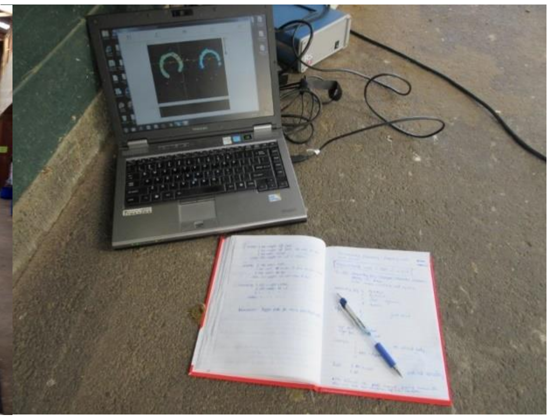
Exploring the use of a standing pressure plate for limb pain detection in high-intensity trained Thoroughbred racehorses

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Abstract

Background: In Thoroughbred racing loss of training days due to musculoskeletal injuries (MSI) is a significant threat to the industry. In humans, it is reported that postural sway, as measured from the Centre of Pressure (CoP) displacement, is altered by MSI even before gait adaptations are apparent; the use of pressure plates for that purpose has not been evaluated in horses yet.

Aim of the study: To measure the effect of a period of high-intensity workload on the CoP displacement and the static pressure distribution under the fore hooves of Thoroughbred racehorses.

Methods: CoP data were captured using a 0.5m Footscan pressure plate over an 8-week period from 15 Thoroughbred racehorses. The horses were from one single training stable where they were trained with a high workload. The horses stood with both forelimbs on the pressure plate. Data were collected at 15 Hz for three sequential one minute recordings per week. The CoP data were filtered using a discrete wavelet transformation with a cut-off frequency of 3.75 Hz and velocity, amplitude and frequency of the CoP displacement were calculated. Pressure scans were collected and analysed to determine the static pressure distribution. Significance level was set at $p<0.05$.

Results: At week 8 there was a significant increase in the frequency of the CoP displacement in the mediolateral axis compared to week 1 (0.28±0.01 vs. 0.30±0.01 Hz, $p<0.05$). There was no difference in velocity (1.88 ±0.32 vs. 1.87±0.28 mm/s) or amplitude (27.31± 5.09 vs. 22.60±3.77mm). Percentage of the total pressure was consistently greater under the right than the left limb (59.94±1.44% vs. 40.06± 1.44%, $p <0.05$). More pressure was located under the cranial half of the hoof than the caudal half of the hoof (61.1±1.34% vs. 38.8±1.34%, $P<0.05$). For left limbs the pressure was higher under the medial side of the hoof than on the lateral side of the hoof (24.1 ±0.88% vs. 21.6±0.8%, $p<0.05$).

Conclusions: The frequency of the CoP displacement seems the easiest reproducible parameter and it changes during eight weeks of training with a high workload and thus might be an indicator of painful limbs. The unloading of the left limb and the lateral side of the left hoof might be due to the counter clockwise training regimen where these areas sustain the most strain. The pressure plate still needs to be validated for CoP measurements.

Introduction

Thoroughbred racing in New Zealand is a major equestrian activity and a contributor to the economy. A significant threat to the racing industry is wastage; in a broad term it covers the loss of training days for one horse but also the loss of race horses from the race industry. Loss of training days may lead to less efficient training and fewer horses entering races. Wastage thus has an economic impact on trainers and the racing industry and may also be an indicator of animal welfare. The highest level of wastage is seen in the young racehorses: 2-year-olds spend 40% of their time in a so called spell or lay up period, and this percentage declines to 12 to 15% when the horses are around 4 to 5 years of age (Perkins et al. 2003). Spelling can be voluntary or involuntary. Voluntary spells are the spells where the trainer decides to give the horse a break, for example to grow and strengthen or mature mentally, but the horse is physically still able to work. When the horse has a condition or injury which makes it unable to train, the spell is considered involuntary (Bolwell 2012, Perkins et al. 2003). In a group of 205 2-year-old racehorses 65.4% had a spell, of which 85.8% were voluntary interruptions. Of the involuntary spells, most (83.0%) were due to musculoskeletal injuries (MSI) (Bolwell 2012). Involuntary spells in 2-year-olds due to MSI have a longer duration than those due to a respiratory system or miscellaneous event (Perkins 2005a). Therefore, it is important to reduce the number of spells due to MSI.

The most common MSI seen in 2-year-old racehorses is dorsal metacarpal disease (DMD) due to cyclic overload of the third metacarpal bone (MCIII), also known as shin soreness or bucked shins (Bailey 1998, Perkins et al. 2003, Wilsher 2006). In New Zealand 16% of the 2-year-olds and 7.5% of the 3-year-olds were spelled due to DMD (Perkins 2005b), and in Australia 42% of the 2-year-olds were reported to present with DMD, however not all of them were spelled (Bailey 1999). DMD can affect one or both forelimbs, but generally the left forelimb is affected first. This may be due to the fact that Thoroughbreds are trained and raced counter clockwise and the left forelimb is the leading limb which presumably receives the highest strain. Horses with DMD show symptoms such as heat, pain, swelling and tenderness of the dorsal surface of MCIII or the limb, and eventually lameness (Nunamaker 2002). Young racehorses with mild lameness associated with DMD, may present a bilateral reduction in stride length. This suggests that subtle symptoms such as unwillingness to stride out and go forward during training can indicate the beginning of DMD (Rogers 2005). However, this can be difficult for the clinicians to observe, unless they had good previous knowledge of the horse. Early detection of the onset of DMD - before gait deficits visible for the human eye appear (subclinical lameness) - could permit modification of training programmes to minimize MSI and wastage (Nunamaker 2002). Therefore, a method to diagnose DMD even in the early stage of subclinical lameness would be beneficial.

It has been shown that horses with MSI have a different loading pattern than sound horses when walked over a force plate. Vertical peak force and impulse of the lame limb are significantly decreased in horses in an attempt to unload the lame limb. The altered loading pattern is apparent in the subclinical phase, before the horse is visually clinically lame (Dow 1991, Ishihara 2005, Ishihara 2009).

Currently, most of the research on loading patterns and lameness in horses is performed using force plates and by walking the horses over the plate. It can be challenging to hit the force plate with a walking, trotting or even galloping horse. Measuring the displacement of the Centre of Pressure (CoP) can be performed while the horse is standing still on the force plate. The CoP is the point of application of the ground reaction force. If the CoP is measured during bilateral standing, it is located between the limbs. Measuring the displacement of the CoP is a way to quantify the postural sway. In humans, postural sway measurements have been used for balance assessments. Impaired balance is observed in individuals with musculoskeletal injuries such as knee osteoarthritis. Regardless whether the osteoarthritis is unilateral or bilateral (Wegener et al. 1997, Hirata et al. 2013), it results in greater postural sway. Even before gait adaptations are apparent, in the early stage of knee osteoarthritis, postural sway is altered (Duffell et al. 2014). In horses, postural sway also has been measured to assess locomotor balance. Various conditions that may influence the horses' balance such as detomidine administration (Bialski 2004), underwater treadmill exercise (King 2013) and blindfolding (Clayton 2014) have been investigated, but the influence of musculoskeletal injuries on the postural sway has not been studied yet. It is likely that horses with joint pain, inflammation or altered muscle activation have impaired motor control, which may result in changes in postural sway (King 2013).

The common way of measuring postural sway is on force plates, and this method has already been validated for horses (Clayton et al. 2003, Clayton and Nauwelaerts 2012). In a few studies on humans the pressure plate has been used to measure postural sway (Clark and Redding 2012, Hoskovcová et al. 2013) and this has also been done with horses (Gomes-Costa et al. 2015), but the measurements have not been done simultaneously with a force plate and thus the outcome has not been validated yet. A major advantage of the pressure plate over the force plate is that it does not require a laboratory setting. There are pressure plates available that are small, light and mobile. Therefore, pressure plates may be convenient not only for research, but also for routine clinical use. The pressure plate can be taken to the patients, and all the features mentioned above can be measured in an environment that is familiar to the patient.

A pressure plate consists of a matrix of sensors that each individually display the pressure. This feature makes it possible to measure the loading distribution of all the limbs that are on the plate at the same time and also determine the pressure distribution underneath one hoof (Oosterlinck 2010, Oosterlinck 2011, Oomen et al. 2012, Oosterlinck 2013, Oosterlinck et al. 2014). In this way, unequal loading of the limbs due to pain i.e. MSI or differences in hoof balance caused by hoof abnormalities can be quantified easily (Rogers 2007). Most of this research has been done at walk or trot, but can also be done with the horse standing (Rogers and Back 2003).

The aim of this project was to measure changes in the CoP displacement in a cohort of Thoroughbreds during eight weeks of intense training. The cyclic overload caused by the training with a high workload may lead to soreness in the limbs of the Thoroughbreds and makes them prone to develop DMD.

Additionally, the static pressure distribution underneath the fore-hooves will be investigated. Because of the training of racehorses in a predominantly counter clockwise direction, the left limb presumably experiences the most strain.

The research questions addressed in this paper are:

- What is the influence of a high workload of a group of Thoroughbred racehorses on the three parameters amplitude, velocity and frequency of CoP displacement?

  Hypothesized is that due to a high workload during the eight weeks of training the forelimbs of the Thoroughbreds become sore. To unload both forelimbs a decrease in amplitude and an increase in velocity and frequency of ML CoP displacement is expected.
- How is the static pressure distribution underneath the forehooves of a group of Thoroughbred racehorses?

  The expectation is that there will be less pressure on the lateral side of the left hoof and the medial side of the right hoof, because the horses are trained and raced in a counter clockwise direction. This may lead to a higher workload on the lateral side of the left hoof and the medial side of the right hoof and these sides therefore could become sore and the horses may try to unload them.

Materials and methods

Horses: A convenience sample of fifteen Thoroughbred racehorses (7 mares, 7 geldings and 1 stallion) ranging in age from 2 to 6 (median = 4, IQR = 2.5 - 4) were included in the study. The horses were from one single training stable. Horses from this stable were used for this study because the trainer of this stable uses a more intense training schedule to train his horses than trainers from surrounding stables. All horses were sound and in training at the beginning of the study.

Data collection: The pressure plate used for this study was the RsScan footscan® 0.5m high-end system (RSscan International NV, Belgium). A rubber mat (3 mm thick) was glued on the top of the pressure plate to make it less vulnerable to nail head penetration from shod horses. The pressure plate was inserted into a plywood frame to level the pressure plate with its surroundings and to reduce the possibility of damage to the plate by a horse standing on the edge of the plate. On top of the frame was a rubber sheet equal to the one on the pressure plate, so the horses could not differentiate between the plywood frame and the pressure plate.

The fifteen horses were followed for 8 weeks. Each week postural sway data was collected using the dynamic measurement option of the Footscan® 7 gait software. All recordings were conducted in the same place within the stable, on a concrete surface that was visually evaluated at providing a horizontal surface. The horses stood with the forelimbs squarely positioned on the pressure plate perpendicular to the long axis of the plate.

Data was collected at 15 Hz and for a duration of one minute. Three separate sequential recordings were performed per horse each week. A recording was considered valid if the horse stood still for at least 15 seconds without any obvious movement. The handler had as little contact with the horse as possible, and preferably stood in front of the horse. A static pressure scan from the two forehooves of the horse was also performed each week.

The trainer of the horses provided a daily training diary. Within the diary the distance and speed of the workout was recorded for each horse, and additional health notes were made if necessary.

Data analysis: For extraction of the data the Footscan® 7 gait software was used. The pressure scans from the two forehooves were analyzed in the software itself, but also exported as Static Images. In the software, the distribution of the pressure between hooves or within one hoof could be made visible.

For the postural sway recordings both hooves of the horse were selected as one foot in the software to get the CoP displacement below both forelimbs together. The Centre of Force line and the Entire Centre of Force were exported from the software. Preferably, the full 66.67 seconds of recording were used for analyzing the Centre of Force line and the Entire Centre of Force. Data were visually screened for integrity and acute displacement of the horse. When the horse moved too much during the recording, for example by lifting its feet up, shaking its head or trembling because of flies on its limbs, only the sections where the horse stood still were used for analysis.

The Entire Centre of Force data was used to determine the velocity, amplitude and frequency of the ML CoP displacement. Before analyzing the CoP displacement, the data was filtered with RStudio Version 0.98.1103, using a Fast Fourier filter with a cut-off frequency of 3.75 Hz to remove high frequency noise from the data. The filtered data was imported into MS Excel 2010 for further manipulation. From the filtered data the velocity, amplitude and frequency of the CoP displacement were calculated.

The Centre of Force line data were used to make graphs of the CoP displacement in ML and CC (craniocaudal) direction (instead of just looking at the ML CoP displacement). The first location of the CoP recording was set as (0,0), and the displacement of the following CoP locations from that point were calculated and plotted in a graph.

The workload was calculated by multiplying distance with velocity, which results in the cumulative workload index (CWI) (Rogers 2007, Rogers 2004). The velocities used to calculate the CWI are listed in

Table 1. The CWI's of each horse were summed per week and for the total eight weeks. The number of times that a horse was trained at a gallop speed (gallops) was counted per horse.

gallop	15.5 m/sec
3/4 pace / steady	13.0 m/sec
1/2 pace	11.5 m/sec
1/4 pace	9.5 m/sec
slow canter	5.0 m/sec

TABLE 1: Velocities used for calculating the CWI (Rogers 2004).

Statistical analysis

Stata IC 12.0 was used for statistical analysis of the data. Descriptive statistics were made for each variable (the velocity, amplitude, frequency, CWI and gallops). Normality of distribution of each variable was tested by using a Shapiro-Wilk normality test. The CoP displacement variables (velocity, amplitude and frequency) from week 1 and week 8 were compared using a one-way-ANOVA. One-way-ANOVA's with a Bonferroni *post hoc* test were used to test for repeated samples within week. The effect of injury, age, number of gallops or incomplete recordings due to movements by the horse was tested using one-way-ANOVA. Differences were considered significant if $P < .05$. To test if there was a relationship between the CWI, or number of gallops, and the frequency of CoP displacement, scatterplots were made, and correlations coefficients were determined.

Results

The CWI per horse per week is displayed in Figure 1. Median CWI was 181,000 (IQR = 147,300 – 207,000). There was some variation in the CWI across weeks and between horses (Figure 1). Horse 3 had a lower workload than the rest of the group, as it was a recently broken-in 2-years-old. In week 5, horse 2 and 12 were spelled from training due to acute MSI. In week 6 horse 5 was spelled for unknown reasons and horse 13 due to chronic MSI. Horse 7 was spelled from training in week 8, due to poor performance.

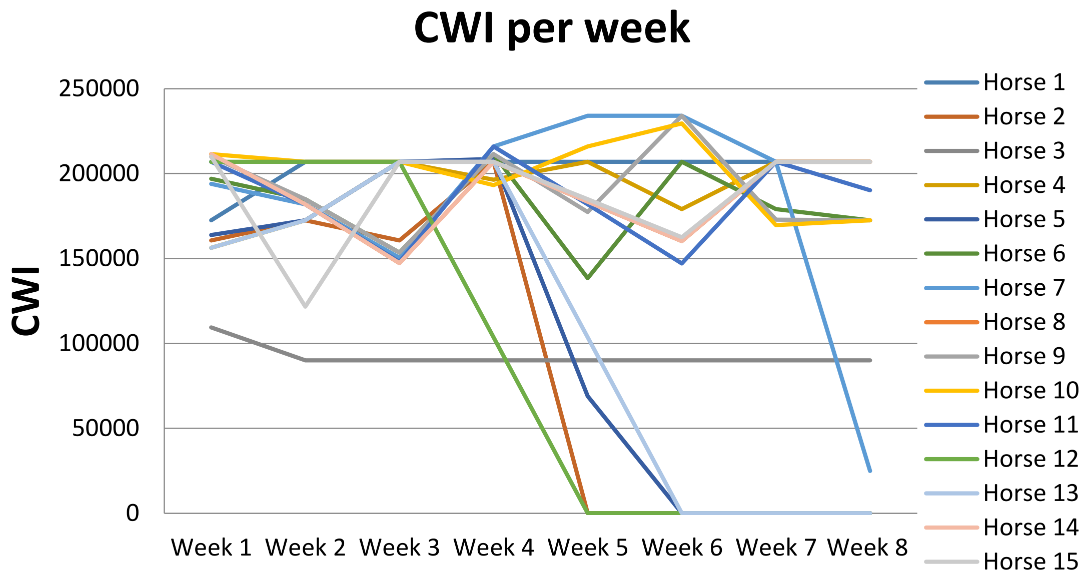

FIGURE 1: The amount of CWI per horse per week.

Figure 2 shows total workload and number of gallops per horse over the observation period. Mean CWI was 1,266,043 (SE 95,623). Median total number of gallops was 4 (IQR = 2 – 6). The horses that were spelled during the trial (horse 2, 5, 12, 13) had a lower total workload and horse 3 has a lower total workload, due to a low daily workload. Horse 1, 3 and 12 did not gallop. Horse 3 and 12 were just broken in 2-years-olds and did not achieve the training milestone of galloping during the trial. Reasons why horse 1 did not gallop were unknown.

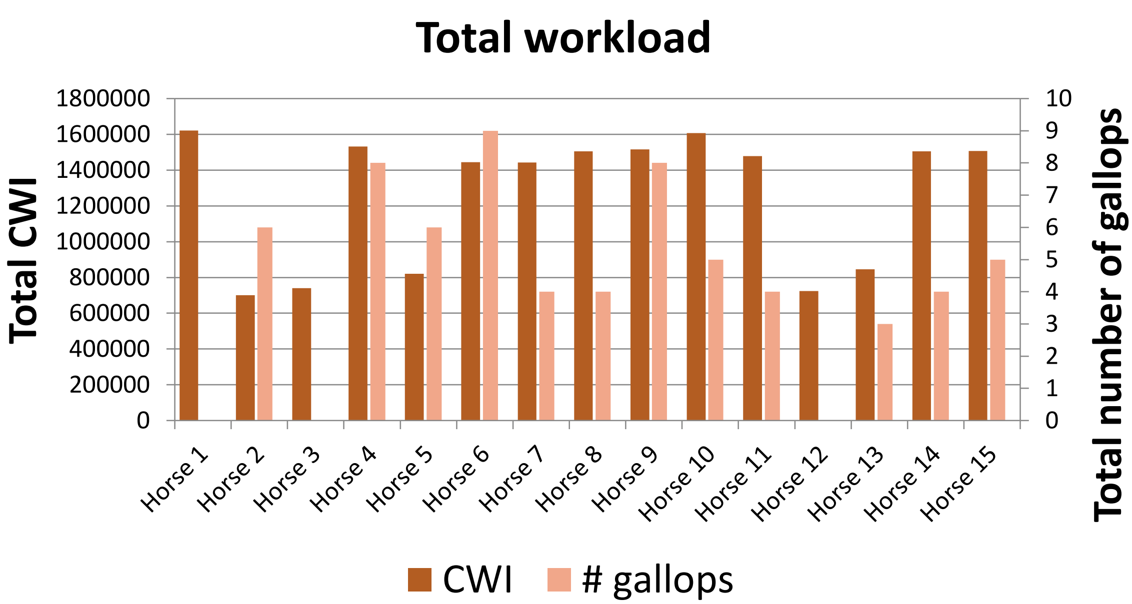

FIGURE 2: Mean of total CWI and median of total number of gallops of all horses over all weeks.

There was no significant effect of repeat within a measurement session on ML CoP frequency, velocity or amplitude. The ML CoP frequency values were significantly different between week 1 and week 8 (Table2). ML CoP frequency values seemed to be higher in the horses that were spelled during this trial, however this is not quantified due to the low number of horses that were spelled and therefore low statistical value of this group.

There were no differences between week in the velocity or amplitude of the ML CoP. Horse age or presence of an MSI did not affect the frequency. No linear relationship between CWI or gallops and frequency of the ML CoP displacement was found. Velocity and amplitude were linearly related to each other (R = 0.77). Velocity was influenced by movements of the horse. The velocity was significantly higher (P = 0.005) in the group of horses that moved during recording, even though the parts of the recording where the horse actually moved were not used for data analysis.

	Week 1		**Week 8**		**P-value**
	mean	SE	mean	SE	
Frequency (Hz)	**0.28**	**0.01**	**0.30**	**0.01**	**0.03**
Velocity (mm/s)	1.88	0.32	1.87	0.29	NS
Amplitude (mm)	27.31	5.09	22.60	3.77	NS

TABLE 2: Frequency, velocity and amplitude of the ML CoP displacement averaged over all horses per week. The P value indicates that the difference in frequency between week 1 and week 8 was significant. Velocity and amplitude did not differ significantly between the weeks. Significant differences are bolded.

The graphs of the Centre of Force line show the stabilogram of the CoP. Distinctive types of stabilograms were observed. Some stabilograms had a CoP displacement predominantly in ML or CC direction, displayed in Figure 3 and Figure 4 respectively. Figure 5 is an example of CoP displacement in both directions (ML and CC).

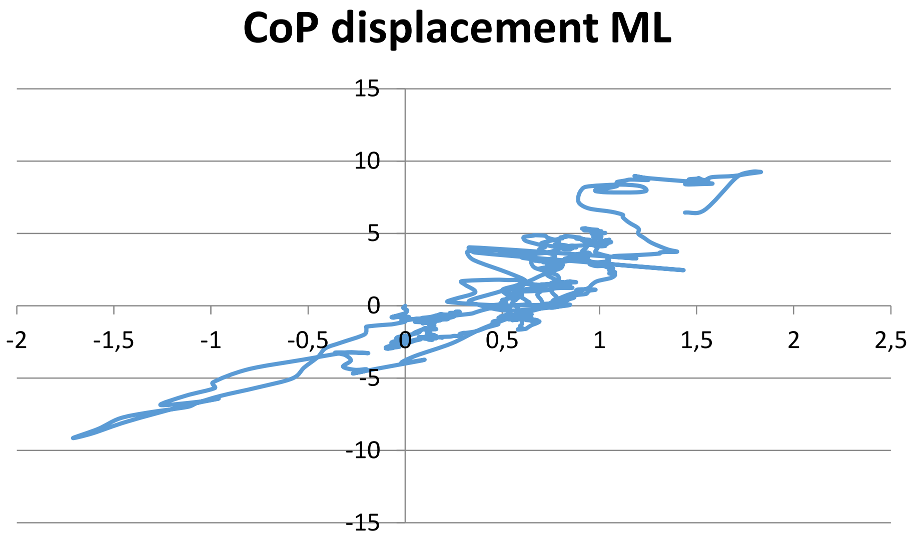

FIGURE 3: CoP displacement mainly in the ML direction. Displacement seen with frame 1 as starting point (0,0). Example by horse 1 week 1.

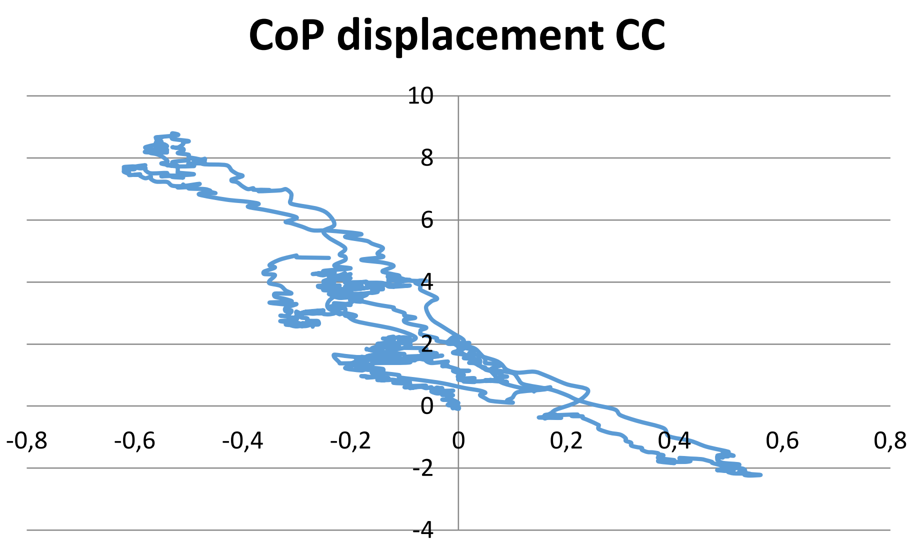

FIGURE 4: CoP displacement mainly in the CC direction. Displacement seen with frame 1 as starting point (0,0). Example by horse 8 week 8.

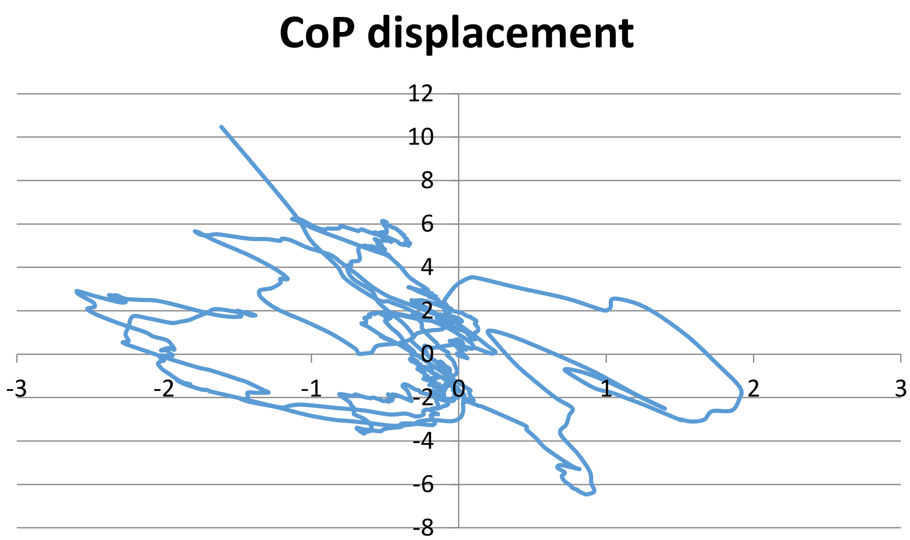

FIGURE 5: CoP displacement in ML and CC direction. Displacement seen with frame 1 as starting point (0,0). Example by horse 4 week 1.

The pressure scans showed the weight distribution over the two limbs and the balance per hoof. Some horses had unequal loading of the limbs as can be seen in Figure 6. Figure 6 shows that in this horse the left limb had less load (44.86%) than the right limb (55.14%) An unequal weight distribution of more weight on the right limb than on the left limb was a consistent observation (24/30 measurements, $P<0.05$) with 40.06% (SE 1.44) of the weight on the left limb and 59.94% (SE 1.44) on the right limb.

In Figure 6 it can also be observed that in this horse more pressure was located in the cranial region (57.73%) than in the caudal region (42.27%). All horses in this population had this pressure distribution (30/30 measurements, $P<0.05$), with 61.1% (SE 1.34) of the pressure in the cranial region.

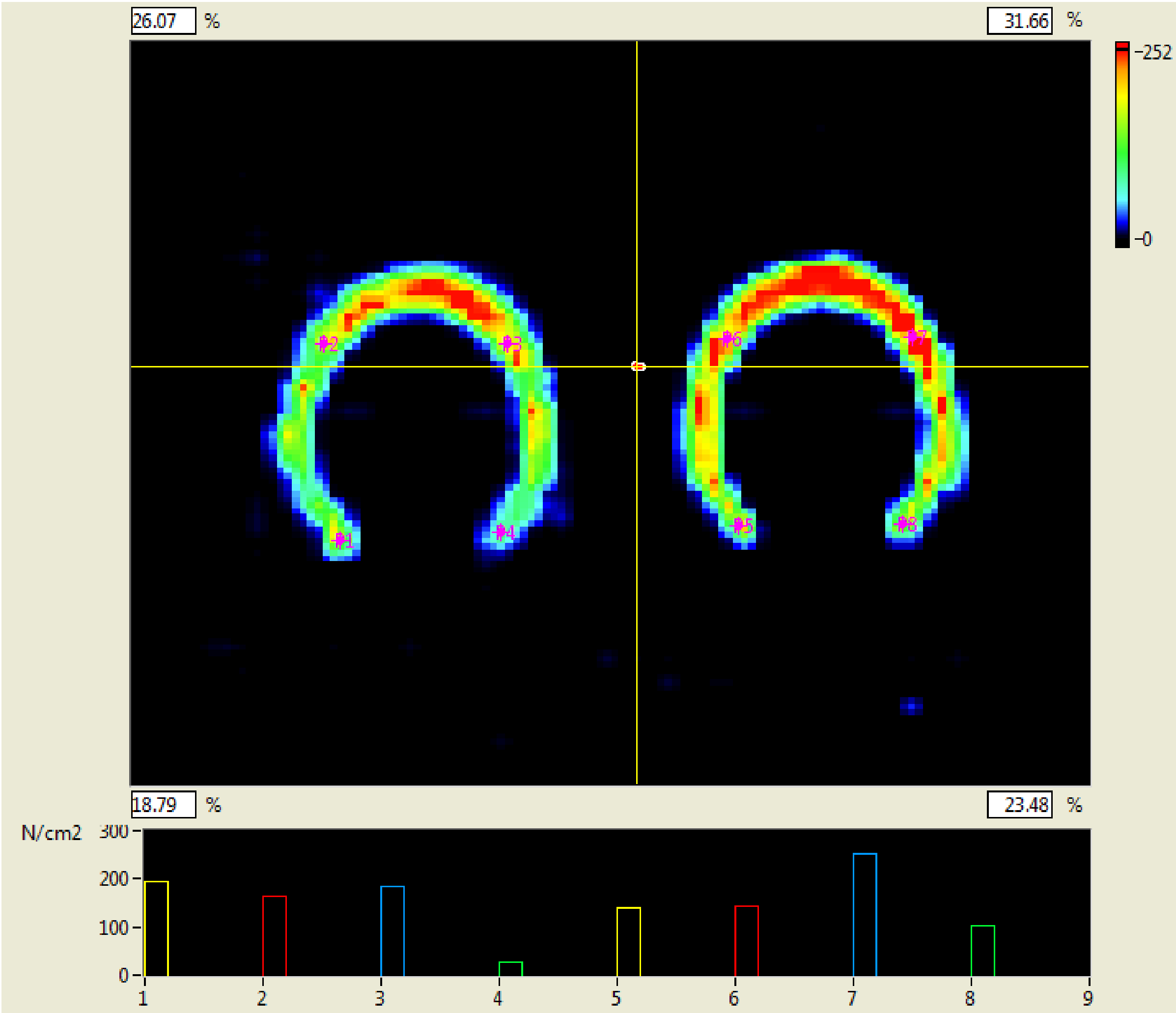

FIGURE 6: Example of a pressure scan distribution demonstrating more weight on the right hoof than on the left hoof, and more weight on the toes than on the heels.

The CoP from the forelimbs is indicated by the red dot between the hooves. The yellow lines through the CoP divide the pressure scan in 4 areas. The amount of weight bearing is shown as percentage of the total pressure per area. The column-chart below the pressure scan shows the amount of pressure on 8 certain points. The 8 points are indicated by purple dots. Points 1 until 4 are positioned on the pressure scan of the left hoof. Point 1 is on the lateral heel, point 2 on the lateral toe, point 3 on the medial toe and point 4 on the medial heel. Points 5 until 8 are positioned on the pressure scan of the right hoof. Point 5 is on the medial heel, point 6 on the medial toe, point 7 on the lateral toe and point 8 on the lateral heel. Example by horse 10 week 4.

In Figure 7 a pressure scan is displayed which shows the medial and lateral pressure distribution within the limbs. This horse had greater pressure on the medial side of the left and lateral side of the right limb. This pressure distribution was observed in most of measurements. In 22/30 measurements ($P<0.05$) the horses had more weight on the medial side of the left hoof (24.07%, SE 0.88) than on the lateral side of the left hoof (21.62%, SE 0.80). In 16/30 measurements the horses had more weight on the lateral side of the right hoof than on the medial side of the right hoof, however this was not significant.

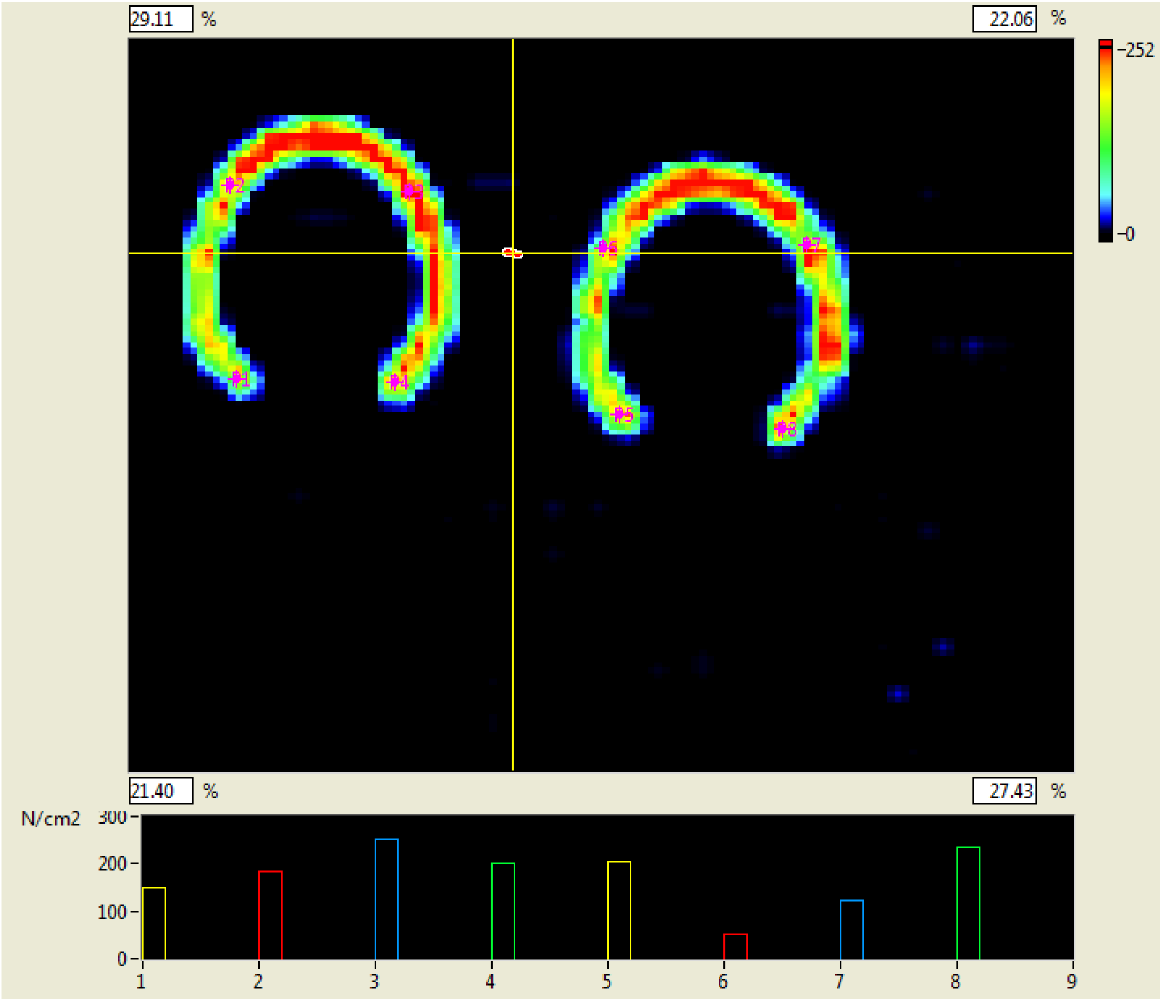

FIGURE 7: Pressure scan of the front hooves, where the horse has more pressure medial (left limb) and lateral (right limb). The CoP from the forelimbs is indicated by the red dot between the hooves. The yellow lines through the CoP divide the pressure scan in 4 areas. The amount of weight bearing is shown as percentage of the total pressure per area. The column-chart below the pressure scan shows the amount of pressure on 8 certain points.

The 8 points are indicated by purple dots. Points 1 until 4 are positioned on the pressure scan of the left hoof. Point 1 is on the lateral heel, point 2 on the lateral toe, point 3 on the medial toe and point 4 on the medial heel. Points 5 until 8 are positioned on the pressure scan of the right hoof. Point 5 is on the medial heel, point 6 on the medial toe, point 7 on the lateral toe and point 8 on the lateral heel. The table shows how the weight is distributed over the hooves. Example by horse 11 week 4.

Left front hoof		Right front hoof	
50.5%		49.5%	
Left lateral side	Left medial side	Right lateral side	Right medial side
23.09%	27.41%	23.25%	26.25%

Discussion

In this study the CoP displacement of a group of Thoroughbred racehorses was measured during eight weeks of intense training. Frequency, velocity and amplitude of the CoP displacement were measured.

The frequency of CoP displacement significantly increased after 8 weeks of training with a median Cumulative Workload Index (CWI) of 181,000 per week per horse. The frequency changed significantly from 0.28 (SE 0.01) Hz in week 1 to 0.30 (SE 0.01) Hz in week 8 ($P<0.05$). Velocity and amplitude stayed the same around 1.88 mm/s and around 25 mm respectively. Nonetheless, within this group of horses, different stabilograms were displayed. Some shifted their weight only in ML or CC direction during the recording, where others shifted their weight in both directions

With the pressure scans of the hooves, it was shown that most of the horses had more weight on their right limb (24/30 measurements, $P<0.05$) and loading of the cranial aspect of the hoof (30/30 measurements, $P<0.05$). There were also differences in the medial vs lateral loading per hoof; more weight on the medial side of the left hoof than on the lateral side of the left hoof was seen in 22/30 measurements ($P<0.05$) and, more weight on the lateral side of the right than on the medial side of the right hoof was seen in 16/30 measurements (NS).

The horses were in race training during this study, so there was an increase in the cumulative load cycles the limbs were exposed to, which is quantified with the CWI. Connective tissues adapt as a response to workload. How they adapt, depends on the balance between exercise and recovery periods. The tissues can develop positively and become stronger after every training session and then the performance of the horse improves. When the recovery period is too short, the tissues can become fatigued, MSI can occur and the horse can become lame.

When more studies use the CWI to describe their workload, it would be possible to compare different training strategies, and find out when the workload is too high and the risk on MSI increases.

The CWI from these horses was on average 181,000 per week. This CWI seems higher than previously reported workloads calculated by Rogers that are ranging from 63,000-172,000 per week (Rogers 2004). (Verheyen et al. 2006) showed an increased risk on stress fractures with a CWI of 154,000 per week. The high CWI in the current study may have overworked the horses and led to (subclinical) MSI. Three of the fifteen horses were spelled due to an MSI, however none of them was diagnosed with DMD. Cyclic overload injuries such as DMD can be expected, especially in 2-year-olds (Bailey 1999, Nunamaker 2002, Perkins 2005b). For this study only two 2-year-olds were available. One of the 2-year-olds, horse 3, had a lower CWI than the rest of the horses. This horse might have been just in training to get used to the procedures (psychological training), and not for actual physiological training, and was therefore not in risk of developing DMD. With a larger group of 2-year-olds, there is greater chance that some of them would develop DMD, and it would be interesting to measure the affected horses to determine how their CoP displacement changes.

In humans it is known that musculoskeletal pain affects balance negatively (Lihavainen 2010, Hirata et al. 2011, Hirata et al. 2012, Patel et al. 2014). This leads to a larger postural sway which can be quantified by measuring the CoP displacement. Horses with MSI are likely to have impaired balance as well (King 2013). The horses in this study experienced a high workload, compared with previous reported workloads, and probably were on risk for developing MSI. The increase in frequency of the ML CoP displacement might be a sign of an impaired balance due to (subclinical) MSI. The horses that were injured during this research also seemed to have a higher frequency of the CoP displacement than sound horses. The difference was not significant, but this may be due to the low number of injured horses (3 horses out of 15).

In addition to the higher frequency of CoP displacement after the 8 weeks of training with a high CWI, there were other indicators of tissue response to cyclic load (and possible subclinical injuries). The pressure scans showed that most horses had less weight on their left hoof (40.06%, SE 1.44) than on their right hoof (59.94%, SE 1.44) and when looked more in detail the horses had less weight on the lateral side of the left hoof (21.62%, SE 0.80) than on the medial side of the left hoof (24.07%, SE 0.88). During training and racing in a counter clockwise direction, the leading (left) limb is on a higher risk for dorsal carpal fractures and superficial digital flexor tendinopathy and the left limb is often also affected first when a horse develops DMD (Denoix 1994, Nunamaker 2002, Whitlock 2012). (Firth et al. 2005) found most subchondral bone remodelling of MCIII on the lateral side of the left and the medial side of the right limb of trained Thoroughbreds and suggested that this phenomenon is caused by high strain in these areas. Even though the horses of this study were not visibly lame, (subtle) pain caused by the cyclic load and high strain of the race training may be present and the horses' division of weight a first attempt to unload their overworked limbs or parts of their hooves.

Another phenomenon that all horses showed was that they put more weight on their toes than on their heels. This cannot be explained by the counter clockwise training, but it is in agreement with previous findings of (Rogers et al. 2003) who investigated hoof loading in a group of sound Dutch warmblood horses. They suggest that this weight division might be due to hoof conformation and shoeing.

The frequency of the CoP displacement found in this study is in agreement with previous findings of Clayton on a force plate in other sound horses, where the ML CoP displacement was 0.30 Hz. Clayton also measured the velocity and amplitude of the CoP displacement and found a velocity of 2.2 mm/s and an amplitude of 9.3 mm (Clayton 2014). (Gomes-Costa et al. 2015) also published data on velocity and amplitude of CoP displacement, 4.3 mm/s and 3.2 mm respectively, and this data was collected on a pressure plate. For both studies can be said that the velocity is a little higher than the velocity found in this study and the amplitude is lower. These differences may be due to horse breed differences or fatigued horses, since neither of the studies used Thoroughbreds with a high CWI. However, they may also be explained by the setup of the trial. Clayton analysed 15 seconds and Gomes-Costa 8 seconds. With a frequency of CoP displacement of approximately 0.30 Hz only 2-4 CoP displacements were captured in these recordings, which may be too few to be representative for the CoP displacement. By recording for approximately 60 seconds, as was performed in the current study, more CoP displacements were measured, and this method therefore gives a better indication of the amplitude of the CoP displacement. Another reason for the difference in amplitude is that Gomes-Costa considered a recording valid if the amplitude of the CoP of each limb in CC and ML direction was smaller than 10 mm. She found that larger displacements were due to gross movements of the head or limbs. Clayton also did not accept recordings where legs moved or where the head moved more than within a 5 cm x 5 cm x 5 cm volume around a head marker. In the present study the same validations for a recording were made approximately. Movements of the limbs were not allowed, and neither were gross movements of the head, but these movements were only determined visually. The higher velocities that Clayton and Gomes-Costa found can probably also be explained by the fact that they captured data with a recording speed of 60 Hz and 50 Hz respectively, and not 15 Hz. Small and quick displacements of the CoP can be detected and taken into account when calculating the velocity, but the risk to include noise into the calculations will increase. To remove noise from the recordings in this paper a Fast Fourier filter of 3.75 Hz was used. With this filter the CoP displacement frequency of 0.30 Hz reported earlier by Clayton would not be filtered away, and the form of the CoP displacement graph was smoothened out without losing its original form. However, the large variance in this research of the amplitude and velocity of the CoP displacement, and the significant differences between reported amplitudes and velocities of the CoP displacement in several studies show that more research is necessary to find out what the meaning of these two parameters is, and how they can be measured best.

In the current study there was a large standard deviation measured for the velocity and amplitude of the CoP displacement. This could be due to the fact that the horses were not homogenous. They were all a different age and therefore in a different stage of training. This could affect their balance, but also their mental focus on standing still on the pressure plate. By using a more homogenous group of horses, variance can be minimised and then little changes in postural sway can be detected. Another reason for the large variance could be that the environment during measuring was not entirely the same every week. Some days the horses could have been less focussed due to weather conditions, the farrier or new horses that were arriving. Also, the horses were allowed to freely pick their position on the pressure plate, as long as they stood with both forelimbs completely on the pressure plate and facing in the same direction each time. These different factors could have led to more variance in CoP displacement measurements than just the variance due to individual differences.

Different types of stabilograms of the displacement of CoP were found. Some horses had a postural sway only in the ML or CC direction, where others had to balance in all directions. Since the body axis of the horse is longer in the CC direction than in the ML direction, they are probably more stable in the CC direction than in the ML direction. That would explain why horses would shift their weight mostly in the ML direction, although the weight shifting exclusively in ML direction seems unnatural. An explanation for that phenomenon still remains to be found. It would also be interesting to find out why there are several horses that only shift their weight in the CC direction. Clayton also displayed a stabilogram with this phenomenon (Clayton and Nauwelaerts 2012). Hypothetically, it might be an attempt of the horses to unload both their front or their hind limbs when they are bilateral sore, and the horses do not want to have more weight on their left limb than on their right limb.

There are several parameters of the CoP displacement that can be measured. The frequency of the CoP displacement seems the easiest reproducible parameter and it changes during eight weeks of training with a high workload and thus might be an indicator of overworked and painful limbs. Amplitude and velocity of CoP displacement show great variance within this research, but also between different studies. More research needs to be done to determine the value of these two parameters. Stabilograms display the direction of the CoP displacement and thus give visual information about the CoP displacement.

The pressure scans of the hooves give information on how the horse distributes its weight during standing. The static pressure distribution may give an indication on which parts of the horses' hooves or limbs are painful and evaluating the distribution can be useful to monitor recovery during therapy.

At this point it seems possible to measure CoP displacement with a pressure plate. However, the pressure plate needs to be validated for measuring CoP displacement. When the pressure plate is validated for measuring CoP displacement, more data can be collected outside of the laboratories. It would be interesting to establish reference values for CoP displacement of sound horses and to know how CoP displacement changes with different types of training or with lameness such as DMD. Therefore, more research needs to be done before it can be stated that the standing pressure plate can be used for pain detection in Thoroughbred racehorses.

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