D. R. (1983). Running and breathing in mammals. *Science*, 219, 251–256. <https://doi.org/10.1126/science.6849136>
- Carrier, D. (1990). Activity of the hypaxial muscles during walking in the lizard iguana iguana. *Journal of Experimental Biology*, 152, 453–470.
- Carrier, D. (1993). Action of the hypaxial muscles during walking and swimming in the salamander *dicamptodon ensatus*. *Journal of Experimental Biology*, 180, 75–83.
- Cottrill, S., Ritruethai, P., & Wakeling, J. (2009). *The effects of training aids on the longissimus dorsi in the equine back* (accessed 20 October 2011).
- Deban, S. M., Schilling, N., & Carrier, D. R. (2012). Activity of extrinsic limb muscles in dogs at walk, trot and gallop. *The Journal of Experimental Biology*, 215, 287–300. <https://doi.org/10.1242/jeb.063230>
- Demes, B., & Gunther, M. (1989). Biomechanics and allometric scaling in primate locomotion and morphology. *Folia Primatologica*, 53, 125–141. <https://doi.org/10.1159/000156412>
- Falaturi, P. (2001). Computerkinematographie (CKG) als geeignetes Verfahren zur objektiven Bewegungsanalyse- Beschreibung und Ergebnisse. *Pferdeheilkunde*, 1, 30–41. <https://doi.org/10.21836/PEM20010104>
- Gellman, K., & Bertram, J. (2002). The equine nuchal ligament 1: Structural and material properties. *Veterinary and Comparative Orthopaedics and Traumatology*, 15, 1–6.
- Gunther, M., Ishida, H., Kumakura, H., & Nakano, Y. (1991). The jump as a fast mode of locomotion in arboreal and terrestrial biotopes. *Zeitschrift für Morphologie und Anthropologie*, 78, 341–372.
- Hohn, B., Preuschoft, H., Witzel, U., & Distler, C. (2013). Biomechanics and functional preconditions for terrestrial lifestyle in basal tetrapods, with special consideration of Tiktaalik roseae. *Historical Biology*, 25, 167–181. <https://doi.org/10.1080/08912963.2012.755677>
- Kienapfel, K. (2015). The effect of three different head-neck positions on the average EMG activity of three important neck muscles in the horse. *J Anim Physiol Anim Nutr*, 99, 132–138. <http://doi.org/10.1111/jpn.12210>
- Konrad, P. (2011). *EMG-Fibel, Eine praxisorientierte Einführung in die kinesiologische Elektromyographie*, 1.1th ed. USA: Velamed, Noraxon INC.
- Kummer, B. (1959). *Biomechanik des Säugetierskelets*. Berlin: de Gruyter.
- Larson, S. (1995) Unique aspects of quadrupedal locomotion in nonhuman primates. In E. Strasser, J. Fleagle, A. Rosenberger & H. Mc. Henry (Eds.), *Primate locomotion, Recent advances* (pp. 157–173). New York: Plenum Press.
- Licka, T. (2001). Electromyographic activity of the longissimus dorsi muscle in horses during trotting on a treadmill. *American Journal of Veterinary Research*, 2, 155–158.
- Licka, T., Frey, A., & Peham, C. (2009). Electromyographic activity of the longissimus dorsi muscles in horses when walking on a treadmill. *The Veterinary Journal*, 180, 71–76. <https://doi.org/10.1016/j.tvjl.2007.11.001>
- Loitsch, C. (1993). *Kinematische Untersuchung über den Canter von Pferden (Equus caballus)*. Bochum: Ruhr Universität Bochum.
- Milner-Brown, H., & Stein, R. (1975). The relation between the surface electromyogram and muscular force. *The Journal of physiology*, 246, 549–569. <https://doi.org/10.1113/jphysiol.1975.sp010904>
- Nickel, R., Schummer, A., Seiferle, E., & Frewin, J. (2004). *Lehrbuch der Anatomie der Haustiere, Band I: Bewegungsapparat*, 8. Stuttgart: unveränd. Aufl. Parey.
- Preuschoft, H. (1976). Funktionelle Anpassung evolvierender Systeme. 5. Arbeitsgespräch zu Phylogenetik und Systematik. In G. Altmann,

- J. Dörjes, P. Dullemeijer, J. L. Franzen, M. Grasshoff, W. F. Gutmann, H. Heine, G. W. Hoffmann, W. Lehfeldt, D. Mollenhauer, D. S. Peters & H. Preuschoft (Eds.), *Evoluierende Systeme I und II. 4. und 5. Arbeitsgespräch zu Fragen der Phylogenetik und Systematik in der Außenstelle Lochmühle*, 1.-4.4.1974 und 10.-13.3.1975. 1-202, 45 Abb., 1976. Frankfurt: Kramer Verlag, ISBN 3-7829-1062-1.
- Preuschoft, H. (1985). On the quality and magnitude of mechanical stresses in the locomotor system during rapid movements. *Zeitschrift für Morphologie und Anthropologie*, 75, 245–262.
- Preuschoft, H. (Ed.), (1987) *Studien zu den Bewegungen von Sportpferden*. Warendorf: Wissenschaftliche Publikation. Deutsche Reiterliche Vereinigung Vol. 9. Verl. d. Dt. Reiterl. Vereinigung.
- Preuschoft, H., & Fritz, M. (1977). Mechanische Beanspruchungen im Bewegungsapparat von Springpferden. *Fortschritte der Zoologie*, 24, 75–97.
- Preuschoft, H., & Günther, M. M. (1994). Biomechanics and body shape in primates compared with horses. *Zeitschrift für Morphologie und Anthropologie*, 80, 149–165.
- Preuschoft, H., Hohn, B., Distler, C., Witzel, U., & Sick, H. (2005). Ribs and rib cages in terrestrial vertebrates: Their mechanical function and stressing, analysed with the aid of FESA. *Journal of Vertebrate Paleontology*, 31 (suppl 3), 101.
- Preuschoft, H., & Klein, N. (2013). Torsion and bending in the neck and tail of sauropod dinosaurs and the function of cervical ribs: Insights from functional morphology and biomechanics. *PLoS ONE*, 8, e78574. <https://doi.org/10.1371/journal.pone.0078574>
- Preuschoft, H., Witzel, U., Hohn, B., Schulte, D., & Distler, C. (2007) Biomechanics of locomotion and body structure in varanids with special emphasis on the forelimbs. In H.-G. Horn, W. Böhme & U. Krebs (Eds.), *Proceedings of the "Third Multidisciplinary World Conference on Monitor Lizards": Mertensiella, advances in monitor research III* (pp. 59–78). Bonn. <https://www.sauropod-dinosaurs.uni-bonn.de/publikationen> (accessed 21 October 2016).
- Ritter, D. (1996). Axial muscle function during lizard locomotion. *Journal of Experimental Biology*, 199, 2499–2510.
- Ritter, D., Nassar, P., Fife, M., & Carrier, D. (2001). Epaxial muscle function in trotting dogs. *Journal of Experimental Biology*, 204, 3053–3064.
- Robert, C., Audigie, F., Valette, J., Pourcelot, P., & Denoix, J. (2001). Effects of treadmill speed on the mechanics of the back in the trotting saddlehorse. *Equine Veterinary Journal*, 33, 154–159. <https://doi.org/10.1111/j.2042-3306.2001.tb05380.x>
- Robert, C., Valette, J., Degueurced, C., & Denoix, J. (1999). Correlation between surface electromyography and kinematics of the hindlimb of horses at trot on a treadmill. *Cells Tissues Organs*, 165, 113–122. <https://doi.org/10.1159/000016681>
- Robert, C., Valette, J., & Denoix, J. (2000). Surface electromyographic analysis of the normal horse locomotion: A preliminary report. *Conference on Equine Sports Medicine and Science*, 32, 80–85.
- Robert, C., Valette, J., & Denoix, J. (2001). The effect of treadmill inclination and speed on the activity of three trunk muscles in the trotting horse. *Equine Veterinary Journal*, 33, 466–472.
- Robert, C., Valette, J., Pourcelot, F., Audigie, J., & Denoix, J. (2002). Effects of trotting speed on muscle activity and kinematics in saddlehorses. *Equine Veterinary Journal*, 34, 295–301. <https://doi.org/10.1111/j.2042-3306.2002.tb05436.x>
- Schilling, N., & Carrier, D. (2009). Function of the epaxial muscles during trotting. *The Journal of Experimental Biology*, 212, 1053–1063. <https://doi.org/10.1242/jeb.020248>
- Slijper, E. J. (1946). *Comparative biologic-anatomical investigations on the vertebral column and spinal musculature of mammals*. Amsterdam: North-Holland Publishing Company.
- Sloet van Oldruitenborgh-Oosterbaan, M., & Clayton, H. (1999). Advantages and disadvantages of track vs. treadmill tests. *Equine Exercise Physiology*, 31, 645–647.
- Stern, J., Wells, J., Vangor, A., & Fleagle, J. (1977). Electromyography of some muscles of the upper limb in Ateles and Lagothrix. *Yearbook of Physical Anthropology*, 20, 498–507.
- von Scheven, C. (2010). *The anatomy and function of the equine thoracolumbar Longissimus dorsi muscle*. München: Ludwig-Maximilians-Universität.
- Wakeling, J., Rituechai, P., Dalton, S., & Nankervis, K. (2007). Segmental variation in the activity and function of the equine longissimus dorsi muscle during walk and trot. *Equine and Comparative Exercise Physiology*, 4, 95–103.
- Witte, H., Lesch, C., Preuschoft, H., & Loitsch, C. (1995a). Die Gangarten der Pferde: Sind S chwingungsmechanismen entscheidend? Teil I: Pendelschwingungen der Beine bestimmen den Schritt. *Pferdeheilkunde*, 11(3), 199–206. <https://doi.org/10.21836/PEM19950305>
- Witte, H., Lesch, C., Preuschoft, H., & Loitsch, C. (1995b). Die Gangarten der Pferde: Sind Schwingungsmechanismen entscheidend? Teil II: Federschwingungen bestimmen den Thab und den Galopp. *Pferdeheilkunde*, 11(4), 265–272.
- Witzel, U., Mannhardt, J., Goessling, R., de Michaelis, P., & Preuschoft, H. (2011). Finite element analyses and virtual synthesis of biological structures and their application to sauropod skulls. In N. Klein, K. Remes, C. Gee and M. Sander. (Eds.), *Biology of the Sauropod dinosaurs: Understanding the life of giants* (pp. 171–181). Bloomington: Indiana University Press, ISBN: 978-0-253-35508-9.
- Zschokke, E. (1892). *Untersuchungen über das Verhältnis der Knochenbildung zur Statik und Mechanik des Vertebratenskelettes*. Zürich: Orell Füssli.
- Zsoldos, R., Kotschwar, A., Rodriguez, C., Peham, C., & Licka, T. (2010). Activity of the equine rectus abdominis and oblique external abdominal muscles measured by surface EMG during walk and trot on the treadmill. *Equine Veterinary Journal*, 42, 523–529. <https://doi.org/10.1111/j.2042-3306.2010.00230.x>

How to cite this article: Kienapfel K, Preuschoft H, Wulf A, Wagner H. The biomechanical construction of the horse's body and activity patterns of three important muscles of the trunk in the walk, trot and canter. *J Anim Physiol Anim Nutr.* 2017;00:1–10. <https://doi.org/10.1111/jpn.12840>