Graduate School for Cellular and Biomedical Sciences
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Kinetics and kinematics of the tölt:
Effects of rider interaction and shoeing manipulations

PhD Thesis submitted by

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Content

Thesis Abstract

Introduction – Compared to most equine horse breeds which are able to walk, trot and canter /gallop, the gait repertoire of the Icelandic horses additionally includes the lateral gait tölt and frequently also the pace. With respect to the tölt gait, special shoeing, saddling and riding techniques have been developed for Icelandic horses in order to enhance its expressiveness and regularity. Toes are left unnaturally long and heavy shoes and paddings, as well as weighted boots are used to enforce the individual gait predisposition. For the same reason, the rider is placed more caudally to the horse's centre of mass as compared to other riding techniques. The biomechanical impact of these methods on the health of the locomotor system has so far never been subject of systematic research.

Objectives – The aims of the presented study are
(1) to describe the kinetic and kinematic characteristics of the tölt performed on a treadmill,
(2) to understand the mechanical consequences of shoeing manipulation (long hooves, weighted boots) on the loading and protraction movement of the limbs, as well as
(3) to study the pressure distribution and effects on the gait pattern of 3 different saddle types used for riding Icelandic horses.

Materials and methods – Gait analysis was carried out in 13 Icelandic horses at walk and at slow and medium tölting and trotting speeds on a high-speed treadmill instrumented for measuring vertical ground reaction forces as well as temporal and spatial gait variables. Kinematic data of horse, rider and saddle were measured simultaneously. Gait analysis was first carried out with high, long hooves (S_H) without and in combination with weighted boots (ad aim (2)). Afterwards, horses were re-shod according to current horseshoeing standards (S_N) and gait analysis was repeated (ad aims (1) and (2)). In a second trial, horses were additionally equipped with a pressure sensitive saddle mat and were ridden with a dressage-like saddle (S_{Dres}), an Icelandic saddle (S_{Icel}) and a saddle cushion (S_{Cush}) in the standard saddle position (ad aim 3).

Results and conclusions – Compared to trot at the same speed, tölting horses had a higher stride rate and lower stride impulses. At the tölt loading of the forelimbs was increased in form of higher peak vertical forces (Fz_{peak}) due to shorter relative stance durations (StD_{rel}). Conversely, in the hindlimbs, longer StD_{rel} resulted in lower Fz_{peak}. Despite the higher head-neck position at tölt, there was no measurable shift in weight to the hindlimbs. Footfall rhythm was in most horses laterally coupled at the tölt and frequently had a slight four-beat and a very short suspension phase at trot; underlining the fact that performance of correct gaits in Icelandic horses needs special training. Gait performance as it is currently judged in competition could be improved using a shoeing with S_H, resulting in a 21 ± 5 mm longer dorsal hoof wall, but also a weight gain of 273 ± 50 g at the distal limb due to heavier shoeing material. Compared to S_N, S_H led to a lower stride rate, a longer stride length and a higher, but not wider, forelimb protraction arc, which were also positively associated with speed. At the tölt, the footfall rhythm showed less tendency to lateral couplets and at the trot, the suspension phase was longer. However, on the long term, S_H may have negative implications for the health of the palmar structures of the distal foot by increased limb impulses, higher torques at breakover (up to 20%); as well as peak vertical forces at faster speeds. Compared to the shoeing style, the saddle type had less influence on limb forces or movements. The slight weight shift to the rear with S_{Cush} and S_{Icel} may be explained by the more caudal position of the rider relative to the horse's back. With S_{Cush}, pressure was highest under the cranial part of the saddle, whereas the saddles with trees had more pressure under the caudal area.

General Introduction

The Icelandic horse – a gaited horse breed

The Icelandic horse is the only existing horse breed in Iceland since more than 1000 years. Its earliest ancestors were probably taken there by Viking Age Scandinavians between 860 and 935 AD (Edwards, 1994). Later settlers from Ireland, the Isle of Man and the Western Isles of Scotland arrived with ponies which would elsewhere become Shetland, Highland and Connemara ponies and which were crossed with the animals previously imported to Iceland (Bongianni, 1988). Other breeds with similar characteristics include the Yakut pony, the Nordlandshest of Norway, the Faroe pony of the Faeroe Islands and the Norwegian Fjord horse (Edwards, 1994; Edwards and Candida, 1987; Neville, 2008). Attempts to introduce Eastern blood into the Icelandic horse breed about 900 years ago were not successful (Edwards, 1994). In 982 AD, the Icelandic parliament passed laws prohibiting the importation of horses into Iceland, thus ending any crossbreeding (Evans, 2008).

In the 1940s, Icelandic horses were introduced to the European continent. Particularly over the last years, their popularity for pleasure riding but also for competing at highest levels has been growing constantly. Beside the friendly character and robust nature of this pony breed, its attractiveness might be mainly due to its ability to perform additional gaits. There are also three-gaited Icelandic horses, but most of them have a natural predisposition for either four- or five gaits. Four-gaited horses naturally show walk, trot, tölt and canter and five-gaited horses are additionally able to pace. What makes the tölt particularly attractive is the fact that it can be performed over a wide speed range, from walking up to galloping speeds, and that it is very comfortable for the rider travelling over long distances.

In riding manuals and guidelines for Icelandic horse competitions, the tölt is described as a symmetric and even four-beat gait pattern with a footfall sequence of left hind - left fore - right hind - right fore (**Figure 1**). There is a sequence of single support and double support phases; the latter alternating between ipsilateral and diagonal double supports. Ideally, the duration of diagonal and ipsilateral stance phases should be the same (Anonymous, 2014c; Feldmann and Rostock, 1986c). Traditionally, tölt is considered as a gait without airborne phase; however, Zips et al. (2001) described the presence of an airborne phase depending on speed. The pace is a lateral two-beat gait with a suspension phase which is usually only ridden at high speed over short distances (Feldmann and Rostock, 1986c).

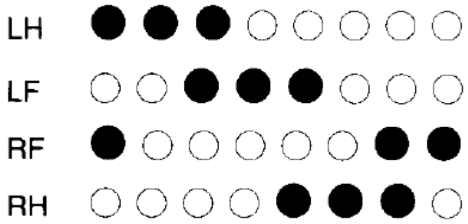

Figure 1: Footfall pattern of the true tölt as described by Zips et al. (2001). Black circles indicate limbs supporting weight; open circles indicate unweighted limbs. L, R, F and H specify left, right, fore and hind limbs.

Lateral gaits are naturally occurring in different animal species and horse breeds. There is evidence that even the ancestors of the modern horse living 3.5 million years ago found in Africa (Hipparion) had the ability to tölt (Feldmann and Rostock, 1986a). The tölt was common also in Mid-European horse breeds and was eliminated via breeding with the beginning of the road system, when horses started to be used rather for drawing carriages than for being ridden so that the comfort for the rider lost its importance (Feldmann and Rostock, 1986a).

The tölt is a biomechanically very interesting gait as it can be ridden even at fast speeds of up to 11 m/s without the occurrence of a suspension phase (Anonymous, 2014b). Due to this difference in gait mechanics, e.g. compared to trot, it would be interesting, particularly for orthopaedic reasons, to compare limb loading at the tölt with that of the trot at the same speed.

Traditional Icelandic riding and management techniques with possible implications for horse welfare

With respect to their particular gaits, special gait competitions for Icelandic horses have been developed where besides speed and engagement of the horse also the correctness of the footfall rhythm, its posture and the expression of its movements are evaluated (Anonymous, 2014c). A clear and regular footfall rhythm, a high head-neck position (HNP), as well as a light and shortly stepping forehand with a high forelimb protraction arc are currently rewarded with good marks (Anonymous, 2014c). In order to improve the footfall rhythm particularly of the tölt gait and enhance its expressiveness, special practices concerning shoeing, saddling and riding have been developed in Iceland over ages and were adopted for exported Icelandic horses also in other countries. Hooves are systematically grown unnaturally high and long (**Figure 2**) and for the tölt training, long toes and heavy shoes, often combined with weighted boots (**Figure 3**), are used to help the horse to find a regular gait pattern and enforce its balance. Horses with the tendency to trot require weighting of the hind limbs, whereas pacey horses need additional weight in the front limbs to improve their tölt (Feldmann and Rostock, 1986c).

Figure 2: Very high left front hoof with atrophied frog and asymmetric heels.

Figure 3: Commonly used weighted boot.

In competition, high, long hooves and weight at the level of the distal forelimbs are used to additionally achieve both longer strides and higher action in order to increase the expressiveness of the gaits. The inventiveness of riders and trainers to develop different means of gait manipulation was high, particularly in former times, and partly interfering with horse welfare. Therefore, the inclusion of detailed guidelines for trimming, shoeing and permitted boots in the rules for Icelandic sport and breeding horses became necessary in order to prevent excess (Anonymous, 2013). Maximal dorsal hoof length is now limited to 95 mm in sport competitions, excluding horses with a height at the withers of 145 cm which are allowed to have 100 mm long dorsal hoof walls. In breeding competitions, these rules are slightly stricter limiting dorsal hoof length to 90 mm. As exceptions, a dorsal hoof length of 95 mm is allowed in horses with a height at the withers of 137 to 144 cm and, as in sport competitions, for horses measuring 145 cm or more a length of 100 mm is permitted. However, these regulations still allow for much more than what would be considered as physiologic in other horse breeds. Still today, many Icelandic horses are seen in competition with very long toes and/or high hooves in relation to their bodyweight and size.

In order to ride a horse in tölt, it is stated in riding literature that the rider needs to induce a slight shift in weight towards the horse's hindquarters (Feldmann and Rostock, 1986c). This is thought to be achieved by the rider having a more caudal position in relation to the horse's back and/or by elevation of head and neck (**Figure 4**). The approach aims to 'free-up the shoulder', allowing an increased movement of the shoulder and, consequently, the forelimb which is a desirable effect in Icelandic horse competitions. There are two different ways to position the rider more caudally with respect to the horse's centre of mass (CoM); either by placing him in the rear part of the saddle or, more effectively, by positioning the whole saddle further caudally on the horse's back. However, it is neither known if and to which extent the CoM of horse and rider can thus be altered, nor whether this really increases the performance ability of the tölt.

Figure 4: Icelandic horse ridden with a high head-neck position and a caudally placed saddle by an unproportionally heavy rider.

Due to the relatively small size of the Icelandic pony and the fact that they are often ridden by heavy adults (**Figure 4**), saddle fitting in general is a challenge in Icelandic horses. The saddle on one hand should not be too large for their short backs and on the other offer enough space for the rider and provide enough contact area to redistribute its weight. Traditionally, large, flat saddles with padded bars (Trachtensättel) extending into the lumbar region with the deepest point of the saddle far back were used to ride long distances comfortably. They allowed the rider to choose or change his seat more freely on the horse's back than in saddles of other breeds. Their large contact area probably might have kept the pressures under the saddle relatively low even when riders were heavy or the saddle did not fit perfectly well. As a consequence of biomechanical studies in other horse breeds, these traditional saddling and riding methods considered as "normal" over a long period of time in Icelandic horses are being judged with increasing scepticism among riders and trainers (Schwörer-Haag and Haag, 2013). A new type of saddle for Icelandic horses has recently been developed which has a design similar to that of English dressage saddles. These saddles are to be positioned according to the recommendations for English saddles used in non-gaited horse breeds (Harman, 2004) and are likely to be a clear improvement if they are fitted well to the horse. However, if this is not the case, they might be even more harmful as their contact area is much smaller. Treeless saddles are also widely used in Icelandic horses, based on the idea that they fit every horse and allow the rider to adjust its seat position according to the need to support the gait similar to the formerly used Trachtensattel.

The abovementioned shoeing, saddling and riding practices used in Icelandic horse have been developed empirically over centuries and are commonly applied in an exaggerated way without scientific proof of their effects on the gait. The functional and biomechanical impact of these methods on the locomotor system and their consequences on health and welfare of the horses has so far never been subject of systematic research.

Scientific background

Compared to the three basic equine gaits which have been under study since many years (Barrey, 2013), relatively few scientific investigations have been carried out on footfall pattern and kinetic and kinematic aspects of the tölt (Biknevicius et al., 2004, 2006; Nicodemus and Clayton, 2003; Robilliard et al., 2007; Zips et al., 2001). Even less data is available about the influence of additional weights at the level of the limbs (Boehart et al., 2013; Pecha et al., 2011; Rumpler et al., 2010) and there are no studies investigating the effects of different shoeing and saddling methods or riding style.

Additional gaits

The ability of the Icelandic horse to perform lateral gaits such as the tölt could recently be attributed to a mutation of the DMRT 3 gene (Andersson et al., 2012). The tölt is biomechanically a very interesting as it can be performed from walking up to cantering speed without the presence of a suspension phase.

In previous investigations, it could be shown that the clearness of its four-beat rhythm was limited in individual animals to a small velocity range (Zips et al., 2001). Beside the “true” tölt (**Figure 1**), different four-beat variations were observed and categorised as support sequences of tölt with lateral and diagonal couplets (minor variation) and support sequences of four-beat pace and four-beat trot (major variation). At slow speeds, the most frequent gait pattern was a tölt sequence with lateral couplets; at medium and high speeds, four-beat pace was the most frequent fault. The study confirmed empirical observations that the footfall pattern of tölt alternates between single support and double limb support phases; however, it also demonstrated that, depending on speed and the horse’s body tension, three-limb support and suspension phases may occur (Zips et al., 2001). It is important to understand the gait characteristics of the tölt in order to be capable to distinguish physiological from pathological variations and thereby provide adequate veterinary care.

The tölt is difficult to categorise within the traditional locomotion classification for quadrupeds based on criteria like duty factor, presence of a suspension phase, Froude number, phase relationship between potential and kinetic energies and vertical ground reaction force profile (Alexander and Jayes, 1983; Biknevicius and Reilly, 2006; Gatesy and Biewener, 1991; Hildebrand, 1965, 1989; Pratt and O'Connor, 1976). According to this multidimensional approach, the tölt is neither a true walking (pendulum like mechanism) nor a running gait (spring-like mechanism) (Cavagna et al., 1977). Depending on speed, the tölt may display both, walking and running characteristics, but was recently judged to be more similar to a run (Biknevicius et al., 2004; Biknevicius and Reilly, 2006; Robilliard et al., 2007; Starke et al., 2009). With duty factors between 0.41 and 0.66, Froude numbers ranging from 0.21 to 3.13 and phase shifts of kinetic and potential energy mostly at <90°, classification of the tölt was somewhat ambiguous (Biknevicius et al., 2006; Starke et al., 2009). The percentage of elastic energy recovery in tölt was also intermediate in comparison to walk (high values) and trot (low values) (Biknevicius et al., 2006). It was hypothesised that Icelandic horses take advantage of energy saving spring-mass mechanics while retaining a large basis of pedal support due to longer relative stance durations and frequent proprioceptive feedback from ground interaction as it is typical for slower gaits (Biknevicius et al., 2006).

Features of tölt, characteristic for a walking gait, were the footfall pattern of a lateral-singlefoot gait, the almost complete absence of a suspension phase and the low range of vertical excursion of the back (12 mm instead of 53 mm at the trot) (Biknevicius et al., 2006; Buchner et al., 2000). However, the occurrence of an aerial phase has been described by (Zips et al., 2001), particularly at higher speeds (4.4 m/s).

It has been hypothesised that there might be advantages of lateral gaits, lacking a suspension phase as the tölt, over other running gaits regarding reduced musculoskeletal strain and increased balance due to prolonged limb contact times. Estimations about the level of peak vertical forces at the tölt compared to trot can be found in the literature, but so far have yielded conflicting results. One group presumed that extremely low duty factors might lead to higher peak forces at tölt (Robilliard et al., 2007), whereas others argued that greater overlap of limb support might result in lower peak vertical forces compared to horses trotting or cantering at similar speeds (Biknevicius et al., 2004). Peak vertical forces of tölt of the first mentioned study were indirectly calculated from kinematic measurements; the latter group used a force plate and compared the results with those of similar studies in other breeds from the literature. In the Icelandic horse itself, peak vertical forces of different gaits at the same speed have never been determined yet. Lower musculoskeletal forces at the tölt would be advantageous in regard to limb health and might have been a determinant for the development and use of this gait.

Shoeing manipulation (“mechanical doping”)

Proper and adequate trimming and shoeing are crucial for horse health. They affect not only the hoof capsule causing pathological changes of the hoof capsule, but also internal structures of the foot affecting the hoof mechanism and its nutrition, but also have a direct biomechanical influence on the distal and proximal limb loading. Many veterinarians and farriers claim that a large proportion of lamenesses could be prevented by proper shoeing (Butler, 1985).

The shoeing should one hand restore a good cranio-caudal and medio-lateral balance and on the other create correct hoof dimensions in relation the horse`s size. How to correctly balance a hoof is relatively well described in literature. There are 3 common approaches applying geometric or dynamic principles or using the “natural balance concept” (Ovnicek et al., 2003). The combination of these 3 concepts has been proposed as the most functional solution for trimming and shoeing (Balch et al., 1995). However, the optimal, physiologic hoof length of an individual horse is still difficult to define. Some authors have claimed that it depends on the relative position of the 3rd phalanx within the hoof capsule, the thickness of the hoof wall, the hoof shape and the horse’s athletic endeavour (O'Grady and Poupard, 2003). One categorisation based on the weight of the horse proposes 7.6 cm for the length of the dorsal hoof wall in small horses (360-400kg), 8.25 cm in medium sized (425-475kg) and 8.9 cm in large horses (525-575kg) (O'Grady and Poupard, 2003).

Excessive toe length increases stress on the dorsal hoof wall with the possibility of hoof capsule distortion due to the longer lever arms (O'Grady and Poupard, 2003; Parks, 2003). It might also play a role in the initiation of the long toe-underrun heel-syndrome (O'Grady and Poupard, 2003). High hooves compromise the hoof mechanism and lead to an underdevelopment of the frog due to a lack of pressure; consecutively under-run heels might develop. The relative lengths of the medial and lateral hoof walls determine the medio-lateral orientation and balance of the hoof. Sheared heels might develop when a difference of the length of the heels is present (O'Grady and Poupard, 2003). Increased pressure on one heel may predispose the foot to pain, subsolar bruising, corns, quarter and heel cracks, fracture of the bar, pedal osteitis, ossification of the hoof cartilages, deep fissures within the base of the frog and thrush if the frog is narrow (O'Grady and Poupard, 2003).

Concerning the biomechanical effects of the shoeing, the longer lever arm of the toe requires a higher tension within the deep digital flexor tendon and its accessory ligament during breakover and leads to increased compression of the navicular bone (Page and Hagen, 2002). Breakover itself is delayed resulting in a prolonged stance phase (Clayton, 1990b).

It could be demonstrated that the use weighted boots notably increases energy consumption (Wickler et al., 2004), reduces lateral bending at the withers and increases it at L3 when applied in the forelimbs (Wennerstrand et al., 2006). There are a few recent studies dealing with the effect of weight on the motion pattern of gaited horses. In Icelandic horses, it could be shown that weighted boots increase peak height of the forelimb flight arc and prolong ipsilateral stance duration (Boehart et al., 2013; Pecha et al., 2011; Rumpler et al., 2010). Height of the forelimb flight arc was also positively correlated with speed. The effect of weighted boots on limb loading was not measured directly, but was presumed to be higher based on observed higher velocity of the distal limb at first contact (Boehart et al., 2013).

In order to prevent hoof and orthopaedic disease in Icelandic riding horses, quantitative information on the effects of the long toe, high hoof conformation as well as of weight manipulations are urgently needed.

Gait manipulation by saddling and riding style

Saddling (caudal position of rider and saddle in relation to the back of the horse) and riding (high HNP) techniques developed for Icelandic horses might potentially compromise back health when taking into account studies in other horse breeds (Nyikos et al., 2005; Weishaupt et al., 2006b). Basic principles applied in English riding are aiming to place the rider close to the horse's CoM and the deepest point of the seat approximately at the centre of the saddle; what makes it easier for the rider to find his balance and move in harmony with the horse (Harman, 2004). Conversely, Icelandic saddles place the rider in the caudal part of the back which is known to be particularly sensitive to load (Nyikos et al., 2005). Large saddles or caudal placement of the saddle might impede back motility in the lumbar region and thus may compromise back health. A high carriage of head and neck as it is most often encountered in tölting Icelandic horses is known to reduce the mobility of the back in Warmblood horses (Rhodin et al., 2005). Back extension narrows the spaces in between the spinous processes, potentially resulting in kissing spines and is thought to be at the origin of back problems in other breeds (De Cocq et al., 2004). Furthermore, even if absolute elevation of head and neck might shift the CoM of the horse to the hindquarters, it also changes the movement pattern of the forelimbs in a way that higher peak forces occur (Weishaupt et al., 2006a)

Despite these potentially negative implications, the effects of these Icelandic saddling and riding practices on back and orthopaedic health, as well as on the footfall pattern and the ROM of back and forelimbs, have not yet been studied. In this context, it is worth noting that Icelandic horses are rarely presented clinically due to back pain, although they are frequently ridden by heavy adult riders. The reason might be their rather stoic nature which might mask possible discomfort.

Outline and purpose of this thesis

When reviewing scientific literature, the three most common gaits of equids, walk, trot and canter/gallop, have been extensively studied since many years (Barrey, 2013). Only in the last decade, the various alternate gaits as they are shown by gaited horse breeds have been subject of scientific analysis (Biknevicius et al., 2004, 2006; Nicodemus and Clayton, 2003; Robilliard et al., 2007; Rumpler et al., 2010; Zips et al., 2001). There is not only a lack of scientific knowledge of the biomechanics of these gaits themselves, but also in regard to the special shoeing and saddling practices used in Icelandic horses. When referring to studies in other breeds, shoeing and saddling methods might have the potential to compromise the health of the locomotor system as described above (Boehart et al., 2013; Nyikos et al., 2005; Weishaupt et al., 2006b). These facts and the growing Icelandic horse community which more and more questions the traditional training methods urgently require objective and quantitative data on these topics which lead to the definition of the following three aims for the presented thesis:

1) In a first part, the kinetic and kinematic characteristics of the tölt should be described and compared to trot at the same speeds. For this purpose, simultaneous kinetic and kinematic gait analysis was carried out on a high-speed treadmill. This experimental set-up involved treadmill integrated force measuring (Weishaupt et al., 2002) synchronised with a high-speed motion analysis system (Oqus 600, Qualysis). This allowed measurement of limb timing and forces, but also determination of movements of the limbs and posture of the horse and thus a comprehensive description of both gaits. Speed is known to have profound influence on gait mechanics (Weishaupt et al., 2010); the treadmill situation offered the possibility to very precisely control the velocities of each trial. Prior to the experiment, horses were thoroughly accustomed to the treadmill in all three gaits. For this experiment, horses were shod with a standard shoeing and correctness of gait and posture were evaluated by a judge for international Icelandic gait competitions.

2) The second aim of the study was to determine the mechanical consequences of shoeing manipulation as it is currently applied in Icelandic horses in competition compared to a standard shoeing (S_N). For this purpose, hooves were grown high and long and horses were shod with commonly used pads and packing material (S_H). Gait analysis as described above was then carried out with and without weighted boots at walk, as well slow and medium tölting and trotting speeds. With this experimental set-up, shoeing effects on the footfall pattern as well as on loading and protraction movement of the limbs could be determined.

3) The third part of the presented thesis addressed the saddling situation in the Icelandic horse. For this part, a saddle pressure measurement mat was additionally placed under the saddle and all three measuring systems were synchronised. This experimental set-up allowed studying the pressure distribution under a dressage-like saddle (S_{Dres}), an Icelandic saddle (S_{Icel}) and a saddle cushion (S_{Cush}) currently used for riding Icelandic horses and at the same time determining their effect on gait mechanics.

The objective was to provide a scientific biomechanical description of the tölt gait as well as to contribute substantial quantitative information on topics of high interest in the current discussion on riding Icelandic horses which would be directly applicable to the situation of the Icelandic horse in training and competition. This scientific database would allow for reviewing current shoeing and training practices, as well as sport regulations of Icelandic horse sport objectively to assure animal welfare standards.

PhD Publications

I. Comparison of tölt and trot at the same speed: Differences in limb loading and movement.

Nina M. Waldern, Thomas Wiestner, Lea C. Ramseier, Michael A. Weishaupt.
Submitted to the American Journal of Veterinary Research (2014).

II. Effects of shoeing on limb movement and ground reaction forces in Icelandic horses at walk, tölt and trot.

Nina M. Waldern, Thomas Wiestner, Lea C. Ramseier, Claude Amport, Michael A. Weishaupt.
The Veterinary Journal (2013); 198 Suppl 1: e103-108.

III. Effects of shoeing on intra- and inter-limb coordination and movement consistency in Icelandic horses at walk, tölt and trot.

Michael A. Weishaupt, Nina M. Waldern, Claude Amport, Lea C. Ramseier,
Thomas Wiestner.
The Veterinary Journal (2013); 198 Supplement 1: e109-e113.

IV. Saddle pressure distributions of three saddles used for Icelandic horses and their effects on ground reaction forces, limb movements and rider positions at walk and tölt.

Lea C. Ramseier, Nina M. Waldern, Thomas Wiestner, Katja Geser-von Peinen,
Michael A. Weishaupt.
The Veterinary Journal (2013); 198 (Suppl. 1): e81-e87.

I. Comparison of tölt and trot at the same speed: Differences in limb loading and movement.

Nina M. Waldern, Thomas Wiestner, Lea C. Ramseier, Michael A. Weishaupt.

Submitted to the American Journal of Veterinary Research (2014).

Abstract

Objective – To compare the gait mechanics of tölt and trot at same speeds and to determine the loading of the distal limbs in order to estimate its impact on orthopedic health.

Animals – 12 sound Icelandic horses.

Procedures – Simultaneous kinetic and kinematic gait analysis was carried out at slow and medium velocity at tölt and trot on an instrumented treadmill. 1-way RM ANOVAs were used to test for differences between both gaits at same speeds.

Results – Compared to trot, tölting horses had a higher stride rate and lower stride impulses. In the forelimbs, shorter relative stance durations (StD_{rel}) lead to higher peak vertical forces (Fz_{peak}) and, conversely, in the hindlimbs, longer StD_{rel} resulted in lower Fz_{peak}. The higher head-neck position at tölt caused no measurable weight shift to the hindlimbs but might be related to the distinctly higher front hoof flight arc and the reduced forelimb pro-retraction. Based on hindlimb kinetic and kinematic variables, there was no evidence of increased collection. Stride-to-stride variability of limb timing at tölt, but also at trot compared to 3-gaited horses was high. The footfall rhythm of trotting Icelandic horses was frequently slightly 4-beated and had very short suspension phases. Energetic estimations suggest that tölt at slow and medium speed is energetically less advantageous than trot.

Conclusions and clinical relevance – Tölt compared to trot at same speeds increased loading of the forelimbs in form of higher Fz_{peak} due to shorter StD_{rel}. Despite the higher head-neck position at tölt, there was no weight shift to the hindlimbs.

Abbreviations

at Fz_{peak}	Variable's value at time of peak vertical force
FC	Limb first contact
at limb FC	Variable's value at time of limb first contact
CoM	Center of mass
delta	Difference of 2 values
Fz_{peak}	Peak vertical force
GRF	Ground reaction force
HNP	Head-neck position
Iz	Vertical limb impulse
Iz_{fore}	Percentage of total vertical impulse carried by both forelimbs
Iz_{SD}	Total vertical impulse during stride (sum of all 4 Iz)
Max	Maximum
Min	Minimum
$OSwL_{caud}$	Caudal overswing length
$OSwL_{cran}$	Cranial overswing length
ProRetrA	Total pro- and retraction angle
ProRetrL	Total pro- and retraction length
ProtrL	Protraction length
RetrL	Retraction length
ROM	Range of motion
SD	Stride duration
SL	Stride length
sMean	Mean value of entire stride
SpD	Suspension duration
SR	Stride rate
StD_{abs}	Stance duration absolute
StD_{rel}	Stance duration relative to SD
$StpD_{lat}$	Lateral step duration
TAC	Time of advanced completion
TAP	Time of advanced placement
TiF	Treadmill-integrated force measuring system
V_1	Slow speed
V_2	Medium speed

Introduction

The 3 most common gaits of equids, walk, trot and canter/gallop, have been extensively studied since many years (Barrey, 2013). Only in the last decade, the various alternate gaits as they are shown by gaited horse breeds have been subject of scientific analysis (Biknevicius et al., 2004, 2006; Nicodemus and Clayton, 2003; Robilliard et al., 2007; Rumpler et al., 2010; Zips et al., 2001). Although footfall pattern, limb timing and foot placement are often specific for each breed, they might encompass a high inter- and intra-individual natural variability. So far little is known about the extent of limb loading in comparison to each other or to 1 of the 3 main gaits.

The tölt of the Icelandic horse belongs to the 4-beat ambling gaits and should follow a symmetric regular footfall pattern with the forelimb landing about 25% of stride duration after the ipsilateral hindlimb. Scientific data describing temporal, spatial variables and GRF of this gait as well as its kinematics are available (Biknevicius et al., 2004; Nicodemus and Clayton, 2003; Robilliard et al., 2007; Waldern et al., 2013; Weishaupt et al., 2013; Zips et al., 2001); however, a direct comparison of tölt and trot at the same speed has not yet been carried out. Such an assessment would be highly interesting as it would allow for comparison between a gait with and a gait without suspension phase and be important to understand the effect of these differences with regard to gait mechanics and limb loading. Estimations about the level of Fz_{peak} at the tölt compared to trot can be found in the literature, but so far have yielded conflicting results. One group presumed that extremely low duty factors might lead to higher Fz_{peak} at tölt (Robilliard et al., 2007), whereas others argued that the greater overlap of limb support might result in lower Fz_{peak} (Biknevicius et al., 2004).

To ride Icelandic horses at the tölt, riders claim that they need to re-balance them on the hindlimbs and raise their head and forehand. In order to induce and facilitate this presumed weight shift, saddle and/or rider are traditionally placed further backwards in Icelandic horse riding (Feldmann and Rostock, 1986b). However, whether and to which extent this technique induces an alteration of the horse's forelimb-hindlimb balance has never been confirmed or quantified scientifically.

This study aims to assess the differences in GRF, limb movement and posture of the horse at tölt versus trot at the same velocity, at slow and medium speed in order to gain an insight into their potential impact in orthopaedic health. It was hypothesized that, compared to the trot, (1) the higher HNP at the tölt would lead to a weight shift to the hindlimbs and (2) the higher protraction arc of the forelimbs at the tölt would lead to shorter contact times and thus to higher Fz_{peak}.

Material and Methods

Horses and riders

The study group consisted of 12 sound Icelandic horses (4 stallions, 3 geldings, 5 mares); with an average age of 10 ± 3 years (mean ± S.D.), a body mass of 354 ± 24 kg and a height at the withers of 1.37 ± 0.03 m. They were judged to be free of lameness and pain or dysfunction of the back based on a thorough clinical examination. Horses were shod according to standard shoeing principles with 20 x 8 mm steel shoes without pads or padding material. They were accustomed over at least 4 days to tölt and trot on a high-speed treadmill[a].

Experimental design

All horses were ridden by 1 of 2 riders experienced in riding Icelandic horses. Measurements were carried out at 2 tölting and trotting speeds each (V_1: 3.4 m/s; V_2: 3.9 m/s). Slow trot was ridden fully seated such as the tölt; medium trot was ridden in a forward seat (seat slightly raised from the saddle, full weight in the stirrups, upper body tilted slightly forwards). Bridles with snaffle bits were used and a dressage-style saddle for Icelandic horses fitted to the horses in a standard saddle position (Harman, 1999). For each trial, gait accuracy and posture of the horse were assessed by an experienced judge for Icelandic horse competitions.

Data acquisition

Ground reaction force and temporal variables of each limb were measured with TiF (Weishaupt et al., 2002). Simultaneous synchronized kinematic data was obtained by tracking reflective spherical markers (diameter 19 mm) placed over anatomical landmarks on both sides of horse and rider: At the wings of the atlas, the spinous processes of L4, L5, tuber sacrale and S3, as well as on the lateral side of both forelimbs (fetlock, carpus, tuberculum majus), both hindlimbs (fetlock, tarsus, stifle, tuber coxae), and at the lateral hoof wall at the level of the coffin joint on all hooves. Markers placed on the rider were located at both shoulders (acromion) and hips (tuber coxae). Qualisys Track Manager software[b] was used to control 9 high-speed infrared cameras[c] and to calculate the kinematic xyz-data. The left-handed coordinate system was aligned with the treadmill; the x-axis pointing in direction of the horse's head, the y-axis pointing towards its right side and the z-axis upwards. For both systems, a sampling frequency of 480 Hz was applied. Recording time lasted 15 s which resulted in more than 25 strides in both gaits.

Data analysis

The following kinetic variables were determined from the force curves and limb positional data of the TiF system: SD, SR; SL, StD, $StpD_{lat}$, SpD, TAP (time interval of hind hoof impact prior to diagonal front hoof), TAC (time interval of hind hoof lift-off prior to diagonal front hoof), Iz_{SD}, Iz_{fore}, as well as Iz and Fz_{peak} of individual limbs. All time variables were standardized as percentage of stride duration (%SD); only for stance duration, both StD_{abs} and StD_{rel} are given. Force and impulse values were additionally standardized to the combined mass of horse and rider (N/kg and Ns/kg, respectively). Variables' values of the multiple strides in a record were averaged. Velocity data were derived from treadmill belt speed.

The following kinematic variables were determined for each limb: ProRetrA, ProRetrL, ProtrL, RetrL, $OSwL_{cran}$, $OSwL_{caud}$ as well as height and time point of maximal height of the coffin joint flight arc (Coffin). Additionally, movement of the head (Head), shoulder (Shoulder) and sacrum (Sacrum), as well as angulation and movement of the caudal back (Caudal Back Angle) and croup (Croup Angle, Croup Shape) during the limb loading phase were determined. In order to quantify the extent of "Hankenbeugung", heights of Sacrum, stifle (Stifle), fetlock (Fetlock) as well as vertical segment lengths (Sacrum – Stifle, Stifle – Fetlock) were measured at limb FC and at Fz_{peak}. Position and movements of the rider's hip (Rider Hip), rider's position in relation to the horse's back (Rider Position) and the forward tilt of the rider's upper body (Rider Tilt) were calculated.

Time series of kinematic variables and discrete limb contact times from TiF were imported into MatLab[d] for further analyses. Based on stride-cycle times of the left forelimb, time series were split into strides. Data for each stride-cycle were time-standardized to 501 points (0 to 100% stride duration) and all strides of a recording were averaged to a standardized stride of which sMean, ROM, Max and Min for the x- and z-dimensions were calculated.

Corresponding kinetic and kinematic variables of the contralateral limbs were pooled for each condition and horse and reported as forelimb and hindlimb values, respectively. Finally, group means (± S.D.) for each gait condition were calculated from the values of all 12 horses.

Statistical method

Statistical analysis was performed with commercially available software[e]. Normality (Kolmogorov-Smirnov test) and equal variance of data were tested prior to analyses. Differences between values at tölt and at trot were tested with 1-way repeated measures ANOVAs for each speed separately at a significance level of $P < 0.05$.

Ethical review

The experiment was carried out with the approval of the Animal Health and Welfare Commission of the Canton of Zurich (No. 206/2010).

Results

All horses could be ridden on the treadmill without problems. Mean (± S.D.) velocities of both gaits were not significantly different at V_1 (tölt: 3.44 ± 0.04 m/s; trot: 3.42 ± 0.02 m/s) and V_2 (tölt: 3.91 ± 0.09 m/s; trot: 3.90 ± 0.11 m/s), respectively. Results of gait analysis comparing tölt and trot at the 2 velocities are listed in **Table 1** and **2**. At both speeds, footfall pattern at tölt was characterized by lateral coupling; i.e. the relative $StpD_{lat}$ was with <18.0 %SD clearly shorter than expected for a perfectly regular 4-beat rhythm (25 %SD). At the trot, half of the horses had an airborne phase at V_2 and only 2 horses at V_1. Most kinetic and kinematic variables differed significantly between tölt and trot at the same speeds and differences between the 2 gaits were similar at both speeds. Compared to the trot, SD and SL were shorter at the tölt and fore- and hindlimb Iz lower. The rider's mean position in relation to the horse`s back as well as the impulse balance between fore- and hindlimbs were similar at both speeds at the tölt and at V_1 at the trot. At the faster trotting speed, the rider's position was about 68 mm further cranial what increased Iz_{fore} (+2.7%). At the tölt, horses carried their heads higher and shorter StD_{rel} and higher Fz_{peak} were measured in the forelimbs; in the hindlimbs, longer StD_{rel} resulted in lower Fz_{peak}. At the tölt, the shape of the vertical force curves had a spiked apex in the forelimbs and a blunter apex in the hindlimbs compared to trot (**Figure 1**).

Table 1: Kinetic variables of Icelandic horses (n = 12) measured at tölt and trot at the same velocities.

Variable	Limb	Unit	TROT V_1	TÖLT V_1	TROT V_2	TÖLT V_2
Velocity		m/s	3.42 ± 0.02	3.44 ± 0.04 (0.6%)	3.90 ± 0.11	3.91 ± 0.09 (0.1%)
SD		ms	602 ± 20	550 ± 24 (-8.7%) [a]	574 ± 20	523 ± 23 (-8.9%) [a]
SR		1/min	99.8 ± 3.3	109.4 ± 4.7 (9.6%) [a]	104.7 ± 3.8	115.0 ± 4.9 (9.8%) [a]
SL		mm	2'058 ± 61	1'891 ± 79 (-8.1%) [a]	2'237 ± 91	2'042 ± 90 (-8.7%) [a]
StD_{abs}	fore	ms	294 ± 10	260 ± 17 (-11.5%) [a]	268 ± 10	237 ± 11 (-11.7%) [a]
	hind	ms	278 ± 8	282 ± 15 (1.7%)	251 ± 9	258 ± 15 (2.7%)
StD_{rel}	fore	%SD	48.8 ± 1.8	47.3 ± 3.0 (-3.1%) [a]	46.9 ± 2.3	45.4 ± 2.2 (-3.2%) [a]
	hind	%SD	46.1 ± 1.8	51.3 ± 1.5 (11.3%) [a]	43.9 ± 2.2	49.4 ± 1.9 (12.7%) [a]
$StpD_{lat}$		%SD	47.5 ± 2.3	18.0 ± 2.2 (-62.2%) [a]	46.7 ± 3.4	17.9 ± 2.6 (-61.7%) [a]
SpD		%SD	0.1 ± 2.2		1.5 ± 4.3	
TAP		%SD	-2.5 ± 2.3		-3.3 ± 3.4	
TAC		%SD	0.2 ± 2.2		-0.3 ± 3.9	
Iz_{SD}		Ns/kg	5.90 ± 0.19	5.39 ± 0.24 (-8.7%) [a]	5.63 ± 0.20	5.13 ± 0.22 (-8.9%) [a]
Iz	fore	Ns/kg	1.70 ± 0.06	1.55 ± 0.07 (-8.9%) [a]	1.66 ± 0.08	1.47 ± 0.07 (-11.4%) [a]
	hind	Ns/kg	1.25 ± 0.05	1.15 ± 0.07 (-8.3%) [a]	1.16 ± 0.05	1.10 ± 0.06 (-5.4%) [a]
Iz_{fore}		$\%Iz_{SD}$	57.5 ± 1.1	57.3 ± 1.2 (-0.3%)	58.8 ± 1.4	57.2 ± 1.1 (-2.7%) [a]
Fz_{peak}	fore	N/kg	8.88 ± 0.46	9.52 ± 0.63 (7.2%) [a]	9.58 ± 0.66	9.96 ± 0.61 (4.0%) [a]
	hind	N/kg	7.49 ± 0.41	6.61 ± 0.29 (-11.8%) [a]	7.57 ± 0.35	6.93 ± 0.28 (-8.5%) [a]

Data are group means ± standard deviations (mean percentage difference of tölt versus trot in brackets).

[a] : Significant difference ($P < 0.05$) between values at tölt and trot of the same velocity.

Velocity, treadmill speed. Unless stated otherwise, times are given as percentage of SD (%SD).

For abbreviations refer to the text.

Table 2: Kinematic variables of Icelandic horses (n = 12) measured at tölt and trot at the same velocities.

Variable	Limb	Type	Unit	TROT V$_1$	TÖLT V$_1$	TROT V$_2$	TÖLT V$_2$
ProRetrA	fore	ROM	°	52.1 ± 1.7	46.0 ± 3.2 (-11.6%)[a]	53.7 ± 2.3	47.6 ± 2.1 (-11.4%)[a]
ProRetrL	fore	x-ROM	mm	948 ± 28	847 ± 46 (-10.6%)[a]	981 ± 28	877 ± 32 (-10.6%)[a]
ProtrL	fore	x-Max	mm	472 ± 23	399 ± 34 (-15.3%)[a]	494 ± 40	424 ± 29 (-14.1%)[a]
RetrL	fore	x-Min	mm	-476 ± 42	-448 ± 39 (-5.9%)[a]	-487 ± 41	-453 ± 40 (-7.1%)[a]
OSwL$_{cran}$	fore	delta x	mm	35 ± 13	35 ± 24 (-1.1%)	44 ± 17	43 ± 27 (-0.9%)
OSwL$_{caud}$	fore	delta x	mm	-5 ± 3	-3 ± 1 (-34.7%)	-6 ± 3	-5 ± 4 (-11.8%)
Coffin	fore	z-ROM	mm	168 ± 23	199 ± 50 (18.9%)[a]	185 ± 36	219 ± 56 (18.1%)[a]
		Time of Max	%SwD	33.8 ± 2.6	44.8 ± 5.9 (32.8%)[a]	35.3 ± 4.1	46.8 ± 6.7 (32.6%)[a]
ProRetrA	hind	ROM	°	39.7 ± 1.5	40.2 ± 1.4 (1.3%)	40.8 ± 1.5	41.4 ± 1.2 (1.5%)
ProRetrL	hind	x-ROM	mm	871 ± 27	881 ± 38 (1.2%)	894 ± 34	907 ± 29 (1.5%)
ProtrL	hind	x-Max	mm	513 ± 34	525 ± 54 (2.3%)	520 ± 40	542 ± 45 (4.1%)[a]
RetrL	hind	x-Min	mm	-358 ± 21	-356 ± 29 (-0.5%)	-373 ± 25	-365 ± 29 (-2.2%)
OSwL$_{cran}$	hind	delta x	mm	4 ± 5	6 ± 7 (79.1%)[a]	5 ± 5	7 ± 8 (46.6%)
OSwL$_{caud}$	hind	delta x	mm	-65 ± 18	-8 ± 4 (-87.7%)[a]	-66 ± 18	-11 ± 7 (-83.3%)[a]
Coffin	hind	z-ROM	mm	73 ± 20	72 ± 14 (-1.3%)	82 ± 18	76 ± 11 (-8.2%)[a]
		Time of Max	%SwD	56.7 ± 25.9	41.2 ± 27.3 (-27.4%)	42.9 ± 21.9	34.6 ± 21.5 (-19.4%)
Head		z-sMean	mm	1'408 ± 38	1'528 ± 50 (8.5%)[a]	1'400 ± 48	1'525 ± 30 (9.0%)[a]
Shoulder		z-sMean	mm	1'000 ± 27	1'026 ± 35 (2.7%)[a]	1'000 ± 31	1'025 ± 29 (2.5%)[a]
		z-ROM	mm	58 ± 8	54 ± 8 (-7.7%)[a]	56 ± 8	54 ± 7 (-3.6%)
		z at Fz$_{peak}$	mm	999 ± 29	1'010 ± 31 (1.1%)[a]	998 ± 29	1'004 ± 27 (0.7%)[a]
Sacrum		z-sMean	mm	1'282 ± 37	1'295 ± 33 (1.0%)[a]	1'282 ± 34	1'292 ± 34 (0.8%)[a]
		z-ROM	mm	47 ± 7	31 ± 6 (-34.3%)[a]	43 ± 6	31 ± 5 (-27.1%)[a]
		z at Fz$_{peak}$	mm	1'261 ± 37	1'284 ± 33 (1.8%)[a]	1'263 ± 34	1'280 ± 34 (1.3%)[a]
Caudal Back Angle		at Fz$_{peak}$	°	-9.4 ± 1.6	-6.2 ± 2.4 (-34.3%)[a]	-8.9 ± 2.4	-5.2 ± 2.5 (-42.0%)[a]
Croup Angle		at limb FC	°	-14.1 ± 2.8	-18.2 ± 3.4 (29.2%)[a]	-14.6 ± 3.0	-19.0 ± 3.1 (30.3%)[a]
		at Fz$_{peak}$	°	-14.0 ± 3.1	-20.3 ± 3.1 (44.7%)[a]	-14.2 ± 2.7	-20.8 ± 2.8 (46.1%)[a]
Croup Shape		at limb FC	°	156.3 ± 2.4	152.8 ± 2.3 (-2.2%)[a]	156.7 ± 2.7	152.8 ± 2.7 (-2.5%)[a]
		at Fz$_{peak}$	°	156.6 ± 2.9	153.6 ± 2.6 (-2.0%)[a]	156.9 ± 2.9	154.0 ± 2.8 (-1.8%)[a]
Stifle		z at Fz$_{peak}$	mm	635 ± 19	637 ± 18 (0.3%)	638 ± 17	637 ± 17 (-0.2%)
Fetlock	fore	z at Fz$_{peak}$	mm	89 ± 11	92 ± 9 (3.2%)[a]	86 ± 10	88 ± 9 (2.7%)[a]
	hind	z at Fz$_{peak}$	mm	74 ± 11	80 ± 11 (8.3%)[a]	73 ± 9	76 ± 9 (4.1%)[a]
Sacrum – Stifle		z at Fz$_{peak}$	mm	626 ± 26	646 ± 24 (3.3%)[a]	625 ± 24	643 ± 25 (2.9%)[a]
Stifle – Fetlock		z at Fz$_{peak}$	mm	562 ± 15	558 ± 12 (-0.7%)	565 ± 15	561 ± 13 (-0.8%)
Rider Hip		z-ROM	mm	65 ± 9	29 ± 9 (-56.0%)[a]	46 ± 9	25 ± 5 (-46.6%)[a]
Rider Position		x-sMean	mm	276 ± 37	274 ± 44 (-0.8%)	343 ± 34	275 ± 39 (-19.8%)[a]
Rider Tilt		sMean	°	11.0 ± 1.8	8.6 ± 2.0 (-22.2%)[a]	27.3 ± 3.1	10.0 ± 3.7 (-63.5%)[a]

Data are group means ± standard deviations (mean percentage difference of tölt versus trot in brackets).
[a] : Significant difference ($P < 0.05$) between values at trot and tölt of the same velocity.

Variable Types (for the labeled x- or z-dimension): **sMean**, **ROM**, Max, **Min**, **delta**, **at limb FC**, at **Fz$_{peak}$**.
(for further legends see bottom of opposite page)

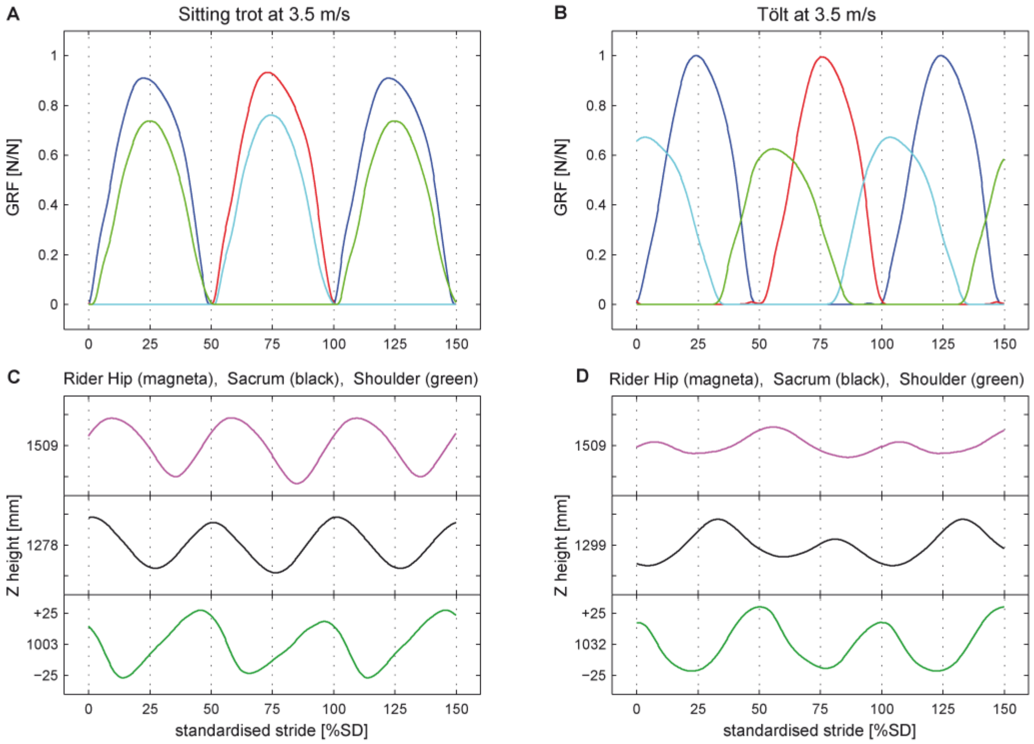

Figure 1. Typical weight-standardized vertical GRF of 1 horse at sitting trot (A) and tölt (B), ridden at the same velocity (limbs: LF (blue), RF (red), LH (cyan), RH (green)). Mean vertical height and ROM of Rider Hip (average of both tuber coxae markers), the horse's Sacrum (tuber sacrale) and the horse's Shoulder (average of both shoulder markers) each centered at the given stride-mean value (C: trot, D: tölt). Depicted are stride-standardized curves (averages of 25 strides) for an interval of 1.5 strides (150 % stride duration). Fore- and hindquarters behaved in a similar fashion in both gaits regarding the occurrence of Fz_{peak} and vertical movement of the trunk: At Fz_{peak} of each limb, the associated proximal body markers (Shoulder or Sacrum) were at their lowest, whereas when limb support changed to the contralateral limb, the respective markers were at their highest position.

Legend to Table 2 (see opposite page)

Kinematic variables (for left-handed coordinate system with x-axis vs. horse's head, z-axis upwards, and angular data projected onto the sagittal plane): **ProRetrA** of forelimb (coffin joint relative to Shoulder) or hind limb (coffin joint relative to the midpoint between left and right tuber coxae (Tuber Coxae)) during stance; **ProRetrL**, total distance horse moves forward while the respective limb rotates for ProRetrA with zero reference for vertical orientation of metacarpus (fetlock – carpus) or metatarsus (fetlock – tarsus), respectively; **ProtrL**, protraction part of ProRetrL; **RetrL**, retraction part of ProRetrL; **$OSwL_{cran}$**, amount of protraction at the end of swing exceeding the one at stance; **$OSwL_{caud}$**, amount of retraction at the beginning of swing exceeds the one at stance; **Coffin**, vertical movement of the hoof (coffin joint) with time of maximal height as a percentage of swing duration (%SwD); Head, height of the midpoint between left and right wing of the atlas; Shoulder, height of the midpoint between left and right spina scapulae; **Sacrum**, height of tuber sacrale; **Caudal Back Angle**, L4 y-rotated around Sacrum, negative if L4 lower than Sacrum; **Croup Angle**, S3 y-rotated around Sacrum, negative if S3 lower than Sacrum; **Croup Shape**, angle L4 – Sacrum - S3; **Fetlock**, **Tarsus**, **Stifle**, height of lateral marker at the level of the respective joint; **Rider Hip**, midpoint between left and right tuber coxae; **Rider Shoulder**, midpoint between left and right acromion of the shoulders; **Rider Position**, x-position of Rider Hip in relation to horse's L5; **Rider Tilt**, angle of Rider Shoulder y-rotated around Rider Hip, positive if rider tilts forward.

Total pro-retraction angle and ProRetrL were smaller in the forelimbs at the tölt but remained unchanged in the hindlimbs. In the forelimbs, maximal ProtrL and RetrL at tölt were shorter. In the hindlimbs, maximal ProtrL was longer at V_2 and RetrL remained unchanged at both speeds. Height of the flight arc of the hoofs (Coffin z-ROM) was higher at the tölt in the forelimbs at both speeds and lower in the hindlimbs at V_2. The time point of the maximal height of the flight arc was delayed in the forelimbs at tölt and in the hindlimbs at trot. Mean height of Sacrum and Shoulder was higher and range of vertical excursion of the Sacrum was reduced at the tölt.

Discussion

This study compared GRF, limb movement and posture of the Icelandic horse at tölt versus trot at the same speed. The aim was to describe the different gait mechanics and to understand the biomechanical characteristics of the 2 gait patterns, as well as to evaluate the loading of the distal limbs in order to estimate its impact on orthopedic health.

Gait comparison tölt versus trot

Overground studies (Clayton, 1994; Holmstrom et al., 1995) as well as investigations performed on a treadmill (Weishaupt et al., 2010; Weishaupt et al., 2004) describe the trot as a 2-beat gait with a suspension phase, whereas the tölt has a 4-beat rhythm and the airborne phase is missing apart from at very high speeds (Biknevicius et al., 2006; Robilliard et al., 2007; Weishaupt et al., 2013; Zips et al., 2001). In the present study, there were generally large kinetic and kinematic dissimilarities between the 2 gaits. Differences were comparable at V_1 and V_2, even though most horses only had a suspension phase at V_2 at the trot. Rider position was the same at both gaits at V_1; therefore, gait comparison mainly focuses on data at this speed. At V_2 at the trot, the rider was sitting further cranially compared to the other situations.

Stride rate at the tölt was higher compared to trot at the same speed. This resulted in a shorter SD and SL, and consequently in lower Iz_{SD}. Stance duration is a decisive variable tuning the Fz_{peak} of a given impulse. Limb stance durations and Fz_{peak} differed between gaits, but also between fore- and hindlimbs at the tölt. At tölt, a mean forelimb duty factor of 0.47 indicating a running gait resulted in a transverse suspension (suspension of contralateral limbs); whereas in the hindlimbs, values of 0.51 were pointing more towards a walking gait. However, vertical movement of the horses' trunks in relation to the limb positions was consistent with the bouncing mechanism of a running gait with the lowest position of Shoulder and Sacrum, respectively, at mid-stance (**Figure 1**). Because the duty factor frequently fails to reliably discriminate between walking and running dynamics, their differentiation should be preferably based on the phase difference of kinetic and potential energies (Biknevicius and Reilly, 2006).

At the tölt, forelimb Fz_{peak} was notably higher (+7.2%) despite reduced limb impulses resulting from shorter SD. This can only be explained by the shorter forelimb StD in connection with the more than twice as long transverse forelimb suspension in comparison with the trot (2.7 %SD vs. 1.2 %SD). However, for the observed -3.1% shorter StD_{rel} an increase in force of the same amount would be expected as forelimb-hindlimb impulse balance was constant. The higher Fz_{peak} might be explained by the different forelimb force profiles of the 2 gaits. At the tölt, the force curves were slender and had a spiked apex compared to the blunter shape observed at the trot. Taking into account the shorter stride cycle in tölting horses, force onset and decline were faster at this gait (**Figure 1**). A possible explanation for these differences might be the higher carriage of the head and neck. A higher HNP is known to restrict cranio-caudal forelimb mobility (Waldern et al., 2009; Weishaupt et al., 2006b) which, in the present study, caused shorter forelimb ProRetrA and ProtrL. This in turn resulted in the higher SR and a prolonged relative forelimb transverse suspension phase.

Additionally, forelimb stiffness at tölt was higher than at trot as there was less limb compression comparing the heights of the fetlock or the shoulder joints in spite of the higher Fz_{peak}. A higher limb stiffness and shorter ground contact times transmit the impulse more directly to the ground generating force profiles with more spiky and thus higher peaks.

The higher forelimb flight arc in combination with the vertical displacement of the trunk due to the longer transverse suspension phase at tölt led to the imposing vertical forelimb action during the swing phase. In spite of the higher flight arc at the tölt, swing duration was approximately 6 % shorter, what requires faster hoof protraction velocities. However, total stride impulse of the tölting horses was not greater than what would be expected from the horse's body mass and SD. This makes a significant active component of downward hoof acceleration before impact unlikely.

Hindlimb force profiles at tölt showed longer StD_{rel} (+11.3%) and lower Fz_{peak} (-11.8%) compared to trot and thus an inverse relationship compared to the forelimbs. Even though ProRetrA were not different between both gaits and ProtrL was only increased at V_2 at tölt, hindlimb ProRetrL was relatively longer due to the shorter SL.

Compared to trot, dorso-ventral excursion of the horse's Sacrum at tölt was reduced by 1 third and was even smaller than at walk (unpublished data). Concurrently, z-ROM of Rider Hip at the tölt was smaller than that of the horse's Sacrum and only half as much as at the trot(Waldern et al., 2013), which explains its high comfort factor even at fast velocities (**Figure 1**, **Table 2**). This corresponds with the smaller vertical excursion of the calculated CoM at tölt compared to trot reported by other authors (Biknevicius et al., 2006; Buchner et al., 2000).

According to riding literature, tölting an Icelandic horse requires increased collection and can be achieved by simultaneous encouraging and restraining aids in combination with raising its head and neck; thus inducing a weight shift to the hindlimbs (Feldmann and Rostock, 1986c). In this context, collection is defined as a relative elevation of head and neck together with an increased flexion of tarsal, stifle and hip joints during the stance phase (Hankenbeugung) resulting in a lowering of the hindquarters (Clayton, 1994; Holmstrom et al., 1995; Weishaupt et al., 2009).

Looking more closely at the posture of the hindquarters, stifle height at mid-stance (as a measure of the combined effect of fetlock hyperextension and tarsal joint flexion) did not differ and height of the sacrum was even higher at the tölt compared to trot; this was probably due to the considerably lower hindlimb Fz_{peak}. Moreover and functionally even more important, there was no shift of impulse to the hindlimbs, even if horses did carry their heads higher at the tölt than at the trot (V_1: +120 mm; V_2: +125 mm). This contrasts measurements in Warmblood dressage horses at the trot where the influence of the HNP was investigated. In these studies, elevation of the HNP led to a weight shift towards the hindlimbs in the ridden (1.8 %) and unridden (1.0 %) situation (Waldern et al., 2009; Weishaupt et al., 2006b). Based on these results, no evidence of increased collection at the tölt could be confirmed. However, tölting horses stepped further towards their CoM, resulting in a longer hindlimb ProtrL at V_2 and a steeper Croup Angle at both speeds.

The longer StD_{rel} and ProRetrL in the hindlimbs and the lack of a hindlimb transverse suspension at slow tölting speeds might resemble the so called 'Groucho' running. This way of moving is characterized by an increased stifle flexion resulting in a reduced spring stiffness of the limbs, longer contact times, prolonged stance lengths, a reduction or lack of a suspension phase and higher energy requirements (McMahon et al., 1987). However, as described above, there was no difference in stifle height at mid-stance between tölt and trot and total hindlimb compression (delta z Sacrum) during load onset (limb FC to time of Fz_{peak}) at tölt was only about 2/3 as much as at trot (**Figure 2**). The hindlimb spring constant at tölt estimated from Fz_{peak} was thus about 32% (V_2) to 50% (V_1; see **Figure 2**) higher, caused by a stiffer proximal segment (hip joint) than at trot. Conversely, the spring constant of the fetlock joint remained equal for all gait conditions. Therefore, despite the longer relative hindlimb ground contact times at the tölt (V_1: 51.3 %SD; V_2: 49.4 %SD) compared to trot (V_1: 46.1 %SD; V_2: 43.9 %SD), there was no evidence that tölt was more similar to a 'Groucho' run than trot in the Icelandic horses. However, there might be a difference in comparison to Warmblood horses which have considerably shorter hindlimb contact times (<40 %SD) at trot (Weishaupt et al., 2010; Weishaupt et al., 2006b).

At the faster trotting velocity (V_2), riders were sitting in a more forward seat compared to the other conditions. This position was chosen to maintain a maximally stable rider position with least disturbance of the horse, particularly when horses had a high limb action. It caused a significant shift of impulse to the forelimbs of +2.7 % compared to the tölt at the corresponding speed and to V_1 at both gaits. This corresponds to results of a previous study which showed that even slight shifts (some centimeters) of the rider's position influence forelimb-hindlimb impulse balance in Icelandic horses (Ramseier et al., 2013).

Comparing the present treadmill data with overground force plate gait analysis in Icelandic horses tölting at medium speeds, values for limb forces, impulses, stance durations and forelimb-hindlimb balance were very similar (Biknevicius et al., 2004).

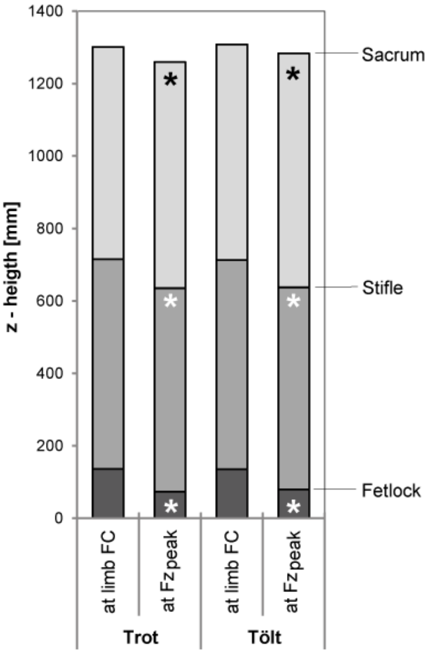

Figure 2: Mean segmental lengths of hindlimbs (12 horses) at tölt and trot (V_1: 3.4 m/s), respectively, at time of limb FC and at time of Fz_{peak}. Significant differences (*P* <0.05) between the segments at the 2 time-points within each gait are marked with asterisks (white *: decrease, black *: increase). For absolute heights of the indicated marker locations at time of Fz_{peak} and the differences between the gaits see **Table 2**. All absolute heights diminished during load onset (limb FC to Fz_{peak}). This reduction was primarily caused by flexion of the fetlock joint and to a minor part by tarsal joint flexion (Stifle – Fetlock). Conversely, the length of the segment Sacrum – Stifle (hip joint) slightly increased.

Comparison of the trot of Icelandic horses to that of 3-gaited Warmblood horses

In the present study, the trot of Icelandic horses displayed a couple of differences compared to the gait pattern of 3-gaited horses. Of these, the very short or lacking airborne phase in the majority of the horses was conspicuous, as both trotting speeds were rather high in relation to the small size of the horses (high Froude numbers). Icelandic horses trotting at V_1 had comparable dynamics (equal Froude numbers) as 1.7 m tall Warmbloods at 3.9 m/s (Weishaupt et al., 2010). In Warmblood horses, suspension phases increase with increasing velocity and are observed even at very slow relative speeds in the unridden (Weishaupt et al., 2010) and ridden trot (Weishaupt et al., 2006b). The shorter or missing suspension phases in Icelandic horses are a consequence of the generally longer StD_{rel} than in Warmbloods. As in Warmblood horses, forelimb support durations in Icelandic horses were longer than in the hindlimbs but closer matched to each other (Weishaupt et al., 2010; Weishaupt et al., 2006b).

In conformity with the subjective impression, the trot of the Icelandic horses on the treadmill was not clearly 2-beated. Fore- and hindlimbs impacted dissociated at both speeds due to a delayed placement of the diagonal hind limb (TAP: V_1 -2.5%SD; V_2 -3.3%SD). In contrast, trot in Warmblood horses at medium speed has a virtually clear acoustical 2-beat footfall rhythm and was shown to have on average a perfect synchronous impact of diagonal limbs (TAP -0.07%SD) (Weishaupt et al., 2010). Temporal key variables of the footfall pattern as StD_{rel}, SpD, TAP, TAC and $StpD_{ipsi}$ of trotting Icelandic horses in the present study had with standard deviations between 1.8 %SD and 4.3 %SD almost twice the variability of those of Warmblood horses (1.1 %SD to 2.3 %SD) (Weishaupt et al., 2010). A large variability regarding the gait pattern is common in Icelandic horses; not only at the trot but even more at the tölt (Weishaupt et al., 2013; Zips et al., 2001). Particularly in 5-gaited horses, correctness of the footfall rhythm is not as stable as in 3-gaited horses. This may be explained by recent genetic research describing a premature stop codon in the DMRT3 gene which is responsible for performing additional gaits, but which leads on the other hand to inferior scores for trot and canter (Andersson et al., 2012). Footfall rhythm in Icelandic horses is also highly sensitive regarding external influences such as speed, imbalance of the horse, riding mistakes and shoeing changes (Feldmann and Rostock, 1986c; Weishaupt et al., 2013).

In spite of these differences in inter-limb timing, compared to Warmblood horses at the trot, the amount of Iz_{fore} was similar in Icelandic horses, but Fz_{peak} were lower due to longer StD_{rel} in fore- and hindlimbs (Weishaupt et al., 2006b).

Energetic estimations

The question whether tölt is energetically more advantageous than trot at the same speed was not a primary aim of this study. However, the presented data allowed estimation of energetic differences between the 2 gaits. It could be shown that the rate of energy consumption ($\dot{E}_{run}$; power) per Newton bodyweight for running is inversely proportional to the mean limb contact time t_c (mean time in seconds, calculated from the 4 individual limb contact times within a stride): $\dot{E}_{run} \sim 1/t_c$ (Kram and Taylor, 1990). From the overall mean stance durations of fore- and hindlimbs in the present data (trot: V_1: 0.286 s; V_2: 0.260 s and tölt: V_1: 0.271 s; V_2:0.248 s), it could be estimated that the metabolic power needed to tölt at the same speed is approximately +5.5% (V_1) higher than to trot; this drawback became slightly smaller (+4.8 %) for the faster velocity.

A recent work assessing the additional energy demands needed to compensate for horizontal deceleration, caused by the braking limb during limb impact, and re-acceleration of the body by the trailing limb (Bertram, 2013). This part of the transport energy, which is much smaller than $\dot{E}_{run}$ due to the considerably lower horizontal GRFs (10% of Fz_{peak}), is higher for smaller angles of attack of the landing limb. In the present study, horizontal energy loss might have been lower at the tölt as a result of the smaller ProRetrA of the forelimbs. In total, these estimations might contradict the expectation that the tölt gait might have developed due to an energetic advantage (Wickler et al., 2003). However, it is in agreement to observations of riders that over very long distances, even 5-gaited horses tend to prefer the trot over the tölt when getting tired (Ingolfsdottir, 2013).

Impact on orthopedic health

The rather frequent occurrence of bone spavin in Icelandic horses has led to the hypothesis that an overload of the hindlimbs at the tölt gait might be 1 of the triggers. However, according to our data, tölt compared to trot at same speeds induces an increased loading of the forelimbs (+7.2%), whereas the hindlimbs are even less loaded with regard to Fz_{peak} (-11.8%) and limb impulses (-8.6%). This finding is in agreement with a previous estimation (Biknevicius et al., 2004) and might be the reason why in investigations of the Icelandic horse population the ability to tölt was not linked with the prevalence of bone spavin (Axelsson et al., 2001).

High HNPs as observed in tölting horses are thought to predispose to back pain due to an extension of the thoracolumbar spine as observed in Warmblood horses (Gomez Alvarez et al., 2006; Rhodin et al., 2009). According to our data, tölting Icelandic horses had a less extended Caudal Back Angle compared to trot at the same speed, despite of the higher HNP at the tölt. This is in agreement with another study in Icelandic horses which found less bridging pressure patterns at the tölt (high HNP) compared to that of a walk (low HNP) (Ramseier et al., 2013). This might indicate that elevation of head and neck might not lead to comparable back extension in Icelandic horses as in other breeds, possibly due to the shorter back and a higher muscle tension.

Conclusions

Comparing the tölt with the trot at same speeds in Icelandic horses, the higher HNP at tölt together with the shorter StD_{rel} resulted in an increased forelimb flight arc and higher Fz_{peak}; conversely, longer StD_{rel} in the hindlimbs led to lower Fz_{peak}. In spite of the higher HNP, there was no measurable weight shift to the hindlimbs and no clear evidence that the tölt requires more collection than the trot. To what extent recent attempts to tölt Icelandic horses with a low HNP similar to trot (Schwörer-Haag and Haag, 2013) may influence the measured kinetic and kinematic variables, remains to be studied.

Overall limb timing in Icelandic horses had a rather large variation at both studied gaits, which was characterized by the tendency towards lateral coupling at the tölt and a slight 4-beat rhythm at the trot compared to Warmblood horses. Further differences to trotting Warmblood horses were longer StD_{rel} resulting in lower Fz_{peak} and a shorter or lacking suspension phase. Energetic estimations suggest that the tölt at slow and medium speed is energetically less advantageous than the trot.

Footnotes

a. Mustang 2000, Graber AG, Fahrwangen, Switzerland.
b. Qualysis Track Manager 2.8, Qualisys, Gothenburg, Sweden.
c. Oqus 300, Qualysis, Gothenburg, Sweden.
d. MathWorks, Natick, MA.
e. SigmaStat 3.5, SPSS Inc, Chicago, Ill.

Acknowledgements
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II. Effects of shoeing on limb movement and ground reaction forces in Icelandic horses at walk, tölt and trot

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Abstract

Tölt is a symmetric four-beat gait with a speed range extending into that of trot and canter. Specific shoeing methods, such as unnaturally high and long hooves, are used to enforce the individual gait predisposition. The aim of this study was to assess the consequences of this shoeing style on loading and movement of the limbs at walk, tölt and trot, and at different velocities. Simultaneous kinetic and kinematic gait analysis was carried out at walk (1.4 m/s) and at two tölting and trotting speeds (3.3 m/s and 3.9 m/s) on an instrumented treadmill. Thirteen sound Icelandic horses were first measured with high, long front hooves (S_H) and, 1 week later, after trimming the hooves according to standard shoeing principles (S_N). Comparing S_H with S_N, front hooves had 21 ± 5 mm longer dorsal hoof walls, and the shoeing material per hoof was 273 ± 50 g heavier. In all three gaits, gait quality, as it is currently judged, was improved with S_H due to a lower stride rate, a longer stride length and a higher, but not wider, forelimb protraction arc, which were also positively associated with speed. Forelimb–hind limb balance remained unchanged, but limb impulses were higher. Apart from an increase of 62.2% in the forelimbs at the faster speed of both tölt and trot, S_H had little influence on vertical peak forces.

Introduction

The tölt of the Icelandic horse is a symmetric and regular four-beat gait with a speed range extending into that of trot and canter, and is comfortable for the rider, even at high speeds (Feldmann and Rostock, 1986c). Most horses need specific training to be able to show the different gaits with a correct footfall rhythm (Feldmann and Rostock, 1986c) and gait irregularities, such as lateral couplets, at the tölt are frequent (Weishaupt et al., 2013; Zips et al., 2001). In addition to speed and posture of the horse, the regularity of the four-beat rhythm at tölt and the height of forelimb action are key points in the judging of Icelandic horse competitions (Anonymous, 2011). To enforce individual gait predisposition and quality, special shoeing, saddling and riding techniques are applied (Feldmann and Rostock, 1986c). Since a high forelimb action is currently rewarded with high scores in competition, it also receives priority in breeding programmes. Shoeing techniques include the growth of unnaturally high and long hooves and the use of weighted boots attached around the hooves. Even though shoe checking procedures have now been established in Icelandic horse competitions (International Federation of Icelandic Horse Associations, 2013), the shoeing still frequently contravenes existing accepted shoeing standards (O'Grady and Poupard, 2003).

A long toe is known to prolong break-over and reduce stride frequency (Weishaupt et al., 2013). The longer lever arm of the toe causes a higher tension within the deep digital flexor tendon and its accessory ligament during break-over, and leads to increased compression of the navicular bone (Page and Hagen, 2002). The influence of such shoeing methods on external limb forces and impulses, and whether they measurably improve forelimb action, has never been studied in Icelandic horses. Weighting of the distal limb and higher velocity both significantly increase the height of the forelimb flight arc during the swing phase in Icelandic horses (Rumpler et al., 2010). In other breeds, this effect of additional weight was observed inconsistently (Wickler et al., 2004; Willemen et al., 1994); however, a delay in the time of peak height of the forelimb flight arc has been described (Singleton et al., 2003).

The aim of this study was to investigate the consequences of high, long hooves on loading and movement of the limbs at walk, tölt and trot, and to determine whether the changes induced by this shoeing style would be consistent at different velocities. It was hypothesized due to a shorter relative stance duration that high, long hooves would (1) increase the peak height of the forelimb flight arc in a speed-dependent manner due to the larger hoof mass and heavier shoes; and (2) lead to higher vertical peak forces in the forelimbs.

Materials and methods

Horses and riders

The study group consisted of 13 sound Icelandic horses (5 stallions, 3 geldings, 5 mares), with an average age of 10 ± 3 years (mean ± standard deviation), a body mass of 356 ± 24 kg and a height at the withers of 1.37 ± 0.03 m. Horses were judged to be free of lameness and pain or dysfunction of the back based on a thorough clinical examination. They were accustomed over at least 4 days to walk, tölt and trot on a high-speed treadmill (Mustang 2000, Graber AG). All horses were ridden by one of two riders experienced in riding Icelandic horses. Trot was ridden in a forward seat (seat slightly raised from the saddle, full weight in the stirrups, upper body tilted slightly forwards). Bridles with snaffle bits were used and a dressage style saddle for Icelandic horses was fitted to the horses in a standard saddle position (Harman, 1999).

The experiment was carried out with the approval of the Animal Health and Welfare Commission of the Canton of Zurich (approval number 206/2010; date of approval 9 November 2010).

Experimental design

Gait analysis was first carried out at the end of the shoeing period. Front hooves were grown high and long (S_H), as commonly practised in competing Icelandic horses, and were shod with 20 mm x 8 mm 3/4 fullered steel shoes, 5 mm plastic pads (Dallmer flat pads, Dallmer) and silicone packing material (Equi-Pak Soft, Vettec). Subsequently, horses were re-shod according to standard shoeing principles (S_N); hooves were adequately trimmed and shod with 20 mm x 8 mm steel shoes only. For each style, dorsal hoof wall length was measured from the transition of the skin to the hoof horn at the coronary band down to the distal edge of the hoof capsule using a measuring tape. Dorsal hoof wall angle was measured using a hoof protractor. The weight difference between shoeings was calculated by subtracting the weight of the new shoe and nails (S_N) from the sum of the weight of the old shoe, including nails, trimmed-off horn, pad and packing material (S_H). Gait analysis was repeated after the horses were allowed at least 1 week to adapt to the new style of shoeing. Measurements were carried out for each shoeing style at one walking (1.4 m/s) and at two tölting and trotting speeds each (V_1: 3.3 m/s; V_2: 3.9 m/s). Gait accuracy and posture of the horse were assessed by an experienced judge of Icelandic horse competitions.

Data acquisition

Ground reaction force (GRF) and temporal variables of each limb were measured with a treadmill integrated force-measuring system (TiF; Weishaupt et al., 2002). Simultaneous kinematic data were obtained by tracking spherical reflective markers (diameter 19 mm) placed over anatomical landmarks on both sides of the horse. Qualisys Track Manager software (QTM 2.5) was used to control nine highspeed infrared cameras (Oqus 600, Qualysis) and to calculate the kinematic xyz-data. The coordinate system was aligned with the treadmill; the x-axis pointing in direction of the horse's head, the y-axis pointing towards its right side and the z-axis upwards. For both systems, a sampling frequency of 480 Hz was applied. Recording time lasted 15 s, which amounted to 12–14 strides at walk, 25–27 strides at tölt and 22–25 strides at trot.

Data analysis

The following temporal, spatial and force variables were determined from the force curves and limb positional data of the TiF-system: stride duration (SD), stride rate (SR), stance duration (StD), ipsilateral step duration ($StpD_{ipsi}$, walk and tölt), stride length (SL), stance length (StL), overreach distance (OR, positive value if the hind hoof lands in front of the ipsilateral front hoof), vertical limb impulse (Iz), vertical stride impulse (Iz_{SD}, as sum of all four Iz) and peak vertical force (Fz_{peak}). StD and StpD were additionally standardised to SD (StD_{rel}, $StpD_{rel}$; unit %SD). To assess the average load distribution between forelimbs and hind limbs during an entire stride cycle, the sum of both vertical forelimb impulses was expressed as a proportion of IzSD (Iz_{fore}%). Force and impulse values were standardised to the combined mass of horse and rider (N/kg and Ns/kg, respectively). All stride variables were averaged per horse and recording. The following kinematic variables were determined (markers involved are given in brackets): Head height (wing of the atlas), dorso-ventral movement of the caudal back (tuber sacrale), maximum forelimb/hind limb protraction and retraction angles (rotation of coffin joint marker around mid spina scapulae/tuber coxae) with zero reference for vertical orientation of metacarpus (carpus, fetlock) or metatarsus (tarsus, fetlock) during stance phase, forearm angle (rotation of carpus marker around elbow with reference to a vertical to the ground through the elbow marker), vertical height of hooves (Z_{coffin}, forelimb and hind limb) and carpus (Z_{carpus}, markers at the respective joints), and time of maximal vertical height of forelimb Z_{coffin} (Z_{coffin}max) as a percentage of swing duration (%SwD).

Time series of kinematic variables and discrete limb contact times from TiF were imported to MatLab (R2009, MathWorks) for further analysis. Based on the stride-cycle times of the left forelimb, time series were split into strides. Data for each stride-cycle were time-standardised to 501 points

(0–100% stride duration), and all strides of a recording were averaged to a standardised averaged stride, of which the stride mean value (mean) was calculated, along with the range of motion (ROM) and the extremes (maximum, max) for the x- and z-dimensions. Corresponding variables of the contralateral limbs were pooled and reported as forelimb and hind limb mean values. All kinematic variables presented in the results refer to the sagittal plane. For illustration purposes, hoof trajectories (coffin joint marker) of all limbs were calculated. To eliminate variation caused by slight translational shifts of the horse on the treadmill, xy-movement data (but not z data) of the respective coffin joint marker were referenced to the horse's tuber sacrale marker (origin of x-axis). An averaged trajectory was calculated from the multiple strides.

Statistical analysis

Statistical analysis was performed with SigmaStat (version 3.5, Systat). Normality (Kolmogorov–Smirnov test) and equal variance of data were tested prior to further analyses. Descriptive data are expressed as means ± standard deviations. At walk, the effect of shoeing style (S_N, S_H) on variables was analysed with a paired t-test or a Wilcoxon signed-rank test. At tölt and trot, the influence of the shoeing styles (S_N, S_H) and velocities (V_1, V_2) was analysed using a two-way repeated measures analysis of variance (ANOVA) separately for each gait. Post hoc multiple comparisons were performed using the Holm–Sidak procedure. The level of significance was set at $P < 0.05$.

Results

One of the horses was not able to trot on the treadmill and was only measured at walk and tölt. Mean ± standard deviation velocities of the measurements were 1.35 ± 0.04 m/s at walk, 3.28 ± 0.04 m/s (V_1) and 3.90 ± 0.10 m/s (V_2) at tölt, and 3.27 ± 0.04 m/s (V_1) and 3.90 ± 0.10 m/s (V_2) at trot. Results of gait analysis comparing the two shoeing styles are shown for the walk in **Table 1**, for the tölt in **Table 2** and for the trot in **Table 3**. At both speeds, the footfall pattern at tölt was characterised by lateral coupling, which was more pronounced in S_N than in S_H; i.e. the relative $StpD_{ipsi}$ was <19.5%SD compared to 25%SD for the regular four-beat rhythm (**Table 2**). At the trot, a suspension phase was lacking at V_1 (Weishaupt et al., 2013).

Influence of shoeing

Weight and size of the front and hind hooves differed significantly between shoeing styles. In S_H, the dorsal hoof walls of the front hooves were 21.3 ± 5 mm and of the hind hooves were 8.1 ± 5 mm longer than in S_N. Dorsal hoof wall angles were smaller by 1.8° in the fore hooves and 1.4° in the hind hooves. The shoes used for the front hooves after trimming (S_N) were 1–2 sizes smaller and the total difference in weight of shoeing material and horn removed was 273 ± 50 g. Re-shoeing led to a reduction of the horses' height at the withers of 14 ± 5 mm. At both speeds of tölt and trot, measurements with S_H showed longer SD and higher forelimb and hind limb Iz compared to S_N ($P < 0.05$); Iz_{fore}% remained unchanged in all three gaits. Peak forces were only increased at V_2 at tölt and trot in the forelimbs; StD_{rel} were shorter at V_2 at trot in the forelimbs and longer in the forelimbs at walk ($P < 0.05$). With S_H, SL was longer in all three gaits and OR was smaller in trotting horses ($P < 0.05$). At all gaits, the height of the arc of flight (ROM of Z_{coffin}) increased in the forelimbs ($P < 0.05$) and, apart from at walk, also in the hind limbs; the moment of peak height of the forelimb arc of flight was delayed (**Figure 1**). There was an increase in maximal protraction angle in the hind limbs at all three gaits ($P < 0.05$), but forelimb and hind limb protraction and retraction angles remained unchanged. S_H had no influence on mean head height in all gaits; however its ROM was decreased at the tölt ($P < 0.05$).

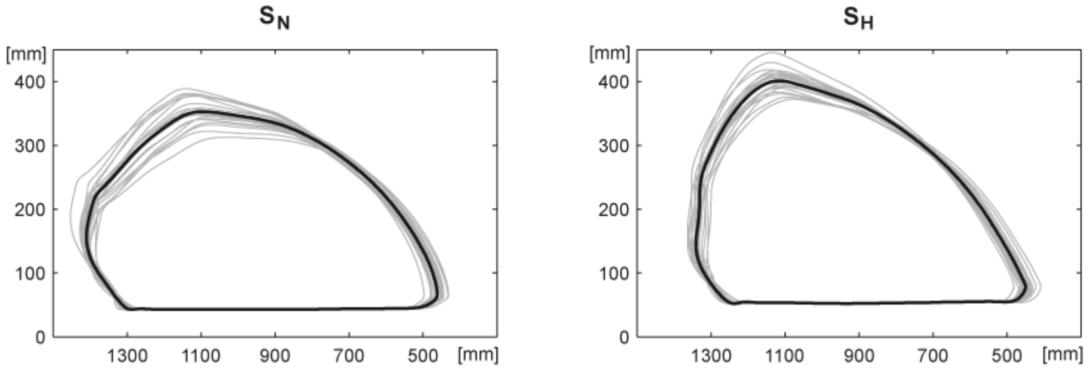

Figure 1: Left hoof trajectories (coffin joint marker) of one horse at the faster speed (V_2 3.90 ± 0.10 m/s) at the tölt, viewed from the left side, projected onto the sagittal plane for the two shoeing styles S_N ('normal', standard shoeing) and S_H (high, long hooves). Depicted are the multiple trajectories (strides, grey) in a record of 15 s and the respective mean (black). There is increased maximal height in S_H compared to S_N and the timing of this maximum is delayed in relation to swing time. Abscissa, positive x-axis pointing to the left, i.e. toward the horse's head (origin at tuber sacrale); ordinate, positive z-axis upwards.

Influence of different speeds at tölt and trot

Most kinetic and kinematic variables differed significantly between V_1 and V_2 at both gaits independent of the shoeing style (**Tables 2** and **3**). Within the same gait, at the faster speed (V_2), SD was shorter and forelimb and hind limb impulses were lower compared with V_1 ($P < 0.05$); impulse distribution between forelimbs and hind limbs was not affected by speed. In forelimbs and hind limbs, StD_{rel} was shorter and F_{zpeak} was higher at V_2. Horses carried their heads higher at the trot. At both gaits at V_2, maximal protraction and retraction angles were increased in the forelimbs and hind limbs ($P < 0.05$), with the exception of retraction angles at the trot in the forelimbs. Range of motion of Z_{coffin} was increased in both forelimbs and hind limbs.

Discussion

High and long hooves biomechanically influence the gait by increasing the weight of the distal limb due to the larger hoof mass, enabling the use of larger and therefore heavier shoes, and by increasing the length of the lever arm, directly affecting breakover. The aim of this study was to examine the effects of this shoeing style (S_H) on limb loading and movement to confirm or refute its empirically assumed effect on a horse's movement pattern and to identify a potentially negative impact of this style of shoeing on the soundness of the locomotor system. Studying the horses on the treadmill made it possible to simultaneously measure forces on all four limbs under controlled conditions with respect to velocity and rider position. Our results were comparable to tölt measurements of an over-ground force plate study at a larger velocity range and with unspecified shoeing condition (Biknevicius et al., 2004). By allowing hooves to grow high and long, and thus using larger shoes and more packing material, it was possible to achieve a weight gain at the level of the distal phalanx equal to that of commonly used weighted boots in Icelandic sport competitions (250 g). The mean dorsal hoof length of 103 ± 5 mm in S_H slightly exceeded the maximal length currently permitted in Icelandic horse competitions (95 mm for horses with a withers height of <1.45 m; 100 mm for larger horses) by the Federation of Icelandic Horse Associations (FEIF) (Anonymous, 2013). Assessing gait quality in Icelandic horse competition takes into account beat regularity and forelimb action (Anonymous, 2011). The frequently observed beat irregularity of lateral coupling at the tölt (Zips et al., 2001), quantified by $StpD_{ipsi}$, was demonstrably reduced in horses shod in the S_H style in the present study (Weishaupt et al., 2013). The desired increase in the height of the forelimb flight arc (Z_{coffin} ROM) was also induced by S_H and was most pronounced at the tölt, accompanied by a lower SR and longer SL. The increase in height of the forelimb flight arc (+41 mm) at the faster tölting speed was slightly higher than that observed in a comparable study in Icelandic horses (+31 mm), where weighted boots of 280 g were used, but without an accompanying change in shape and size of the hoof (Rumpler et al., 2010). This indicates that, in addition to weight, hoof conformation can influence the height of the forelimb protraction movement. The concurrent increase in maximal protraction angle in weighted forelimbs described by Feldmann and Rostock (1986c) was not observed in our study. However, even though shoeing changes were predominantly made in the forelimbs, S_H resulted in an increase in maximal protraction angle at all three gaits and a higher protraction arc at tölt and trot in the hind limbs. At tölt and trot, horses with S_H moved at the same speed and with longer strides, which resulted in longer SD and consequently higher Iz_{SD}. Forelimb and hind limb impulses increased proportionally and, since head height was not affected by S_H, impulse balance remained unchanged (Weishaupt et al., 2006b). In contrast to our hypothesis, there was little influence of shoeing on StD_{rel} and Fz_{peak}. At the tölt, StD_{rel} had a tendency to shorten in the forelimbs and to be longer in the hind limbs, whereas both forelimb and hind limb StD_{rel} tended to shorten at the trot. Only at the faster speed (V_2) and solely in the forelimbs, Fz_{peak} was significantly increased by 1.4% (tölt) and 2.2% (trot), with the latter being associated with a significant StD_{rel} reduction in the forelimbs. Stance duration is the critical variable for Fz_{peak} for a given Iz. In dressage horses, Weishaupt et al. (2006b) showed that the duration of stance changed Fz_{peak} in an inversely proportional manner, dependent on the riding style (head–neck position and overall tension of the movement): a shorter StD_{rel} was associated with a higher Fz_{peak} and vice versa. A shortening of forelimb StD_{rel} at trot also prolonged the suspension phase at V_2, which in turn required a higher vertical acceleration force. Some of the observed increase in forelimb Fz_{peak} might be attributed to the increased effort required to achieve this higher vertical acceleration force in addition to the effect of shoeing. Although increases in Fz_{peak} were small, they might have an effect on limb health during locomotion at higher speeds or during long term repeated exposure. Moreover, a longer lever arm during break-over (i.e. a longer toe) increases forces on internal structures of the distal limb (Page and Hagen, 2002; Van Heel et al., 2006).

During the swing phase, the higher inertial forces due to the increased hoof mass and higher limb action might place additional stresses on muscles, tendons and ligaments. The later occurrence of Z_{coffin}max as a consequence of the application of weight at the distal limb, which was also previously reported in other breeds (Singleton et al., 2003), might lead to steeper hoof landing angles (**Figure 1**). This has been positively correlated with the level of impact forces in humans (Elvin et al., 2007). Due to their suddenness and the delay of the proprioceptive reaction time of the muscles, they might be harmful to the locomotor apparatus. The potentially negative implications that this pattern of movement may have on limb loading should be borne in mind when scoring in competition and breeding events, and should be the subject of further studies. With S_H, ROM of the head was reduced suggesting a greater stability of the gait with this type of shoeing. This might indicate that, in S_N, horses needed to re-balance themselves more by moving their head and neck, and therefore required more support in the way of corrective influences by the rider.

The two velocities within each gait investigated in this study were statistically different and corresponded to a slow and moderate speed at tölt and trot. There were significant speed-dependent effects on inter-limb coordination at both gaits. From V_1 to V_2, the number of single limb support phases at the tölt increased and the suspension phase was consistently present at the trot (Weishaupt et al., 2013). Nevertheless, faster speed generally led to shorter SD and StD_{rel}, as well as to higher peak forces in both shoeing styles, similar to observations in other studies examining Warmblood horses at walk and trot with a more consistent movement pattern at different speeds (Khumsap et al., 2002; Weishaupt et al., 2010).

Most of the measured kinetic and kinematic variables were significantly influenced by speed in similar ways for both gaits. However, the extent of these changes differed between shoeing styles, particularly with regard to limb movement. At tölt, the S_H-induced increase in peak height and delay of Z_{coff}max of the front hoof flight arc were almost equal at both speeds, whereas these parameters were more pronounced at V_2 at trot. The higher Z_{coffin} ROM at trot could not be explained by a higher vertical excursion of the trunk during the airborne phase, since the ROM of the tuber sacrale remained unchanged, and is therefore likely to be caused by an absolute increase in height of the forelimb arc of flight.

Conclusions

At all three gaits, comparing S_H to S_N, gait quality, as currently judged, was improved due to a lower SR, longer SL and a higher, but not wider, forelimb protraction arc, which was positively associated with speed. Forelimb–hind limb balance was unchanged, but limb impulses were higher. S_H had little influence on Fz_{peak}, apart from increasing in the forelimbs at the faster speed of both tölt and trot. Shoeing with high, long hooves may improve gait performance but, in the long term, might adversely affect limb loading and compromise the soundness of the locomotor system.

Table 1: WALK: Group means ± standard deviations (percentage differences) of temporal, spatial and kinematic variables of Icelandic horses (n = 13) at walk for two shoeing conditions (S_N, 'normal', standard shoeing; S_H, shoeing with high, long hooves) at a mean walking velocity of 1.35 (±0.04) m/s.

Variable (limb)	Type	Unit	S_N	S_H
SD		ms	1038 ± 50	1058 ± 40 (+2.0%)
SR		1/min	58.0 ± 2.8	56.8 ± 2.2 (-2.0%) [a]
StD_{abs} (fore)		ms	677 ± 35	697 ± 33 (+3.0%) [a]
StD_{abs} (hind)		ms	687 ± 30	699 ± 25 (+1.8%)
StD_{rel} (fore)		%SD	65.2 ± 0.8	65.9 ± 1.0 (+1.0%) [a]
StD_{rel} (hind)		%SD	66.3 ± 1.4	66.1 ± 1.4 (-0.2%)
$StpD_{ipsi}$		%SD	25.0 ± 3.0	26.4 ± 3.2 (+5.6%) [a]
Iz_{SD}		Ns/kg	10.18 ± 0.49	10.38 ± 0.39 (+2.0%)
Iz (fore)		Ns/kg	3.05 ± 0.17	3.11 ± 0.16 (+2.3%)
Iz (hind)		Ns/kg	2.04 ± 0.10	2.08 ± 0.07 (+1.6%)
Iz_{fore}%		$\%Iz_{SD}$	59.8 ± 1.1	60.0 ± 1.1 (+0.3%)
Fz_{peak1} (fore)		N/kg	6.35 ± 0.22	6.36 ± 0.22 (+0.2%)
Fz_{peak1} (hind)		N/kg	4.06 ± 0.17	4.07 ± 0.17 (+0.2%)
Fz_{peak2} (hind)		N/kg	3.81 ± 0.18	3.81 ± 0.11 (+0.1%)
SL		m	1.39 ± 0.05	1.43 ± 0.05 (+2.4%) [a]
StL (fore)		m	0.91 ± 0.04	0.92 ± 0.03 (+1.9%) [a]
StL (hind)		m	0.90 ± 0.03	0.91 ± 0.03 (+1.9%) [a]
OR		m	-0.04 ± 0.08	-0.05 ± 0.08 (-29.8%)
Protraction (fore)	Max	°	17.7 ± 0.6	18.1 ± 0.6 (+1.8%)
Retraction (fore)	Max	°	-26.1 ± 0.6	-26.7 ± 0.3 (+2.1%)
Protraction (hind)	Max	°	23.0 ± 0.3	23.8 ± 0.3 (+3.1) [a]
Retraction (hind)	Max	°	-17.5 ± 0.4	-17.4 ± 0.4 (-0.4%)
Forearm angle	Max	°	43.3 ± 1.0	44.9 ± 0.8 (+3.8%) [a]
Z_{coffin} (fore)	z-ROM	mm	91 ± 3	96 ± 3 (+6.2%) [a]
Z_{coffin} (hind)	z-ROM	mm	49± 4	49± 3 (-0.2%)
Z_{coffin}max (fore)	Time	%SwD	33.1 ± 1.3	38.7 ± 1.0 (+17.0%)
Z_{carpus} (fore)	z-ROM	mm	129 ± 4	134 ± 2 (+3.6%)
Head height	z-mean	mm	1371 ± 12	1369 ± 10 (-0.1%)
Head height	z-ROM	mm	21 ± 6	16 ± 5 (+7.0%)
Tuber sacrale	z-ROM	mm	46 ± 10	51 ± 9 (+11.0%) [a]

Kinetic variables: **SD**, stride duration; **SR**, stride rate; **StD_{abs}**, absolute stance duration; **StD_{rel}**, stance duration as percentage of SD; **$StpD_{ipsi}$**, lateral step duration as percentage of SD; **Iz_{SD}**, total impulse during SD; **Iz**, limb impulse; **Iz_{fore}%**, percentage of total impulse carried by both forelimbs; **Fz_{peak1}, Fz_{peak2}**, first and second vertical force peak; **SL**, stride length; **StL**, stance length; **OR**, overreach distance (positive if the hind hoof lands in front of the ipsilateral front hoof).

Kinematic variables: **Protraction/retraction**, limb angle of forelimb (coffin joint relative to shoulder) or hind limb (coffin joint relative to tuber coxae) with zero reference for vertical orientation of metacarpus or metatarsus, respectively; **forearm angle**, forward rotation of carpus marker around elbow, referenced to a vertical to the ground through the elbow marker; **Z_{coffin}/Z_{carpus}**, vertical movement of indicated marker; head height, vertical height of atlas; tuber sacrale, vertical movement of tuber sacrale.

Type: **Max**, maximum; **z-ROM**, vertical range of movement; **z-mean**, vertical mean value during SD.

Units: **%SwD**, percentage of swing duration.

[a] Significant differences ($P < 0.05$) between S_N and S_H; percentage differences are given in brackets.

Table 2: TÖLT: Group means ± standard deviations (percentage differences) of temporal, spatial and kinematic variables of Icelandic horses (n = 13) at tölt for two shoeing conditions (S_N, 'normal', standard shoeing; S_H, shoeing with high, long hooves) and two velocities (V_1 and V_2).

			V_1 (3.28 ± 0.04 m/s)		**V_2** (3.90 ± 0.10 m/s)	
Variable (limb)	**Type**	**Unit**	**S_N**	**S_H**	**S_N**	**S_H**
SD		ms	560 ± 24	576 ± 23 (+2.9%) ^{a}	523 ± 22 ^{b}	537 ± 20 (+2.7%) ^{a,b}
SR		1/min	107.3 ± 4.4	104.3 ± 4.1 (-2.8%) ^{a}	115.0 ± 4.7 ^{b}	112.0 ± 4.2 (-2.6%) ^{a,b}
StD_{abs} (fore)		ms	267 ± 10	270 ± 18 (+1.0%)	237 ± 11 ^{b}	241 ± 16 (+1.6%) ^{b}
StD_{abs} (hind)		ms	292 ± 14	303 ± 17 (+3.7%) ^{a}	260 ± 15 ^{b}	268 ± 15 (+3.3%) ^{a,b}
StD_{rel} (fore)		%SD	47.8 ± 1.9	46.9 ± 3.3 (-1.8%)	45.4 ± 2.2 ^{b}	44.9 ± 2.9 (-1.1%) ^{b}
StD_{rel} (hind)		%SD	52.2 ± 2.0	52.6 ± 1.7 (+0.8%)	49.7 ± 2.0 ^{b}	50.0 ± 1.9 (+0.7%) ^{b}
$StpD_{ipsi}$		%SD	17.7 ± 2.6	19.5 ± 3.2 (+10.3%) ^{a}	17.7 ± 2.5	19.4 ± 2.6 (+9.5%) ^{a}
Iz_{SD}		Ns/kg	5.50 ± 0.24	5.65 ± 0.23 (+2.8%) ^{a}	5.13 ± 0.21 ^{b}	5.26 ± 0.19 (+2.6%) ^{a,b}
Iz (fore)		Ns/kg	1.58 ± 0.08	1.61 ± 0.06 (+1.9%) ^{a}	1.47 ± 0.06 ^{b}	1.50 ± 0.07 (+2.1%) ^{a,b}
Iz (hind)		Ns/kg	1.17 ± 0.06	1.22 ± 0.06 (+4.2%) ^{a}	1.09 ± 0.06 ^{b}	1.13 ± 0.05 (+3.3%) ^{a,b}
Iz_{fore}%		%Iz_{SD}	57.5 ± 1.3	57.0 ± 1.0 (-0.9%)	57.3 ± 1.1	57.0 ± 1.2 (-0.6%)
Fz_{peak} (fore)		N/kg	9.44 ± 0.49	9.57 ± 0.69 (+1.4%)	9.97 ± 0.59 ^{b}	10.11 ± 0.73 (+1.4%) ^{a,b}
Fz_{peak} (hind)		N/kg	6.49 ± 0.32	6.43 ± 0.32 (-0.9%)	6.88 ± 0.33 ^{b}	6.86 ± 0.29 (-0.3%) ^{b}
SL		m	1.83 ± 0.08	1.89 ± 0.07 (+2.9%) ^{a}	2.03 ± 0.09 ^{b}	2.09 ± 0.08 (+2.9%) ^{a,b}
StL (fore)		m	0.88 ± 0.03	0.89 ± 0.06 (+0.4%)	0.93 ± 0.03 ^{b}	0.94 ± 0.05 (+1.0%) ^{b}
StL (hind)		m	0.92 ± 0.03	0.95 ± 0.04 (+3.5%) ^{a}	0.96 ± 0.03 ^{b}	0.98 ± 0.04 (+2.3%) ^{a,b}
OR		m	0.50 ± 0.11	0.52 ± 0.11 (+2.8%)	0.66 ± 0.11 ^{b}	0.68 ± 0.10 (+2.0%) ^{b}
Protraction (fore)	Max	°	21.9 ± 2.2	21.7 ± 2.2 (-1.2%)	24.3 ± 2.6 ^{b}	23.7 ± 2.5 (-2.2%) ^{b}
Retraction (fore)	Max	°	-22.0 ± 1.8	-21.4 ± 2.1 (-2.9%)	-22.9 ± 2.1 ^{b}	-22.3 ± 2.2 (-2.4%) ^{b}
Protraction (hind)	Max	°	25.1 ± 1.9	26.9 ± 2.5 (+7.0%) ^{a}	26.7 ± 1.9 ^{b}	27.9 ± 2.0 (+4.5%) ^{a,b}
Retraction (hind)	Max	°	-15.4 ± 1.8	-15.0 ± 1.6 (-2.7%)	-16.0 ± 1.7 ^{b}	-15.9 ± 1.6 (-0.9%) ^{b}
Forearm angle	Max	°	64.3 ± 5.9	68.5 ± 7.2 (+6.5%) ^{a}	68.6 ± 10.0 ^{b}	72.8 ± 9.6 (+6.0%) ^{a,b}
Z_{coffin} (fore)	z-ROM	mm	188 ± 37	231 ± 77 (+23.0%) ^{a}	212 ± 53 ^{b}	253 ± 73 (+19.4%) ^{a,b}
Z_{coffin} (hind)	z-ROM	mm	69 ± 13	78 ± 16 (+11.7%) ^{a}	74 ± 12 ^{b}	82 ± 16 (+9.7%) ^{a,b}
Z_{coffin}max (fore)	Time	%SwD	44.7 ± 6.0	48.6 ± 5.2 (+8.7%) ^{a}	46.6 ± 7.2 ^{b}	49.8 ± 5.6 (+6.9%) ^{a,b}
Z_{carpus} (fore)	z-ROM	mm	199 ± 27	231 ± 52 (+15.8%) ^{a}	222 ± 37 ^{b}	248 ± 49 (+11.9%) ^{a,b}
Head height	z-mean	mm	1533 ± 45	1531 ± 37 (-0.1%)	1539 ± 71	1542 ± 63 (+0.2%)
Head height	z-ROM	mm	60 ± 10	54 ± 6 (-10.4%) ^{a}	67 ± 11 ^{b}	64 ± 10 (-3.7%) ^{a,b}
Tuber sacrale	z-ROM	mm	30 ± 4	31 ± 5 (+4.1%)	30 ± 6	32 ± 5 (+7.9%)

Kinetic variables: **SD**, stride duration; **SR**, stride rate; **StD_{abs}**, absolute stance duration; **StD_{rel}**, stance duration as percentage of SD; **$StpD_{ipsi}$**, lateral step duration as percentage of SD; **Iz_{SD}**, total impulse during SD; **Iz**, limb impulse; **Iz_{fore}%**, percentage of total impulse carried by both forelimbs; **Fz_{peak}**, peak vertical force; **SL**, stride length; **StL**, stance length; **OR**, overreach distance (positive if the hind hoof lands in front of the ipsilateral front hoof).

Kinematic variables: **Protraction/retraction**, limb angle of forelimb (coffin joint relative to shoulder) or hind limb (coffin joint relative to tuber coxae) with zero reference for vertical orientation of metacarpus or metatarsus, respectively; **forearm angle**, forward rotation of carpus marker around elbow, referenced to a vertical to the ground through the elbow marker; **Z_{coffin}/Z_{carpus}**, vertical movement of indicated marker; **head height**, vertical height of atlas; **tuber sacrale**, vertical movement of tuber sacrale.

Type: **Max**, maximum; **z-ROM**, vertical range of movement; **z-mean**, vertical mean value during SD.

Units: **%SwD**, percentage of swing duration.

[a] Significant difference ($P < 0.05$) between S_N and S_H; percentage differences are given in brackets.

[b] Significant difference ($P < 0.05$) between the two tölt velocities.

Table 3: TROT: Group means ± standard deviations (percentage differences) of temporal, spatial and kinematic variables of Icelandic horses (n = 12) at trot for two shoeing conditions (S_N, 'normal', standard shoeing; S_H, shoeing with high, long hooves) and two velocities (V_1 and V_2).

			V_1 (3.27 ± 0.04 m/s)		**V_2** (3.90 ± 0.10 m/s)	
Variable (limb)	**Type**	**Unit**	**S_N**	**S_H**	**S_N**	**S_H**
SD		ms	622 ± 32	636 ± 33 (+2.2%) [a]	574 ± 20 [b]	589 ± 19 (+ 2.6%) [a, b]
SR		1/min	96.7 ± 5.0	94.6 ± 5.2 (-2.1%) [a]	104.7 ± 3.8 [b]	102.0 ± 3.4 (- 2.6%) [a, b]
StD$_{abs}$ (fore)		ms	311 ± 14	317 ± 13 (+1.8%)	268 ± 10 [b]	272 ± 12 (+ 1.3%) [a, b]
StD$_{abs}$ (hind)		ms	287 ± 9	291 ± 11 (+1.2%)	251 ± 9 [b]	255 ± 10 (+ 1.4%) [a, b]
StD$_{rel}$ (fore)		%SD	50.1 ± 1.9	49.9 ± 2.0 (-0.3%)	46.9 ± 2.3 [b]	46.2 ± 2.1 (- 1.4%) [a, b]
StD$_{rel}$ (hind)		%SD	46.2 ± 2.7	45.8 ± 3.3 (-0.9%)	43.9 ± 2.2 [b]	43.3 ± 2.2 (- 1.3%) [b]
Iz$_{SD}$		Ns/kg	6.10 ± 0.31	6.24 ± 0.32 (+2.2%) [a]	5.63 ± 0.20 [b]	5.78 ± 0.19 (+ 2.6%) [a, b]
Iz (fore)		Ns/kg	1.80 ± 0.12	1.84 ± 0.13 (+2.4%) [a]	1.66 ± 0.08 [b]	1.70 ± 0.08 (+ 2.8%) [a, b]
Iz (hind)		Ns/kg	1.25 ± 0.06	1.28 ± 0.05 (+2.0%) [a]	1.16 ± 0.05 [b]	1.19 ± 0.04 (+ 2.5%) [a, b]
Iz$_{fore}$%		%Iz$_{SD}$	59.0 ± 1.5	59.1 ± 1.4 (+0.1%)	58.8 ± 1.4	58.9 ± 1.4 (+ 0.1%)
Fz$_{peak}$ (fore)		N/kg	8.80 ± 0.56	8.90 ± 0.58 (+1.1%)	9.58 ± 0.66 [b]	9.79 ± 0.63 (+ 2.2%) [a, b]
Fz$_{peak}$ (hind)		N/kg	7.22 ± 0.45	7.23 ± 0.39 (+0.2%)	7.57 ± 0.35 [b]	7.63 ± 0.35 (+ 0.7%) [b]
SL		m	2.03 ± 0.09	2.09 ± 0.10 (+2.8%) [a]	2.24 ± 0.09 [b]	2.30 ± 0.07 (+ 2.8%) [a, b]
StL (fore)		m	1.01 ± 0.04	1.03 ± 0.03 (+1.6%) [a]	1.04 ± 0.03 [b]	1.06 ± 0.03 (+ 1.1%) [a, b]
StL (hind)		m	0.89 ± 0.03	0.90 ± 0.03 (+1.7%) [a]	0.94 ± 0.03 [b]	0.95 ± 0.03 (+ 1.5%) [a, b]
OR		m	-0.02 ± 0.07	-0.03 ± 0.07 (-80.5%) [a]	0.07 ± 0.07 [b]	0.05 ± 0.07 (- 26.8%) [a, b]
Protraction (fore)	Max	°	25.7 ± 2.6	25.7 ± 2.6 (+0.3%)	27.7 ± 3.1 [b]	26.9 ± 2.1 (- 2.6%) [b]
Retraction (fore)	Max	°	-25.0 ± 2.1	-24.6 ± 1.3 (+1.4%)	-24.9 ± 2.1	-24.6 ± 1.2 (- 1.2%)
Protraction (hind)	Max	°	24.5 ± 1.9	25.2 ± 1.9 (+2.8%) [a]	25.9 ±1.9 [b]	26.7 ± 1.9 (+ 3.1%) [a, b]
Retraction (hind)	Max	°	-17.4 ± 1.5	-17.3 ± 1.6 (+0.9%)	-18.8 ± 1.6 [b]	-18.7 ± 1.5 (- 0.9%) [b]
Forearm angle	Max	°	57.1 ± 4.6	62.0 ± 6.7 (+8.7%) [a]	59.8 ± 6.0 [b]	65.7 ± 8.9 (+ 9.9%) [a, b]
Z$_{coffin}$ (fore)	z-ROM	mm	158 ± 23	173 ± 31 (+9.3%) [a]	183 ± 34 [b]	211 ± 52 (+ 15.3%) [a, b]
Z$_{coffin}$ (hind)	z-ROM	mm	69 ± 19	75 ± 20 (+9.5%) [a]	83 ± 18 [b]	90 ± 23 (+ 9.2%) [a, b]
Z$_{coffin}$max (fore)	Time	%SwD	34.5 ± 4.1	38.3 ± 4.7 (+10.9%) [a]	35.4 ± 4.4	42.4 ± 7.8 (+ 19.6%) [a]
Z$_{carpus}$ (fore)	z-ROM	mm	187 ± 12	199 ± 17 (+6.3%) [a]	200 ± 18 [b]	218 ± 29 (+ 9.1%) [a, b]
Head height	z-mean	mm	1385 ± 54	1400 ± 49 (+1.1%)	1365 ± 51 [b]	1404 ± 69 (+ 2.9%) [b]
Head height	z-ROM	mm	60 ± 14	57 ± 9 (-3.7%)	70 ± 24	59 ± 7 (- 16.0%)
Tuber sacrale	z-ROM	mm	45 ± 10	43 ± 6 (-4.8%)	47 ± 10	45 ± 5 (- 5.1%)

Kinetic variables: **SD**, stride duration; **SR**, stride rate; **StD$_{abs}$**, absolute stance duration; **StD$_{rel}$**, stance duration as percentage of SD; **StpD$_{ipsi}$**, lateral step duration as percentage of SD; **Iz$_{SD}$**, total impulse during SD; **Iz**, limb impulse; **Iz$_{fore}$%**, percentage of total impulse carried by both forelimbs; **Fz$_{peak}$**, peak vertical force; **SL**, stride length; **StL**, stance length; **OR**, overreach distance (positive if the hind hoof lands in front of the ipsilateral front hoof).

Kinematic variables: **Protraction/retraction**, limb angle of forelimb (coffin joint relative to shoulder) or hind limb (coffin joint relative to tuber coxae) with zero reference for vertical orientation of metacarpus or metatarsus, respectively; **forearm angle**, forward rotation of carpus marker around elbow, referenced to a vertical to the ground through the elbow marker; **Z$_{coffin}$/Z$_{carpus}$**, vertical movement of indicated marker; head height, vertical height of atlas; tuber sacrale, vertical movement of tuber sacrale.

Type: **Max**, maximum; **z-ROM**, vertical range of movement; **z-mean**, vertical mean value during SD.

Units: **%SwD**, percentage of swing duration.

[a] Significant difference ($P < 0.05$) between S_N and S_H; percentage differences are given in brackets.

[b] Significant difference ($P < 0.05$) between the two trot velocities.

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III. Effects of shoeing on intra- and inter-limb coordination and movement consistency in Icelandic horses at walk, tölt and trot

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Contribution of the PhD student to this publication involved planning and accomplishment of the study, as well as assistance with data analysis.

Abstract

To enhance expressiveness of forelimb movement and improve the four-beat rhythm of the tölt, Icelandic horses are commonly ridden with excessively high and long hooves. The aim of this study was to objectively assess the effect of shoeing on intra- and inter-limb coordination and limb movement consistency (inter-stride variability) at walk, tölt and trot. Thirteen sound and fit Icelandic horses accustomed to exercise with a rider on a treadmill were assessed with long and high hooves commonly used for competition (S_H) and with the hooves trimmed according to the standards of normal shoeing (S_N). Limb timing variables were extracted from the four vertical ground reaction force curves measured with an instrumented treadmill. Measurements were taken at walk and at two tölting and trotting speeds. High hooves with long toes reduced stride rate and increased breakover duration. At the tölt, the footfall rhythm showed less tendency to lateral couplets. Movement consistency of the walk remained unchanged, whereas, at the tölt, stride-to-stride variability of selected time parameters increased in S_H and/or at the higher velocity. At the faster trotting speed, variability of hind limb duty factor decreased, whereas variability of contralateral step duration in the forelimb increased. High hooves with long toes improve the clearness of the four-beat footfall rhythm of the tölt, but disturb the movement consistency of the gait. The prolonged breakover duration observed in all gaits may have negative implications for the health of the palmar structures of the distal foot.

Introduction

The Icelandic horse belongs to one of the five-gaited breeds with the ability to perform the tölt and pace in addition to the walk, trot and canter/gallop. In the past, these horses were used to carry or pull loads and for long distance transportation of a rider. Nowadays, they are mainly bred for leisure and competition. The traditional breeding and sports competitions present the different gaits on an oval track with transitions and at different speeds. In addition to tempo, engagement, expressiveness of movements, posture and style of riding, the clearness of the footfall beat and the regularity of the gaits contribute to the scoring of individual performance. In the Sport Judges Guidelines of the International Federation of Icelandic Horse Associations (FEIF), the tölt is defined as 'an even 4-beat gait without suspension, 1 or 2 feet on the ground at any single moment' (Anonymous, 2011). Incorrect gait, e.g., irregular beat or major faults of beat ('pacey', 'trotty' or 'rolling'), three-limb support phases and suspension phases, are reasons for deduction of the score. Previous investigations on the tölt confirmed the footfall pattern between single and double limb support phases and the lack of an airborne phase; however, they also demonstrated that, depending on speed and the horse's body tension, three-limb support and suspension phases occurred (Zips et al., 2001). Furthermore, the clearness of the four-beat rhythm was limited in individual animals to a small velocity range. The majority of strides showed a tölt with lateral couplets that could develop with increasing speed into a four-beat pace. To enhance expressiveness of forelimb movement, but also to improve the clearness of the gait-specific footfall beat and movement consistency, Icelandic horses are commonly ridden with excessively high and long hooves. For competition, the maximal dorsal hoof wall length is regulated to prevent animal welfare infringements. Nevertheless, these criteria still do not conform to standard shoeing guidelines.

The aim of this study was to objectively assess the influence of shoeing style on inter-limb and intra-limb coordination and interstride variability of limb timing at walk, tölt and trot, and at different velocities. We hypothesised that high and long hooves would prolong breakover duration and negatively affect the footfall rhythm of the gait, especially of the tölt and at higher velocities.

Materials and methods

Subjects

Thirteen Icelandic horses fit to compete in 4- and 5-gait competitions were used for this study. The animals comprised five stallions, three geldings and five mares, with a mean age ± standard deviation of 10.1 ± 3.3 years, an age range of 5–15 years, mean body weight ± standard deviation of 356 ± 24 kg and mean height at the withers ± standard deviation of 1.37 ± 0.03 m. All horses were subjected to a thorough orthopaedic examination and were judged to be free from lameness and dysfunction or pain of the back. They were accustomed over at least 4 days to walk, tölt and trot with and without a rider on a high-speed treadmill (Mustang 2200, Graber AG). Horses were ridden by one of two experienced Icelandic horse competition riders. The experimental protocol had been approved by the Animal Health and Welfare Commission of the Canton of Zürich, Switzerland (approval number 206/2010; date of approval 9 November 2010).

Experimental design

In a first trial, horses were assessed at the end of their shoeing period with long and high front hooves (S_H). This shoeing style included 20 mm x 8 mm thick steel shoes, 5 mm thick plastic pads (Dallmer) and silicone packing material (Equi-Pak Soft, Vettec) commonly used in competition. Subsequently, the hooves were trimmed according to the standards of normal shoeing (S_N) and shod with 20 mm x 8 mm steel shoes only. Dorsal hoof wall length was measured from the transition of the skin to the hoof horn at the coronary band down to the distal edge of the hoof capsule using a measuring tape. Dorsal hoof wall angle was measured using a hoof protractor. Hoof horn that was trimmed and rasped off was collected and weighed, together with the horseshoe and, if applicable, with padding and packing material, using a kitchen scale. The horses were left for at least a week to give them time to adapt to the new shoeing situation, while maintaining their usual exercise schedule. Thereafter, the measurements were repeated at the same velocities and with the same rider. Measurements were made at one walking and two identical speeds for tölting and trotting (V_1, V_2). The trot was ridden in a forward seat (seat slightly raised from the saddle, full weight in the stirrups, upper body tilted slightly forwards).

Data acquisition and analysis

Data for gait analysis were collected as soon as the horse was moving at a regular pace. The correctness of execution was judged by an experienced Icelandic Horse competition judge. The two measuring systems that were utilised (ground reaction force, GRF, and kinematics) were started synchronously and recorded for 15 s. Sampling frequency was 480 Hz. The experiment was documented by simultaneously video recording from the left side. Variables of intra- and inter-limb coordination were extracted from the four vertical GRF curves measured with an instrumented treadmill (TiF; Weishaupt et al., 2002): stride duration (SD), stride rate (SR), stance duration (StD), lateral step duration ($StpD_{lat}$), duration of bipedal, tripedal or unipedal support phases at walk and tölt (OD_{2F1H}, OD_{lat}, OD_{2H1F}, OD_{diag}), time of advanced placement and completion at trot (TAP, TAC; time dissociation between diagonal limbs at initial ground contact and at toe-off, respectively) and suspension duration at trot (SpD).

Breakover duration (BoD) of each limb was determined kinematically by capturing the spherical reflective marker affixed to the heel of each hoof. The positions of the markers were tracked with nine infrared high-speed video cameras (Oqus, Qualisys) positioned around the treadmill. Marker co-ordinates were calculated using Qualisys Track Manager software (Qualisys) and exported to Matlab (MathWorks), where the moment of lift-off of the heel marker was determined as percentage of SD. The time of lift-off was set as the moment the vertical displacement of the heel marker exceeded 2.5 mm above the marker's reference height during mid-stance, calculated as average height between 50% and 60% of the respective stance phase. Since the gaits under study are symmetrical gaits and, based on the assumption that horses were not lame, data of the contralateral limbs or corresponding half cycle were pooled. Inter-stride variability was assessed by use of the standard deviation of selected time variables including StD, $StpD_{lat}$, diagonal step duration ($StpD_{diag}$), OD_{2F1H}, OD_{lat}, OD_{2H1F}, OD_{diag} for walk and tölt, and StD, contralateral step duration ($StpD_{cl}$) and SpD for the trot.

Statistical analysis

Statistical analysis of the data was performed with SigmaStat 3.5 (IBM SPSS Statistics). Normality (Kolmogorov–Smirnov test) and equal variance of data were tested prior to further analyses. Descriptive data were expressed as mean ± standard deviation. The effect of shoeing condition (S_N, S_H) on variables at walk was analysed with a paired t test or Wilcoxon signed-rank test. The influences of shoeing condition (S_N, S_H) and velocities (V_1, V_2) were analysed using a two-way repeated measures (RM) analysis of variance (ANOVA) and performed separately for tölt and trot. Differences between tölt and trot were tested with a one-way RM ANOVA at respective velocities (tölt V_1 vs. trot V_1; tölt V_2 vs. trot V_2) and in separate analyses for S_N and S_H. If the ANOVA showed a factorial influence, post hoc all pairwise multiple comparison procedures with Holm–Sidak error control were used to identify group differences. Level of significance was set at $P < 0.05$.

Results

Treadmill adaptation was carried out with all horses without problems; one horse was not able to trot regularly and could only be measured at walk and tölt. Mean velocities ± standard deviations of the measurements at walk were 1.35 ± 0.04 m/s, at tölt 3.28 ± 0.04 m/s (V_1) and 3.90 ± 0.10 m/s (V_2), and at trot 3.27 ± 0.04 m/s (V_1) and 3.90 ± 0.10 m/s (V_2). Horses were on average 14.0 ± 5.0 mm (mean ± standard deviation) taller at the withers and the dorsal hoof wall lengths of the forelimb hooves were on average 21.3 ± 5.3 mm longer, and of the hind hooves 8.1 ± 5.0 mm longer. Trimming and normal shoeing reduced the weight of each front hoof by a mean ± standard deviation of 272.7 ± 50.5 g (range 185–383 g) and the weight of each hind hoof by 14.6 ± 36.7 g. In general, a horseshoe 1–2 sizes smaller could be fitted to the front hoof after trimming.

Intra- and inter-limb timing

Results of temporal data comparing the two shoeing conditions are listed for the walk, the two tölt velocities and the two trot velocities in **Tables 1, 2, and 3**, respectively. At walk, limb support sequence alternated between bipedal and tripedal. At tölt, double limb support phases alternated with single or triple limb supports (**Figure 1**). At V_1, 75.8 ± 22.6% (mean ± standard deviation) of the stride cycles showed single hind limb support phases and 17.2 ± 26.5% single forelimb support phases. At V_2, 95.8 ± 4.4% of the cycles showed single hind limb and 55.3 ± 34.1% single forelimb support phases. Differences in frequencies between the two speeds were significant. The shoeing condition had no influence on these frequencies (means ± standard deviation: V_1, 75.2 ± 30.5% and 10.7 ± 12.9%, respectively; V_2, 89.0 ± 15.7% and 49.7 ± 32.0%, respectively). At the trot, 11/12 horses had first impact with their forelimbs. At diagonal lift-off, the hind limbs preceded the forelimbs in 9/12 horses. Shoeing and velocity had no influence on these frequencies. The number of horses that showed a whole-body aerial phase increased with increasing velocity; at trot V_1, 5/12 horses had an airborne phase, and at trot V_2, 10/12 horses had an airborne phase.

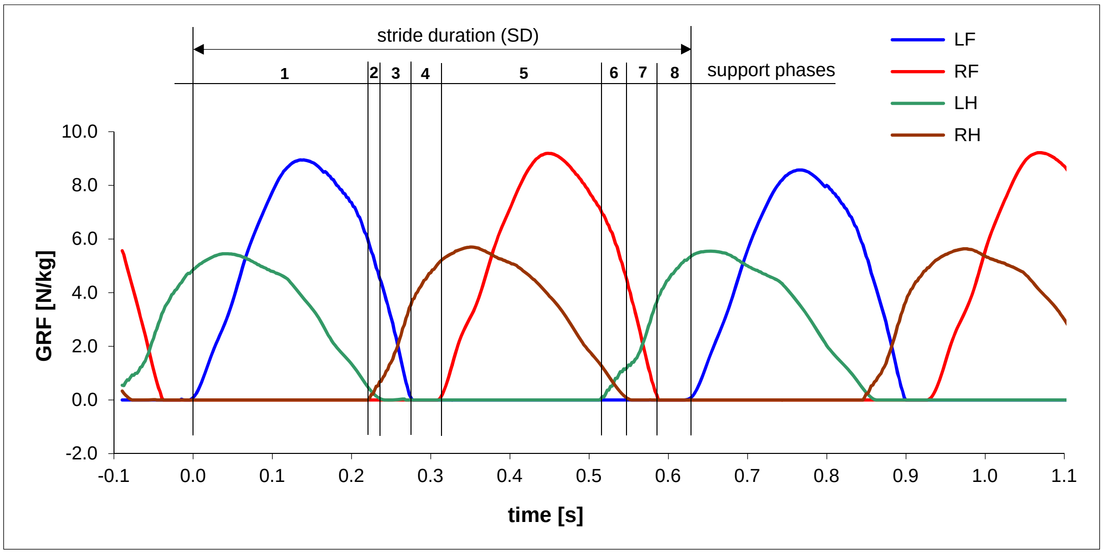

Figure 1: Exemplary time histories of the four vertical ground reaction forces illustrating the inter-limb timing at the slow tölt. LF, left forelimb; RF, right forelimb; LH, left hind limb; RH, right hind limb. (1) Lateral bipedal support phase, LH–LF; (2) tripedal support phase, LH–LF–RH; (3) diagonal bipedal support phase, LF–RH; (4) single limb support phase, RH; (5) lateral bipedal support phase, RH–RF; (6) tripedal support phase, RH–RF–LH; (7) diagonal bipedal support phase, RF–LH; (8) single limb support phase, LH.

Table 1: Means ± standard deviations (percentage differences) of time variables of Icelandic horses (n = 13) at walk (1.35 ± 0.04 m/s) for two shoeing conditions (S_N, normal; S_H, competition).

Variable	Limb	S_N	S_H
SR (1/min)		58.0 ± 2.8	56.8 ± 2.2 (-2.0%) [a]
SD (ms)		1038 ± 50	1058 ± 40 (+2.0%)
StD_{abs} (ms)	Forelimbs	677 ± 35	697 ± 33 (+3.0%) [a]
	Hind limbs	687 ± 30	699 ± 25 (+1.8%)
StD_{rel} (%SD)	Forelimbs	65.2 ± 0.8	65.9 ± 1.0 (+1.0%) [a]
	Hind limbs	66.3 ± 1.4	66.1 ± 1.4 (-0.2%)
$StpD_{lat}$ (%SD)	Half cycle	25.0 ± 3.0	26.4 ± 3.2 (+5.6%) [a]
OD_{2F1H} (%SD)	Half cycle	15.2 ± 0.8	15.9 ± 1.0 (+4.2%) [a]
OD_{lat} (%SD)	Half cycle	9.8 ± 2.9	7.7 ± 3.1 (-21.1%) [a]
OD_{2H1F} (%SD)	Half cycle	16.3 ± 1.4	16.1 ± 1.3 (-0.9%)
OD_{diag} (%SD)	Half cycle	8.7 ± 2.1	10.3 ± 2.3 (+17.9%) [a]
BoD_{abs} (ms)	Forelimbs	66 ± 15	82 ± 21 (+24.2%) [a]
	Hind limbs	76 ± 8	83 ± 10 (+9.6%) [a]
BoD_{rel} (%StD)	Forelimbs	9.7 ± 1.8	11.6 ± 2.7 (+20.4%) [a]
	Hind limbs	11.1 ± 1.2	11.9 ± 1.4 (+7.5%) [a]

SR, stride rate; **SD**, stride duration; **StD_{abs}**, absolute stance duration; **StD_{rel}**, duty factor (StD_{abs} relative to SD); **OD_{2F1H}**, overlap duration of tripedal support, i.e. two forelimbs and one hind limb; **OD_{lat}**, overlap duration of lateral bipedal support; **OD_{2H1F}**, overlap duration of tripedal support, i.e. two hind limbs and one forelimb; **OD_{diag}**, overlap duration of diagonal bipedal support; **$StpD_{lat}$**, lateral step duration; **BoD_{abs}**, absolute breakover duration; **BoD_{rel}**, relative breakover duration; **%SD**, percentage of SD.

[a] Significant difference ($P < 0.05$) between normal and competition shoeing.

Table 2: Means ± standard deviations (percentage differences) of time variables of Icelandic horses (n = 13) at tölt for two shoeing conditions (S_N, normal; S_H, competition) and two velocities (V_1, V_2).

		V_1 (3.28 ± 0.04 m/s)		V_2 (3.90 ± 0.10 m/s)	
Variable	**Limb**	S_N	S_H	S_N	S_H
SR (1/min)		107.3 ± 4.4	104.3 ± 4.1 (-2.8%) [a]	115.0 ± 4.7 [b]	112.0 ± 4.2 (-2.6%) [a,b]
SD (ms)		560 ± 24	576 ± 23 (+2.9%) [a]	523 ± 22 [b]	537 ± 20 (+2.7%) [a,b]
StD_{abs} (ms)	Forelimbs	267 ± 10	270 ± 18 (+1.0%)	237 ± 11 [b]	241 ± 16 (+1.6%) [b]
	Hind limbs	292 ± 14	303 ± 17 (+3.7%) [a]	260 ± 15 [b]	268 ± 15 (+3.3%) [a,b]
StD_{rel} (%SD)	Forelimbs	47.8 ± 1.9	46.9 ± 3.3 (-1.8%)	45.4 ± 2.2 [b]	44.9 ± 2.9 (-1.1%) [b]
	Hind limbs	52.2 ± 2.0	52.6 ± 1.7 (+0.8%)	49.7 ± 2.0 [b]	50.0 ± 1.9 (+0.7%) [b]
$StpD_{lat}$ (%SD)	Half cycle	17.7 ± 2.6	19.5 ± 3.2 (+10.3%) [a]	17.7 ± 2.5	19.4 ± 2.6 (+9.5%) [a]
OD_{2F1H} (%SD)	Half cycle	2.7 ± 1.4	3.8 ± 2.6 (+41.0%) [a]	4.7 ± 2.1 [b]	5.4 ± 2.7 (+14.9%) [a,b]
OD_{lat} (%SD)	Half cycle	31.9 ± 2.5	30.1 ± 3.0 (-5.7%) [a]	31.3 ± 2.4	29.8 ± 2.2 (-4.9%) [a]
OD_{2H1F} (%SD)	Half cycle	2.6 ± 1.5	2.8 ± 1.5 (+8.2%)	2.1 ± 0.8	2.0 ± 0.8 (-2.7%)
OD_{diag} (%SD)	Half cycle	12.9 ± 3.3	13.5 ± 3.9 (+4.7%)	12.7 ± 3.0	13.7 ± 2.5 (+8.2%)
BoD_{abs} (ms)	Forelimbs	30 ± 3	33 ± 5 (+11.6%) [a]	27 ± 3 [b]	30 ± 4 (+10.1%) [a,b]
	Hind limbs	45 ± 5	49 ± 7 (+8.7%) [a]	39 ± 4 [b]	42 ± 5 (+6.6%) [a,b]
BoD_{rel} (%StD)	Forelimbs	11.1 ± 1.0	12.3 ± 1.2 (+10.4%) [a]	11.6 ± 1.2 [b]	12.5 ± 1.2 (+8.0%) [a,b]
	Hind limbs	15.3 ± 1.5	16.1 ± 2.1 (+5.0%) [a]	15.1 ± 1.1	15.5 ± 1.4 (+3.2%) [a]

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SR, stride rate; **SD**, stride duration; **StD$_{abs}$**, absolute stance duration; **StD$_{rel}$**, duty factor (StD$_{abs}$ relative to SD); **OD$_{2F1H}$**, overlap duration of tripedal support, i.e. two forelimbs and one hind limb or single hind limb support; **OD$_{lat}$**, overlap duration of lateral bipedal support; **OD$_{2H1F}$**, overlap duration of tripedal support, i.e. two hind limbs and one forelimb or one single forelimb support; **OD$_{diag}$**, overlap duration of diagonal bipedal support; **BoD$_{abs}$**, absolute breakover duration; **BoD$_{rel}$**, relative breakover duration; **%SD**, percentage of SD.

[a] Significant difference ($P < 0.05$) between normal and competition shoeing.

[b] Significant difference ($P < 0.05$) between the two tölt velocities.

Table 3: Means ± standard deviations (percentage differences) of time variables of Icelandic horses (n = 12) at trot for two shoeing conditions (S$_N$, normal; S$_H$, competition) and two velocities (V$_1$, V$_2$).

		V$_1$ (3.27 ± 0.04 m/s)		**V$_2$** (3.90 ± 0.10 m/s)	
Variable	Limb	S$_N$	S$_H$	S$_N$	S$_H$
SR (1/min)		96.7 ± 5.0 [c]	94.6 ± 5.2 (-2.1%) [a,c]	104.7 ± 3.8 [b,c]	102.0 ± 3.4 (-2.6%) [a,b,c]
SD (ms)		622 ± 32 [c]	636 ± 33 (+2.2%) [a,c]	574 ± 20 [b,c]	589 ± 19 (+2.6%) [a,b,c]
StD$_{abs}$ (ms)	Forelimbs	311 ± 14 [c]	317 ± 13 (+1.8%) [a,c]	268 ± 10 [b,c]	272 ± 12 (+1.3%) [a,b,c]
	Hind limbs	287 ± 9	291 ± 11 (+1.2%) [c]	251 ± 9 [b]	255 ± 10 (+1.4%) [b,c]
StD$_{rel}$ (%SD)	Forelimbs	50.1 ± 1.9 [c]	49.9 ± 2.0 (-0.3%) [c]	46.9 ± 2.3 [b,c]	46.2 ± 2.1 (-1.4%) [b]
	Hind limbs	46.2 ± 2.7 [c]	45.8 ± 3.3 (-0.9%) [a,c]	43.9 ± 2.2 [b,c]	43.3 ± 2.2 (-1.3%) [a,b,c]
TAP$_{abs}$ (ms)		-26 ± 25	-21 ± 22 (+22.3%) [a]	-18 ± 19 [b]	-10 ± 19 (+45.7%) [a,b]
TAP$_{rel}$ (%SD)		-4.4 ± 4.4	-3.4 ± 3.7 (+23.5%) [a]	-3.3 ± 3.4 [b]	-1.8 ± 3.3 (+46.0%) [a,b]
TAC$_{abs}$ (ms)		-2 ± 31	6 ± 29 (-349.4%) [a]	-1 ± 22	7 ± 19 (-583.8%) [a]
TAC$_{rel}$ (%SD)		-0.6 ± 5.3	0.7 ± 4.7 (-221.9%) [a]	-0.3 ± 3.9	1.1 ± 3.3 (-472.2%) [a]
SpD$_{abs}$ (ms)		-13 ± 30	-10 ± 25 (-22.5%)	9 ± 24 [b]	14 ± 16 (+53.3%) [b]
SpD$_{rel}$ (%SD)		-2.3 ± 5.2	-1.8 ± 4.3 (-22.4%)	1.5 ± 4.3 [b]	2.3 ± 2.8 (+55.5%) [b]
BoD$_{abs}$ (ms)	Forelimbs	38 ± 4 [c]	42 ± 4 (+10.0%) [a,c]	33 ± 3 [b,c]	36 ± 4 (+7.6%) [a,b,c]
	Hind limbs	40 ± 5 [c]	43 ± 6 (+6.9%) [a,c]	34 ±5 [b,c]	36 ± 4 (+5.2%) [a,b,c]
BoD$_{rel}$ (%StD)	Forelimbs	12.2 ± 1.0 [c]	13.2 ± 1.1 (+8.0%) [a,c]	12.5 ± 1.0 [b,c]	13.2 ± 1.2 (+6.2%) [a,b,c]
	Hind limbs	14.1 ± 1.7 [c]	14.8 ± 1.8 (+5.4%) [a,c]	13.6 ± 1.6 [b,c]	14.2 ± 1.3 (+4.0%) [a,b,c]

SR, stride rate; **SD**, stride duration; **StD$_{abs}$**, absolute stance duration; **StD$_{rel}$**, duty factor (StD$_{abs}$ relative to SD); **TAP$_{abs}$**, time of advanced placement (negative value if forelimb precedes diagonal hind limb); **TAP$_{rel}$**, **TAP$_{abs}$** relative to SD; **TAC$_{abs}$**, diagonal advanced completion (positive value if hind limb precedes diagonal forelimb); **TAC$_{rel}$**, TAC$_{abs}$ relative to SD; **SpD$_{abs}$**, suspension duration; **SpD$_{rel}$**, SpD$_{abs}$ relative to SD; **BoD$_{abs}$**, absolute breakover duration; **BoD$_{rel}$**, relative breakover duration; %SD, percentage of SD.

[a] Significant difference ($P < 0.05$) between shoeing condition.

[b] Significant difference ($P < 0.05$) between the two trot velocities.

[c] Significant difference ($P < 0.05$) between tölt and trot referring to Table 2

Inter-stride variability

At walk, all selected variables reflecting movement consistency were unchanged by shoeing and faster velocity. At the tölt, variability of forelimb StD$_{rel}$, OD$_{2F1H}$, OD$_{lat}$ and OD$_{2H1F}$ was larger with high and long hooves, and of OD$_{2F1H}$, OD$_{lat}$ and OD$_{diag}$ higher at V$_2$. At trot, variability of hind limb StD$_{rel}$ decreased and variability of forelimb StpD increased at the faster velocity.

Discussion

The time required for hoof growth precluded randomisation of treatments and thus an order effect on the findings cannot be excluded. The S_H situation reproduced with 10.3 ± 0.53 cm quite well the maximum permitted forelimb dorsal hoof wall lengths for competition of 9.5 cm for horses up to 1.44 m withers height and 10.0 cm for horses of 1.45 m and taller (Anonymous, 2013). The weight difference in the forelimbs due to the trimmed-off hoof horn and the difference between the new and the old shoes and shoeing accessories averaged 270 g per forelimb. This slightly exceeds the maximal weight (250 g) of protective equipment (e.g. heel boots) allowed in competition (Anonymous, 2013).

Gaits are traditionally categorised as walking or running on the basis of criteria such as duty factor (DF), dimensionless speed, existence of an airborne phase or the shape of the vertical GRF profile. A DF≥0.5 has been used to indicate a walking gate and <0.5 a running gait (Hildebrand, 1965, 1989; Hoyt et al., 2006). The existence of an airborne phase is associated with the run, as is a single peaked force profile. (Starke et al., 2009) applied a multi-dimensional discrimination approach to limb-timing and trunk movement information and concluded that the tölt, for which the abovementioned criteria assessed each on their own give conflicting results, is most appropriately classified as a running gait. In this study, DFs at walk were 0.65–0.66 and similar for forelimbs and hind limbs; at tölt, DFs for the forelimbs were <0.5 (range 0.45–0.48) and for the hind limbs at $V_1 > 0.5$ (range 0.52–0.53) and at $V_2 \approx 0.5$ (range 0.49–0.50); at trot, DFs were <0.5 (range 0.43–0.47), except in the forelimbs at V_1, where the DF was 0.5. Despite DFs < 0.5, no suspension phases were observed at either tölt velocity or in the majority of the horses at the slower trotting velocity. However, all the vertical force profiles at tölt and trot were single peaked, indicative of a running gait (Waldern et al., 2013). High and long hooves reduced SR, prolonged BoD, changed the clear four-beat rhythm of the walk to a slightly diagonally bound gait pattern and reduced the degree of lateral couplets at the tölt.

For all gaits and speeds, SR was reduced by 2.0–2.8%, which resulted in proportionally longer stride lengths (Waldern et al., 2013). At the tölt, a gait that is typically characterised by a relatively high SR (+10% compared to the trot at the same velocities), the reduced SR together with an unchanged DF enabled a higher forelimb hoof trajectory during the swing phase (Waldern et al., 2013). The lowering of SR with S_H could be directly related to the increase in BoD. The ease of breakover can be influenced by hoof trim, shoe shape and shoe placement relative to the tip of P3. From studies in other breeds, it is known that hooves with long toes prolong breakover time (Balch et al., 1994; Clayton, 1990a, b) and toe modifications on the horseshoe (e.g., rolled toe) ease breakover of the hoof by reducing the length of the lever arm over which the hoof pivots during the last third of stance. Consequently, it is assumed that a long toe leads to increased compression of the navicular region during lift-off (Page and Hagen, 2002; Van Heel et al., 2006). Changes in BoD as a result of shoeing style have not been observed consistently. Eliashar et al. (2002) assessed different types of horseshoes believed to facilitate breakover. Although the distal interphalangeal (DIP) joint moment arm was shorter with these shoes, BoD remained unchanged and neither higher peak DIP joint moments, nor peak compressive forces on the navicular bone, were observed. In this study, hind limb and especially forelimb BoD were clearly prolonged in S_H measurements in all three gaits and differed according to the dissimilar degree of shoeing intervention between hind and front hooves. At tölt, the increase accounted for 10%. Interestingly, forelimb $StpD_{lat}$ changed in the same proportions, prolonging the lateral footing sequence, therefore reducing lateral couplets in S_H. In hooves with a long-toe low-heel conformation, BoD can be even more prolonged. Clayton (1990b) reported changes of up to 30% between a normal shaped hoof where the dorsal hoof wall is aligned with the hoof-pastern axis and an acute hoof angulation with a broken-back hoof-pastern axis.

Empirically, it is known that clearness of the footfall rhythm, especially of the tölt, depends on how the horse is ridden, the level of training, surface properties, if the horse is ridden on a slight uphill/downhill slope and especially on the velocity. Zips et al. (2001) observed a true tölt pattern in the majority of their study horses only within a narrow speed range; at extended speeds, a four-beat pace was recorded or, occasionally, a four-beat trot. In practice, shoeing interventions and changes in forehand–hindquarter balance by rider interaction are used to influence the clearness of the footfall rhythm. At walk, the horses with normal shoeing showed on average a clear four-beat rhythm (25.0 ± 3.0%) and S_H shifted the rhythm slightly toward diagonal couplets (26.4 ± 3.2%). At tölt, based on the definitions of Zips et al. (2001), our horses showed on average a tölt with lateral couplets but never a four-beat pace, as no suspension phases were observed. The high and long front hooves reduced the degree of lateral couplets by 8–10%, confirming the benefit of this practice carried out to rectify a 'pacey' tölt.

Tölt is defined as a symmetrical four-beat, stepping gait with single and double support phases (Anonymous, 2011). Nevertheless, in this study, around 25% (V_1) and 5% (V_2) were two forelimb/one hind limb tripedal support phases, instead of single hind limb supports, and around 85% (V_1) and 45% (V_2) two hind limb/one forelimb tripedal support phases instead of single forelimb supports. Although horses were adapted to the treadmill and riders confirmed that the horses were moving at appropriate speeds and in a manner equivalent to their normal gait, the treadmill situation with its ground surface properties might have influenced the gait pattern, increasing limb overlap and, therefore, the base of support for stability. Similarly, in Warmblood horses, the proportion of tripedal support phases increased at the expense of bipedal supports at slower walking velocities (Weishaupt et al., 2010). Hildebrand (1989) pointed out that, especially in animals with shorter legs, the diagonal bipod would be more stable than the lateral bipod as the line of support crosses the midline of the body. This gait adjustment was observed as an effect of S_H at walk and tölt, during which lateral bipedal support phase decreased and diagonal bipedal support phase increased. When this finding is taken together with the observation that, at tölt, inter-stride variability of forelimb DF and limb support overlaps increased, it can be concluded that high and long hooves might compromise the overall stability of gait and balance in walking and tölting Icelandic horses. At tölt, duration of limb overlaps was velocity-dependent. In accordance with Zips et al. (2001), the number of the single limb support phases increased at the faster velocity. Likewise, other gaited horses, such as the Tennessee Walking Horse, at extended velocities (3.80 m/s) start to replace the tripedal support phase of the running walk with a single support phase (Nicodemus and Clayton, 2003). At even faster velocities, suspension phases replace the lateral and/or diagonal bipedal support phases, resulting in a four-beat pace and four-beat trot, respectively. These shifts occur continuously dependent on the individual gait capacities of the horse.

Conclusions

High hooves with long toes reduced the cadence of all three gaits and changed inter-limb and intra-limb co-ordination. At the tölt, the footfall rhythm became less 'pacey', which is desirable in competition; however, stride-to-stride variability increased. Variation in temporal variables due to conditions other than velocity, such as training and shoeing, may be important for performance, but it must be considered that adverse effects on gait mechanics reflected in this study by prolonged breakover durations can compromise the soundness of the hoof and the locomotor system.

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IV. Saddle pressure distributions of three saddles used for Icelandic horses and their effects on ground reaction forces, limb movements and rider positions at walk and tölt

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Contribution of the PhD student to this publication involved planning and accomplishment of the study, as well as assistance with data analysis and compilation of the manuscript.

Abstract

Icelandic horse riding practices aim to place the rider further caudally on the horse's back than in English riding, claiming that a weight shift toward the hindquarters improves the quality of the tölt (e.g. giving the shoulder more freedom to move). This study compared saddle pressure patterns and the effects on limb kinetics and kinematics of three saddles: an Icelandic saddle (S_{Icel}, lowest point of seat in the hind part of the saddle), a treeless saddle cushion (S_{Cush}) and a dressage-style saddle (S_{Dres}). Twelve Icelandic horses were ridden with S_{Icel}, S_{Cush} and S_{Dres} on an instrumented treadmill at walk and tölt. Saddle pressure, limb forces and kinematics were recorded simultaneously. With S_{Cush}, pressure was highest under the front part of the saddle, whereas the saddles with trees had more pressure under the hind area. The saddles had no influence on the motion patterns of the limbs. The slight weight shift to the rear with S_{Cush} and S_{Icel} may be explained by the more caudal position of the rider relative to the horse's back.

Introduction

Icelandic horses are known for their special gaits, particularly the four-beat tölt, which can be ridden from walking up to cantering speeds. To assist the horse at the tölt, it is stated that the rider needs to induce a slight weight shift toward the horse's hindquarters (Feldmann and Rostock, 1986b). This can be achieved by the rider having a more caudal position in relation to the horse's back and/or by elevation of the head and neck. The aforementioned approach aims to 'free-up the shoulder,' resulting in increased movement of the shoulder and, consequently, the forelimb, a desirable effect in Icelandic horse competitions. With respect to these demands, special saddling and riding techniques have been developed empirically in Iceland and have been adopted world-wide. There are different ways to position the rider more caudally with respect to the horse's centre of mass (COM), either by placing the rider in the rear part of the saddle or, more effectively, by positioning the whole saddle further caudally on the horse's back. Traditionally, large saddles with padded bars (Trachtensättel) extending into the lumbar region with a wide seat and the deepest point of the saddle far back were used to ride long distances comfortably.

Nowadays, Icelandic saddles are shorter, but still have the deepest point of the seat caudal to the centre of the saddle. Treeless saddles are also widely used, based on the idea that they fit every horse and allow the rider to adjust the seat position according to the need to support the gait. The common Icelandic riding and saddling practices are partly contradictory to the basic principles applied in English riding that aim to place the rider close to the horse's COM and the deepest point of the seat approximately at the centre of the saddle; this makes it easier for the rider to balance and move in harmony with the horse (Harman, 2004). Moreover, it is known that the caudal part of the back is particularly sensitive to load (Nyikos et al., 2005). Nevertheless, the effects of these Icelandic saddling and riding practices on back and orthopaedic health, as well as the range of motion of the back and forelimbs, have not yet been studied. In this context, it is worth noting that Icelandic horses are rarely presented clinically due to back pain, although their rather stoic nature might mask possible discomfort.

As a consequence of biomechanical studies of other breeds, the traditional saddling and riding methods considered normal in Icelandic horses are being judged with increasing scepticism (Schwörer-Haag and Haag, 2013). A new type of saddle for Icelandic horses has recently been developed, which has a design similar to that of English dressage saddles. These saddles are to be positioned according to the recommendations for English saddles used in non-gaited horse breeds, as described by (Harman, 2004).

The aim of this study was to compare the effects on pressure distribution under the saddle and effects on limb forces and kinematics of three saddles: two saddles with trees of differing design and with differently localised deepest point of the seat, as well as a treeless saddle. We hypothesised that a saddle with a more caudally positioned deepest point of the seat would load the back more caudally, but would not influence the forelimb–hind limb balance and movements of the horse.

Materials and methods

Experimental design

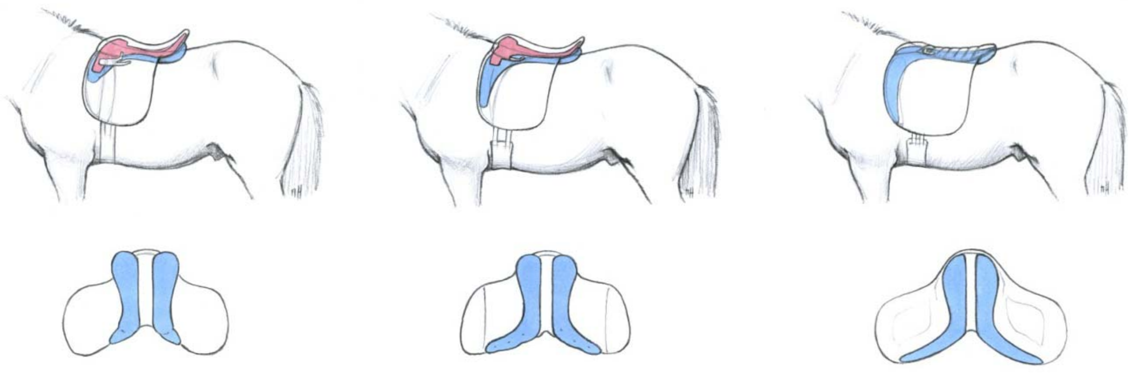
Twelve Icelandic horses (4 mares, 5 stallions and 3 geldings; mean ± standard deviation: age 11.5 ± 3 years; height at the withers 1.37 ± 0.03 m; bodyweight 354 ± 25 kg) were each ridden with three different saddles on a treadmill (Mustang 2200, Graber AG) at walk (1.3 m/s) and tölt (3.4 m/s). Horses were free of lameness and pain or dysfunction of the back. All horses were accustomed to the treadmill and were ridden by one of two experienced riders of 65.2 and 74.5 kg bodyweight; each horse was ridden in all trials by the same rider. Accuracy of gait and posture of the horse were assessed by an experienced judge of Icelandic horses. The experimental protocol was approved by the Animal Health and Welfare Commission of the Canton of Zürich, Switzerland (approval number 206/2010).

Three saddle types (**Figure 1**) placed in the standard position (Harman, 2004) were investigated in random order on the same day: (1) a dressage-style saddle (S_{Dres}; Pleasure II, ChampionRider; weight 8.3 kg) with its deepest point in the middle of the saddle; (2) a traditional Icelandic saddle (S_{Icel}; Z-Sattel, TopReiter; 7.5 kg), with the deepest point of the seat slightly toward the cantle; and (3) a treeless saddle cushion (S_{Cush}; Sattelkissen, TopReiter; 7.3 kg). The S_{Icel} and S_{Cush} were only available in one size. The S_{Dres} was available with four different head plate sizes; based on manual and visual evaluation (Harman, 2004) and saddle pressure measurements, the most suitable saddle was chosen for each horse.

Data acquisition

Kinematic, kinetic and saddle pressure data were measured simultaneously. Vertical ground reaction force (GRF) and temporal and spatial variables of each limb were measured with a treadmill-integrated force measuring system (TiF, Weishaupt et al. 2002). Kinematic data were obtained by tracking spherical reflective markers (diameter 19 mm) placed over anatomical landmarks on both sides of the horse, rider and saddle mat with nine infrared cameras (Oqus 600, Qualysis). Qualisys Track Manager software (Qualysis) was used to control the cameras and to calculate the kinematic xyz-data. The left-handed coordinate system was aligned with the treadmill, the x-axis pointing in direction of the horse's head, the y-axis pointing toward its right and the z-axis upward.

Saddle pressure was measured with a Pliance-X System (Novel) using a Novel MSA600 pressure sensitive mat placed symmetrically on the horse's back, leaving a small gap along the spine. Zero base line was set before saddling and tightening the girth. Calibration of the pressure-sensitive mat was performed each day prior to data collection. Recordings lasted 15 s, which amounted to 12–14 strides at walk and 24–26 strides at tölt. Frame rates of 480 Hz (TiF and Qualysis) and 60 Hz (Pliance-X) were used.



Dressage-style saddle (S_{Dres}) **Icelandic saddle (S_{Icel})** **Saddle cushion (S_{Cush})**

Figure 1: Diagrams of the tree and panel configurations of the three saddles used in the study. Red, head plate and tree; blue, panels. S_{Dres}: wooden spring tree, wool cushions, conventional three-strap girth (Edwards, 1963). S_{Icel}: flexible synthetic tree, latex cushions, two-strap girth with anterior billet attached at the head plate. S_{Cush}: treeless, foam cushions, two billets attached at the sweat flap.

Data analysis

The following temporal, spatial and force variables were determined from the force curves and limb positional data of the TiF-system: stride duration (SD), stance duration relative to SD (StD), ipsilateral step duration relative to SD ($StpD_{lat}$), stance length (StL), overreach distance (OR), vertical limb impulse (Iz) and peak vertical GRF (Fz_{peak}). The percentage of total vertical impulse carried by both forelimbs (Iz_{fore}) was used to assess the horse's impulse balance between forequarters and hindquarters. Limb contact times were converted into stride-standardised times (%SD) and force and impulse values were standardised to the combined mass of horse, rider and saddle (N/kg and Ns/kg, respectively). For each variable, the values of the multiple strides in a record were averaged. Time series of kinematic and saddle pressure data and discrete limb contact times from TiF were imported into MatLab (MathWorks) for further analysis. Based on the stride-cycle times of the left forelimb, time series were split into strides. Data for each stride-cycle were time-standardised to 101 points (0–100% stride duration) and all strides in a recording were averaged. All further analyses were based on this standardised averaged stride. Corresponding variables of the contralateral limbs were pooled and reported as forelimb and hind limb values.

The following kinematic variables were determined (markers involved are given in brackets): (1) horse: head height (wing of the atlas), forelimb/hind limb protraction and retraction angle (rotation of a marker on the lateral hoof wall at the level of the coffin joint around the calculated midpoint between the left and right shoulder joints or tuber coxae), forearm angle (rotation of the carpus around the elbow) and shoulder rotation around the x- and z-axis (both shoulder joints); and (2) rider: rider position relative to horse's back (rider sacrum – horse L5) and rider back angle (rotation of rider C7 around rider sacrum). For each variable, stride mean (mean), range of motion (ROM) and extremes (maximum values) were calculated in three dimensions. Only selected variables are shown in the results; linear dimensions are specified accordingly (e.g. z-mean, x-ROM).

Of the saddle pressure data, the maximally loaded area under each saddle was determined automatically by only including those sensors that had a pressure >2 kPa during at least 1% of SD for at least one of the two gaits. This procedure defined the total area within which the pressure data were processed. Additionally, the total loaded area was mathematically subdivided into transverse thirds (TD_{front}, TD_{mid}, TD_{hind}) of equal length. If the division did not result in an integer number of sensor rows, the pressures at the borders of the thirds were proportionally assigned to the respective thirds. For each third and each point in time of the standardized stride, the loaded area (A), force (F) and averaged pressure (P) were calculated. Subsequently, the respective stride-mean variables (A_{mean}, P_{mean}; mean value during the entire stride) and F_{mean} (percentage of total force acting on a certain third) were derived. Additionally, the maximal averaged pressure (P_{max}) of each third and its time of occurrence within the stride were determined. Finally, a maximum pressure picture (MPP) was calculated that showed the peak pressure (P_{peak}) occurring for each sensor during the stride. Rider stability was quantified by the longitudinal and lateral ROM of the centre of pressure (COP). By means of markers placed on the caudal end of the saddle mat, the position of the COP (COP position) and the most caudal loaded sensor row (caudal edge loaded area) were related to the horse's L5. The length of the loaded area represented the longitudinal extent of the loaded sensors for each trial.

Statistical methods

Statistical analysis was performed with SigmaStat 3.5 for both gaits separately. Differences in saddle pressure data between the saddles and among the sector thirds were tested with two-way analysis of variance (ANOVA) for repeated measures (RM); kinetic and kinematic variables were compared for the saddles with one-way RM ANOVA. Normality of data was tested (Kolmogorov–Smirnov distance) and monitored by normal probability plots prior to analysis. Post hoc multiple comparisons were made using the Holm–Sidak procedure. The level of significance was set at $P < 0.05$. Descriptive statistics were calculated with Excel (Microsoft).

Results

Group mean values of the stride mean variables A_{mean}, F_{mean}, P_{mean} and P_{max}, together with P_{peak}, are listed in **Table 1**. Kinetic and kinematic variables are listed for walk in **Table 2** and tölt in **Table 3**. Unless otherwise stated, all differences reported hereafter are significant.

Pressure distribution within each saddle

The number of sensors loaded across the transverse direction of the pressure mat varied between TD_{front}, TD_{mid} and TD_{hind}, resulting in differences in total loaded areas among the longitudinal divisions. For all saddles, the largest fraction of the total loaded area (A_{mean}) was concentrated on TD_{front} (39–43%); at walk TD_{hind} was greater than TD_{mid}, whereas at tölt the caudal two thirds had similar areas.

A similar pattern of load distribution (F_{mean}) was seen with all saddles. At both gaits, TD_{front} was most loaded, with 38–47% of the total rider and saddle weight. At walk, the saddles with trees had lower loads in TD_{mid} than TD_{hind} (bridging phenomenon). At tölt, the remaining load was evenly distributed between TD_{mid} and TD_{hind} in all saddles. Comparing the longitudinal pressure patterns revealed distinct differences between TD_{front}, TD_{mid} and TD_{hind} for all saddles. At walk, P_{mean} for both saddles with trees was highest in TD_{hind}, whereas in S_{Cush} it was highest in TD_{front}. At tölt, P_{mean} was evenly distributed across all thirds in S_{Icel}, increased from front to caudal in S_{Dres}, with a significant difference only between TD_{front} and TD_{hind}, and decreased from cranial to caudal in S_{Cush}. The P_{max} showed similar characteristics. Localisations of peak pressures are illustrated in **Figure 2**.

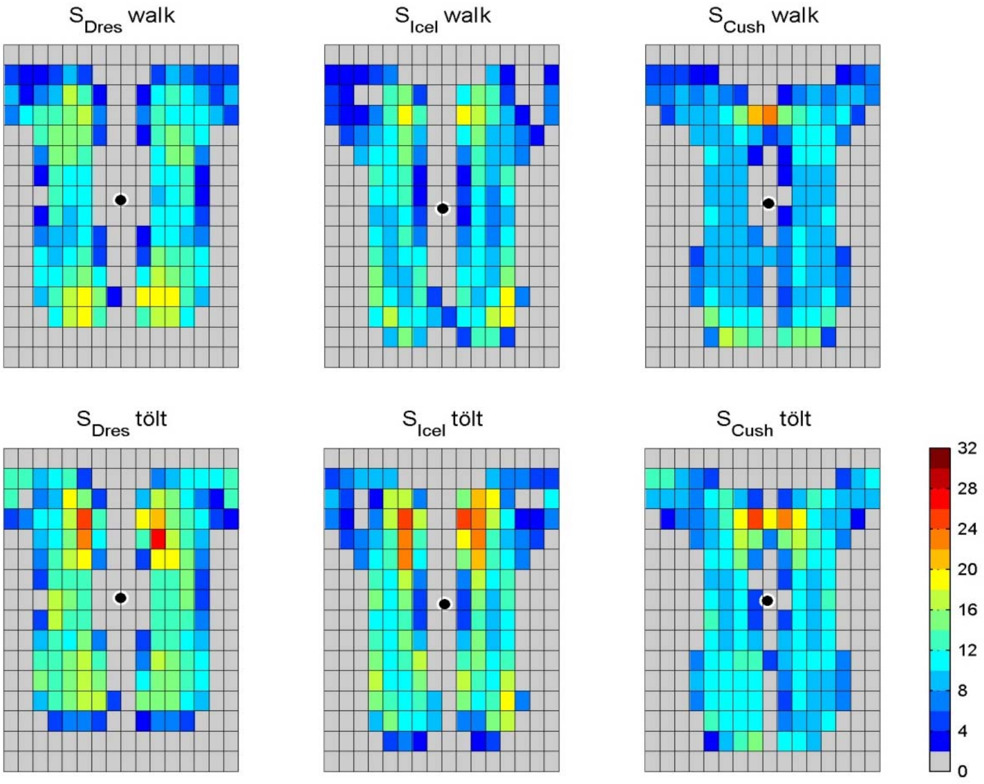


Figure 2: Legend on the next page.

Figure 2: Maximum pressure pictures (MPP) for the three saddles (S_{Dres}, dressage saddle; S_{Icel}, Icelandic saddle; S_{Cush}, saddle cushion) at the walk (top line) and tölt (bottom) for one representative horse. The MPP depicts the peak pressure (P_{peak}, kPa) observed during the standardised, averaged stride for each sensor cell. Superimposed is the COP stride mean position (black dot).

Table 1: Group means (±standard deviations) of loaded area (A_{mean}), percentage of mean total force (F_{mean}), mean pressure (P_{mean}), maximal pressure (P_{max}) and peak pressure (P_{peak}) of three different saddles (S_{Dres}, dressage-style saddle, S_{Icel}, Icelandic saddle and S_{Cush}, treeless saddle cushion) at walk (1.33 ± 0.01 m/s) and tölt (3.43 ± 0.03 m/s).

Variable	Gait	Saddle	$TD_{cranial}$	TD_{middle}	TD_{caudal}	Total value
A_{mean} (cm^2)	Walk	S_{Dres}	$437 \pm 37^{a \lozenge}$	$315 \pm 21^{a \#}$	$375 \pm 19^{a \dagger}$	1127 ± 45^{a}
		S_{Icel}	$465 \pm 42^{b \lozenge}$	$340 \pm 17^{b \#}$	$371 \pm 21^{a \dagger}$	1175 ± 48^{b}
		S_{Cush}	$488 \pm 28^{c \lozenge}$	$324 \pm 22^{ab \#}$	$356 \pm 20^{a \dagger}$	1168 ± 36^{b}
	Tölt	S_{Dres}	$472 \pm 39^{a \lozenge}$	$319 \pm 25^{a \#}$	$336 \pm 31^{a \#}$	1127 ± 49^{a}
		S_{Icel}	$515 \pm 40^{b \lozenge}$	$345 \pm 17^{b \#}$	$335 \pm 33^{a \#}$	1195 ± 62^{b}
		S_{Cush}	$520 \pm 32^{b \lozenge}$	$330 \pm 22^{ab \#}$	$352 \pm 30^{a \#}$	1202 ± 51^{b}
F_{mean} (%)	Walk	S_{Dres}	$38.1 \pm 2.0^{a \lozenge}$	$27.0 \pm 2.0^{ab \#}$	$34.9 \pm 2.1^{a \dagger}$	
		S_{Icel}	$38.6 \pm 3.4^{a \lozenge}$	$28.3 \pm 2.7^{a \#}$	$33.1 \pm 3.2^{b \dagger}$	
		S_{Cush}	$45.8 \pm 3.1^{b \lozenge}$	$25.8 \pm 1.9^{b \#}$	$28.4 \pm 2.8^{c \#}$	
	Tölt	S_{Dres}	$39.9 \pm 3.2^{a \lozenge}$	$29.0 \pm 4.0^{a \#}$	$31.2 \pm 3.2^{a \#}$	
		S_{Icel}	$41.9 \pm 3.0^{b \lozenge}$	$30.1 \pm 3.7^{a \#}$	$28.1 \pm 3.6^{b \#}$	
		S_{Cush}	$46.8 \pm 2.6^{c \lozenge}$	$27.0 \pm 3.1^{b \#}$	$26.2 \pm 3.4^{c \#}$	
P_{mean} (kPa)	Walk	S_{Dres}	$7.6 \pm 0.3^{ab \lozenge}$	$7.5 \pm 0.6^{a \lozenge}$	$8.1 \pm 0.6^{a \#}$	7.7 ± 0.3^{a}
		S_{Icel}	$7.2 \pm 0.4^{b \lozenge}$	$7.2 \pm 0.6^{a \lozenge}$	$7.7 \pm 0.6^{b \#}$	7.4 ± 0.2^{b}
		S_{Cush}	$7.9 \pm 0.6^{a \lozenge}$	$6.7 \pm 0.5^{b \#}$	$6.7 \pm 0.6^{c \#}$	7.2 ± 0.3^{b}
	Tölt	S_{Dres}	$8.4 \pm 0.6^{a \lozenge}$	$8.9 \pm 0.8^{a \lozenge \#}$	$9.2 \pm 0.7^{a \#}$	8.8 ± 0.4^{a}
		S_{Icel}	$8.5 \pm 0.6^{a \lozenge}$	$9.1 \pm 0.9^{a \lozenge}$	$8.7 \pm 0.6^{b \lozenge}$	8.8 ± 0.3^{a}
		S_{Cush}	$8.8 \pm 0.8^{a \lozenge}$	$7.8 \pm 0.5^{b \#}$	$7.2 \pm 0.8^{c \dagger}$	8.1 ± 0.6^{b}
P_{max} (kPa)	Walk	S_{Dres}	$8.6 \pm 0.4^{a \lozenge}$	$8.3 \pm 0.8^{a \lozenge}$	$9.5 \pm 0.7^{a \#}$	8.5 ± 0.4^{a}
		S_{Icel}	$7.9 \pm 0.5^{b \lozenge}$	$8.1 \pm 0.8^{a \lozenge}$	$9.0 \pm 0.7^{b \#}$	8.1 ± 0.4^{b}
		S_{Cush}	$8.6 \pm 0.7^{a \lozenge}$	$7.6 \pm 0.5^{b \#}$	$7.8 \pm 0.8^{c \#}$	7.9 ± 0.4^{b}
	Tölt	S_{Dres}	$10.8 \pm 1.2^{a \lozenge}$	$12.5 \pm 1.2^{a \#}$	$12.6 \pm 1.4^{a \#}$	11.7 ± 1.0^{a}
		S_{Icel}	$10.2 \pm 0.9^{a \lozenge}$	$12.2 \pm 1.2^{a \#}$	$11.6 \pm 1.2^{b \#}$	11.0 ± 0.6^{b}
		S_{Cush}	$10.3 \pm 1.1^{a \lozenge}$	$10.5 \pm 0.8^{b \lozenge}$	$9.2 \pm 1.2^{c \#}$	10.0 ± 0.8^{c}
P_{peak} (kPa)	Walk	S_{Dres}	$16.9 \pm 1.1^{a \lozenge}$	$14.6 \pm 1.9^{a \#}$	$17.4 \pm 2.3^{a \lozenge}$	
		S_{Icel}	$22.0 \pm 3.2^{b \lozenge}$	$14.6 \pm 1.1^{a \#}$	$20.3 \pm 1.9^{b \dagger}$	
		S_{Cush}	$20.2 \pm 2.4^{c \lozenge}$	$12.5 \pm 1.0^{b \#}$	$14.6 \pm 2.0^{c \dagger}$	
	Tölt	S_{Dres}	$27.2 \pm 4.7^{a \lozenge}$	$20.5 \pm 1.6^{a \#}$	$20.6 \pm 2.4^{a \#}$	
		S_{Icel}	$30.2 \pm 3.3^{b \lozenge}$	$22.7 \pm 2.4^{b \#}$	$21.2 \pm 2.1^{a \#}$	
		S_{Cush}	$28.0 \pm 4.4^{ab \lozenge}$	$16.8 \pm 2.1^{c \#}$	$15.4 \pm 2.8^{b \#}$	

Total loaded area was split into equal transverse thirds (TD): $\mathbf{TD_{front}}$, $\mathbf{TD_{mid}}$ and $\mathbf{TD_{hind}}$, front, middle and hind thirds, respectively. All data were derived from an averaged, time-standardised stride.

^{a,b,c} Significant ($P < 0.05$) differences between the saddles for each third or total value and gait are indicated with different superscripts.

$^{\lozenge,\#,\dagger}$ Significant differences within each saddle between front, middle and hind thirds are indicated with different superscripts.

Table 2: Group means (±standard deviations) of temporal, spatial and kinematic variables, including centre of pressure (COP) data, of 12 Icelandic horses ridden with three different saddles (S_{Dres}, dressage-style saddle; S_{Icel}, Icelandic saddle; S_{Cush}, treeless saddle cushion) at walk (mean ± standard deviation 1.33 ± 0.01 m/s).

Variables		Units	S_{Dres}	S_{Icel}	S_{Cush}
SD		s	1.021 ± 0.054	1.023 ± 0.049	1.030 ± 0.043
StD forelimb		%SD	65.2 ± 1.1	65.2 ± 1.2	65.2 ± 0.9
StD hind limb		%SD	66.6 ± 1.7	66.5 ± 1.8	66.8 ± 1.6
StpD$_{lat}$		%SD	24.6 ± 3.5	24.6 ± 3.6	25.0 ± 3.4
StL forelimb		m	0.88 ± 0.06	0.88 ± 0.05	0.89 ± 0.05
StL hind limb		m	0.87 ± 0.04	0.88 ± 0.03	0.88 ± 0.03
OR		m	-0.06 ± 0.08	-0.05 ± 0.09	-0.06 ± 0.08
Fz$_{peak}$ forelimb		N/kg	6.46 ± 0.31 ^{a}	6.37 ± 0.26 ^{b}	6.35 ± 0.30 ^{b}
Fz$_{P1}$ hind limb		N/kg	4.08 ± 0.15	4.09 ± 0.18	4.11 ± 0.20
Fz$_{P2}$ hind limb		N/kg	3.79 ± 0.20	3.78 ± 0.17	3.77 ± 0.17
Iz forelimb		Ns/kg	2.99 ± 0.19	2.99 ± 0.19	2.99 ± 0.16
Iz hind limb		Ns/kg	2.02 ± 0.09 ^{a}	2.03 ±0.08 ^{a}	2.06 ± 0.08 ^{b}
Iz$_{fore}$%		%	59.7 ± 1.1 ^{a}	59.5 ± 1.3 ^{ab}	59.2 ± 1.2 ^{b}
Protraction angle forelimb	Maximum	°	18.7 ± 2.6	18.8 ± 2.4	18.9 ± 2.2
Retraction angle forelimb	Maximum	°	-30.2 ± 1.9	-30.2 ± 1.7	-30.5 ± 1.7
Protraction angle hind limb	Maximum	°	22.8 ± 1.6	22.9 ± 1.5	23 ± 1.5
Retraction angle hind limb	Maximum	°	-16.7 ± 1.4	-16.8 ± 1.2	-17 ± 1.3
Forelimb angle	Maximum	°	43.7 ± 3.6	43.5 ± 3.5	43.9 ± 3.4
Shoulder z-rotation	ROM	°	21.5 ± 3.1 ^{a}	21.3 ± 3.4 ^{a}	22.1 ± 2.9 ^{b}
Shoulder x-rotation	ROM	°	12.5 ± 2	12.4 ± 1.6	12.7 ± 1.5
Head height	z-mean	mm	1390 ± 58	1386 ± 46	1386 ± 55
Rider position	x-mean	mm	234 ± 35 ^{a}	222 ± 31 ^{b}	208 ± 30 ^{c}
	x-ROM	mm	44 ± 8 ^{a}	40 ± 6 ^{b}	37 ± 7 ^{b}
Rider back angle	x-ROM	°	5.7 ± 1.4	5.1 ± 1.7	5.0 ± 1.4
COP position	x-mean	mm	446 ± 36 ^{a}	445 ± 30 ^{a}	426 ± 30 ^{b}
COP	x-ROM	mm	45 ± 8 ^{a}	40 ± 8 ^{b}	30 ± 8 ^{c}
	y-ROM	mm	26 ± 5 ^{a}	24 ± 4 ^{ab}	21 ± 3 ^{b}
Caudal edge loaded area	x-mean	mm	207 ± 39 ^{a}	186 ± 32 ^{b}	128 ± 39 ^{c}
Length loaded area	x-mean	mm	459 ± 17 ^{a}	488 ± 0 ^{b}	516 ± 17 ^{c}

Kinetic variables: **SD**, stride duration; **StD**, stance duration relative to SD; **StpD$_{lat}$**, lateral step duration relative to SD; **StL**, stance length; **OR**, overreach distance (positive if the hind hoof strikes in front of the ipsilateral front hoof); **Fz$_{peak}$**, **Fz$_{P1}$** and **Fz$_{P2}$**, peak vertical forces; **Iz**, limb impulse; **Iz$_{fore}$**, percentage of total impulse carried by both forelimbs.

Kinematic variables (left-handed coordinate system, x-axis vs. horse's head, z-axis upward; mean, mean value of entire stride; **ROM**, range of motion during stride; for the indicated dimensions): **Protraction/retraction**, forelimb or hind limb angles, sagittal plane, with zero reference for vertical orientation of metacarpus (markers: carpus, metacarpophalangeal joint) or metatarsus (markers: tarsus, metatarsophalangeal joint) during stance phase (positive if metacarpophalangeal joint is cranial to carpus); **Forearm angle**, sagittal plane, with reference to a vertical to ground through elbow marker (positive if carpus is cranial to elbow); **Rider position**, distance from rider sacrum to horse lumbar vertebra 5 (L5); **Rider back angle**, with reference to the z-axis through rider's sacrum; COP position, centre of pressure (COP) position relative to horse's L5, as calculated distance of COP – markers at caudal end of saddle mat – L5; COP x-ROM, y-ROM, range of motion of COP; caudal edge of loaded area, distance from most distal loaded sensor row – horse L5; length of loaded area, longitudinal extent of loaded sensor rows. All data were derived from an averaged, time-standardised stride.

^{a,b,c} Significant differences ($P < 0.05$) between saddles are indicated with different superscripts.

Table 3: Group means (±standard deviations) of temporal, spatial and kinematic variables, including centre of pressure (COP) data, of 12 Icelandic horses ridden with three different saddles (S_{Dres}, dressage-style saddle; S_{Icel}, Icelandic saddle; S_{Cush}, treeless saddle cushion) at tölt (mean ± standard deviation 3.43 ± 0.03 m/s).

Variables		Units	S_{Dres}	S_{Icel}	S_{Cush}
SD		s	0.548 ± 0.024	0.548 ± 0.024	0.547 ± 0.023
StD forelimb		%SD	47.2 ± 2.9	46.9 ± 2.7	47.2 ± 2.8
StD hind limb		%SD	51.5 ± 1.5 ^{a}	51.8 ± 1.8 ^{ab}	52.1 ± 1.7 ^{b}
StpD$_{lat}$		%SD	17.8 ± 2.2	18.0 ± 2.7	18.0 ± 2.4
StL forelimb		m	0.90 ± 0.05	0.89 ± 0.05	0.89 ± 0.05
StL hind limb		m	0.93 ± 0.04	0.93 ± 0.04	0.93 ± 0.03
OR		m	0.55 ± 0.11	0.54 ± 0.11	0.53 ± 0.12
Fz$_{peak}$ forelimb		N/kg	9.56 ± 0.61	9.57 ± 0.54	9.49 ± 0.52
Fz$_{peak}$ hind limb		N/kg	6.57 ± 0.31	6.59 ± 0.31	6.57 ± 0.30
Iz forelimb		Ns/kg	1.54 ± 0.07 ^{a}	1.53 ± 0.07 ^{ab}	1.53 ± 0.06 ^{b}
Iz hind limb		Ns/kg	1.15 ± 0.07	1.16 ± 0.06	1.16 ± 0.06
Iz$_{fore}$%		%	57.4 ± 1.1 ^{a}	57.0 ± 1.2 ^{ab}	56.9 ± 1.0 ^{b}
Protraction angle forelimb	Maximum	°	23.7 ± 2.6	23.6 ± 2.7	23.3 ± 2.6
Retraction angle forelimb	Maximum	°	-28 ± 2.4	-27.7 ± 2.7	-27.9 ± 2.1
Protraction angle hind limb	Maximum	°	26.1 ± 2.2	26.1 ± 2.1	26 ± 2.2
Retraction angle hind limb	Maximum	°	-15.2 ± 1.5	-15.2 ± 1.7	-15.2 ± 1.6
Forelimb angle	Maximum	°	65.6 ± 7.2	65.1 ± 7.2	65.4 ± 6.8
Shoulder z-rotation	ROM	°	17.6 ± 3.1	17.4 ± 3	17.5 ± 3.2
Shoulder x-rotation	ROM	°	9.7 ± 2.1	9.9 ± 2.1	9.8 ± 2.3
Head height	z-mean	mm	1536 ± 55	1536 ± 59	1538 ± 60
Rider position	x-mean	mm	250 ± 48 ^{a}	235 ± 44 ^{b}	220 ± 51 ^{c}
	x-ROM	mm	45 ± 11	46 ± 11	46 ± 12
Rider back angle	x-ROM	°	6.0 ± 1.5	5.9 ± 1.6	6.1 ± 1.5
COP position	x-mean	mm	485 ± 44 ^{a}	487 ± 35 ^{a}	461 ± 41 ^{b}
COP	x-ROM	mm	36 ± 12 ^{a}	40 ± 11 ^{a}	28 ± 10 ^{b}
	y-ROM	mm	16 ± 4	15 ± 3	16 ± 4
Caudal edge loaded area	x-mean	mm	250 ± 53 ^{a}	224 ± 42 ^{b}	171 ± 44 ^{c}
Length loaded area	x-mean	mm	450 ± 16 ^{a}	488 ± 23 ^{b}	500 ± 18 ^{b}

Kinetic variables: **SD**, stride duration; **StD**, stance duration relative to SD; **StpD$_{lat}$**, lateral step duration relative to SD; **StL**, stance length; **OR**, overreach distance (positive if the hind hoof strikes in front of the ipsilateral front hoof); **Fz$_{peak}$**, **Fz$_{P1}$** and **Fz$_{P2}$**, peak vertical forces; **Iz**, limb impulse; **Iz$_{fore}$**, percentage of total impulse carried by both forelimbs.

Kinematic variables (left-handed coordinate system, x-axis vs. horse's head, z-axis upward; mean, mean value of entire stride; **ROM**, range of motion during stride; for the indicated dimensions): **Protraction/retraction**, forelimb or hind limb angles, sagittal plane, with zero reference for vertical orientation of metacarpus (markers: carpus, metacarpophalangeal joint) or metatarsus (markers: tarsus, metatarsophalangeal joint) during stance phase (positive if metacarpophalangeal joint is cranial to carpus); **forearm angle**, sagittal plane, with reference to a vertical to ground through elbow marker (positive if carpus is cranial to elbow); **rider position**, distance from rider sacrum to horse lumbar vertebra 5 (L5); rider back angle, with reference to the z-axis through rider's sacrum; **COP position**, centre of pressure (COP) position relative to horse's L5, as calculated distance of COP – markers at caudal end of saddle mat – L5; **COP x-ROM**, **y-ROM**, range of motion of COP; caudal edge of loaded area, distance from most distal loaded sensor row – horse L5; length of loaded area, longitudinal extent of loaded sensor rows.

All data were derived from an averaged, time-standardised stride.

^{a,b,c} Significant differences ($P < 0.05$) between saddles are indicated with different superscripts

Comparison between saddles

The S_{Dres} was the shortest saddle with its total contact area (A_{mean}) being 4.4–6.7% less than that of both other saddles. The S_{Cush} was the longest saddle, with the caudal edge of the loaded area extending the farthest back into the lumbar region (**Tables 2** and **3**). In terms of force distribution (F_{mean}), S_{Cush} was most loaded in TD_{front} and least loaded in TD_{mid} (not significantly different from S_{Dres} at walk) and TD_{hind} at both gaits. Comparing the saddles with trees, S_{Icel} had lower values in TD_{hind} at both gaits, but was more loaded in TD_{front} at tölt. Regarding P_{mean}, S_{Cush} had the highest values in TD_{front} at walk; at tölt, saddles did not differ. The P_{mean} was lowest in S_{Cush} at both gaits in both TD_{mid} and TD_{hind}. The S_{Dres} had the highest TD_{hind} values.

Rider position and stability

Independent of the gait, rider position was more caudal on the horse's back with S_{Icel} (walk -12 mm, tölt- 15 mm) and S_{Cush} (walk - 26 mm, tölt -30 mm) than with S_{Dres}. The COP position did not differ between the saddles with trees; however, in accord with the rider position, it was located furthest caudally with S_{Cush} (-20 to -26 mm). Both riders mentioned that more effort was required to maintain their stability with S_{Cush} compared to the saddles with trees, predominantly at the tölt. However, longitudinal ROM of COP was smallest in S_{Cush} (**Tables 2** and **3**).

Influence of saddles on horse kinetics and kinematics

Compared to S_{Dres} there was an impulse shift of 0.5% toward the hindquarters with S_{Cush}, but there was no significant difference between S_{Dres} and S_{Icel} at either gait. Forelimb action, protraction and retraction angles of the limbs, and temporal and spatial variables did not differ between the saddles. At walk, shoulder z-rotation was more pronounced in S_{Cush} and forelimb forces had a single peak (Fz_{peak}), whereas hind limbs showed typical double peaks (Fz_{P1}, Fz_{P2}) with all saddles. Concomitant to the above mentioned impulse shift cranially in S_{Dres}, a small but significant increase in forelimb Fz_{peak} was observed at walk.

Discussion

This study compared three saddle types currently used in Icelandic horses with regard to the saddle pressure patterns, their influence on the horses' locomotion and rider stability. The highest peak pressures (P_{peak}) occurred in all saddle types predominantly in TD_{front}. Due to the basically different design of the treeless saddle (S_{Cush}) and the saddles with trees, the exact position of P_{peak} within TD_{front} differed (**Figure 2**). With S_{Cush}, P_{peak} was localised adjacent to the spinous processes, especially in horses with more pronounced withers, for which the saddle had no wither clearance. In horses with extremely short backs, the same phenomenon occurred to a lesser extent at the rear end of the saddle.

Unfortunately, the pressures directly over the spinous processes could not be measured, because the standard placement of the pressure sensitive mat always left a small gap along the spine. In the saddles with trees, the high pressure areas were located more laterally, caused by the head plates being slightly too wide for all horses with the S_{Icel} and in some of the horses with the S_{Dres}. Besides the bridging phenomenon, badly fitting head plates are a problem often seen in our clinical cases and also pointed out by (Harman, 1995). Even with the availability of four head plates of different sizes in the S_{Dres}, it was not possible to find a perfect fit for all horses. This emphasises that, even if the majority of horses of the same breed have a similar back shape, the saddle still needs to be fitted individually (Harman, 2004). S_{Cush} was most loaded in TD_{front} and showed (compared to the saddles with trees) a reduced force distribution to the caudal thirds, although riders were sitting in the middle of the saddle. A similar force distribution was observed in a treeless racing saddle when galloping in a racing seat (Latif, 2010); however, this corresponded to the rider's centre of mass. Similarly, with a treeless dressage saddle investigated at sitting trot, most force was concentrated below the rider's COM in the middle third (Belock et al., 2012). These findings are therefore in contrast to our observations that the maximal loaded part was clearly cranial to the rider's centre of mass. There is a great variety of treeless saddles available on the market, making comparisons difficult. The treeless saddle used in this study was new and, therefore, still very rigid, straight and disproportionally long compared to the short backs of the study horses.

The studies cited above were conducted on Arabians and English Thoroughbred racehorses at trot. Since the tölt normally has no suspension phase (Feldmann and Rostock, 1986c) and accounts only for 25% of the vertical excursion of the COM (12 mm; (Biknevicius et al., 2006) in Warmblood horses at trot (3.9 m/s, 53 mm; (Buchner et al., 2000), S_{Cush} might have been rigid enough to distribute the rider's weight to the front and hind thirds. For all saddles, mean and peak pressures were below critical values reported to induce clinical signs of saddle soreness at the withers (von Peinen, 2010). Nyikos et al. (2005) ascertained that pressure tolerance is lower in the lumbar region compared to the withers. However, the threshold pressures reported to be associated with pain were not reached in any of the saddles in this study. In English riding, it is undesirable to have a saddle reaching into the lumbar region. Icelandic horses often have short backs and are ridden by adults who need a large seat to ride comfortably. How a horse's back movement and health are influenced by the distance to which a saddle reaches into the lumbar region remains to be investigated.

According to manuals regarding the riding technique of Icelandic horses, the rider needs to induce a slight weight shift toward the hindquarters in order to support the horse at the tölt. Kinetic measurements in the present study demonstrated that forelimb–hind limb balance was influenced by different rider positions relative to the horse's back. The riders were positioned furthest back in S_{Cush}, which was probably due to the saddle being longer than the saddles with trees. The head–neck position (HNP) can be excluded as the cause of the impulse shift, since horses were ridden with the same head–neck elevation with all three saddles. At the tölt, longitudinal (x-)ROM of COP was smaller in S_{Cush} than in the saddles with trees, although riders subjectively reported needing more effort to maintain stability. Since the riders' longitudinal (x-)ROM was the same for all saddles, the lower x- ROM of COP in the S_{Cush} could be explained by a less effective transfer of rider movement to the back than in the saddles with trees.

A clear four-beat rhythm of the tölt is a prerequisite for Icelandic horses when competing. Zips et al. (2001) stated that only a few horses show a true tölt pattern. In this study, horses showed a tölt with lateral couplets ($StpD_{lat}$ around 18% of SD) and this rhythm was not influenced by the different saddles. Also, the desirable high forelimb action was similar for all saddles, probably due to horses having nearly the same high head–neck elevation. Interestingly, the larger shoulder z-rotation with S_{Cush}, likely due to the lack of a head plate, did not lead to higher forelimb action.

With all saddles, when comparing tölt to walk, an impulse shift of approximately 2.3% to the hindquarters was observed at tölt, although the rider and the COP were more cranially positioned in relation to the horse. This may be explained by a higher HNP at the tölt. Former studies with dressage horses showed that elevating the head and neck both in the ridden (Weishaupt et al., 2006b) and unridden situations (Waldern et al., 2009) shifted weight to the hindquarters.

At walk, a distinct bridging characteristic was observed for S_{Dres} and, to a slightly lesser extent, S_{Icel}; it diminished at tölt. Von Peinen et al. (2006) found that a low (compared to high) HNP redistributed the forces to the centre of the saddle contact area due to a rising of the back. In the present study, a similar phenomenon with respect to force distribution was observed when comparing tölt to walk, despite the high HNP at the tölt. A higher tension and active stabilisation of the trunk to allow the high stride frequency and/or to compensate for the more dynamic vertical movement of the rider at tölt could explain this phenomenon.

Conclusions

The three saddles used in this study exhibited different pressure patterns but, contrary to our hypothesis, the back was not loaded more caudally in S_{Icel} compared to S_{Dres}. In accord with the rider position relative to the horse's back, forelimb–hind limb balance, but not limb movements or forces, was influenced by saddle type. Further investigation is necessary to determine whether these changes can be induced by placing the saddles more caudally, as practised in traditional Icelandic horse riding, above all for the tölt.

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General Discussion and Outlook

Methodology

The present study was carried out on a treadmill which allowed the most precise kinetic and kinematic description of the horses` gait. The treadmill situation assured highest uniformity of the gait pattern and repetition of the trials at virtually the same speeds. In former studies, it could be shown that after adequate accommodation, intraindividual variability of stride variables, e.g. stride duration (SD) was half as high on the treadmill compared to overground locomotion (Buchner et al., 1994). For the present study, horses were thoroughly adjusted to the treadmill situation prior to the experiment over at least 4 days. However, with regards to the general influenceability and variability of the gait mechanics in Icelandic horses the treadmill situation might potentially have had a more pronounced influence on their footfall pattern than in 3-gaited horses. Nevertheless, even in that case, the measured differences are likely to be induced by the different shoeing and saddling conditions since all trials were carried out on the treadmill.

The tendency to pace which was shown by almost all measured horses might be interpreted as a slightly increased tension or stress due to the treadmill situation. However, it was also encountered in overground studies and therefore rather seems to be a common problem in Icelandic horse riding (Boehart et al., 2013).

Comparison of tölt and trot at the same speeds

In contrast to 3-gaited breeds, Icelandic horses have to be trained specifically to maintain a correct and constant footfall pattern at each gait (Feldmann and Rostock, 1986c). Probably caused by the fact that they are capable to fluently change between tölt and trot as well as vice versa, large variation in overall limb timing could be observed at tölt in the present study as already described by other authors (Boehart et al., 2013; Zips et al., 2001), but also at the trot (Waldern et al., 2014b; Weishaupt et al., 2013). At the tölt, lateral coupling was the most frequent gait aberration; whereas at the trot a slight four-beat was observed, when compared to Warmblood horses. Further differences to trotting Warmblood horses were a shorter or lacking suspension phase resulting in longer relative stance duration (StD_{rel}) and therefore lower peak vertical forces (Fz_{peak}).

The footfall pattern of tölt at both measured speeds involved single, bipedal and tripedal support phases. In contrast to descriptions of tölt in riding literature (Feldmann and Rostock, 1986c) but also in scientific investigations (Zips et al., 2001), single support phases only occurred in the hindlimbs but never in a forelimb due to hindlimb duty factors of more than 50% of stride. Conversely, lower duty factors of about 47 %SD resulted in a transverse suspension phase in the forelimbs. Another study, measuring horses at very slow tölting speeds did not identify single support phases at all. This might lead to the conclusion that the tölt can be performed in many ways and that the present definition may be too narrow to encompass the natural variability of this gait. Particularly speed, training level of the horse but also its gait predisposition may influence the gait pattern.

In spite of the difference between fore- and hindlimb contact times, overall gait mechanics of the tölt in the present study were those of a running gait with regard to the phase shift of kinetic and potential energies of both fore- and hindquarters and the single peaked force curves at both measured speeds. As a consequence of the differences in StD_{rel}, tölt compared to trot at same speeds induced an increased loading of the forelimbs (+7.2%), whereas the hindlimbs were even less loaded in regard to Fz_{peak} (-11.8%) and limb impulses (-8.6%).

The amount of limb loading and energetic cost of transport have been proposed as a triggering factor for gait selection in equine locomotion (Wickler et al., 2003), but also for the incidence of specific musculoskeletal pathologies. In regard to peak vertical forces in the hindlimbs, tölt seems to be advantageous compared to trot at the same speed as already estimated by Biknevicius et al. (2004). Conversely, Fz_{peak} in the forelimbs were higher than in trotting horses due to shorter StD_{rel}. It is particularly the overload of the forelimbs which is a common problem in ridden horses due to the additional weight of the rider (Waldern et al., 2009; Weishaupt et al., 2006b) causing a variety of locomotor pathologies. This is why riding methods usually aim at shifting weight from the forelimbs to the hindlimbs (Anonymous, 2014a). In spite of oppositional estimations in riding literature (Feldmann and Rostock, 1986c), tölt did not reduce loading of the forelimbs. The higher HNP in the present study resulting in a shift in weight to the hindlimbs in other breeds (Weishaupt et al., 2006b), did not induce a similar impulse shift in the Icelandic horses and based on hindlimb kinematics there was no clear evidence that the tölt requires more collection than the trot.

High HNPs as observed in tölting horses are thought to predispose to back pain due to an extension of the thoracolumbar spine in Warmblood horses (Gomez Alvarez et al., 2006; Rhodin et al., 2009). However, despite of the higher HNP compared to trot, tölting Icelandic horses had a less extended caudal back angle compared to trot at the same speed (Waldern et al., 2014b). In addition, the saddle pressure pattern at tölt was less bridging (high HNP) compared to that of a walk (low HNP) (Ramseier et al., 2013). This might indicate that elevation of head and neck might not lead to a comparable back extension in Icelandic horses as in other breeds; possibly due to the shorter back and a higher muscle tension. Comparison of horses tölting with a similar HNP as at trot still would be a further interesting and important study aim (Schwörer-Haag and Haag, 2013) as an influence of the different HNPs on gait mechanics cannot be excluded.

In regard to the energy demands, tölt did not seem to offer an advantage compared to trot. Based on the shorter overall mean stance durations of fore- and hindlimbs of tölt compared to trot in the present study, it could be estimated that tölt at slow and medium speed is energetically less advantageous than trot . However, in order to directly determine the energetic needs, future studies would be necessary including measurements of heart rate, blood lactate concentrations or oxygen consumption. Optimally, four- and five-gaited horses should be investigated separately as it is much easier to ride five-gaited individuals in tölt (Feldmann and Rostock, 1986c). Measurements of cortisol and heart rate variability could additional be used to determine the stress level in horses with different gait predispositions, as many people argue that tölt is not a natural gait.

Mechanical influence of the shoeing style on the gait

Gait analysis revealed extensive effects induced by the shoeing on kinetic and kinematic variables of walk, tölt and trot in the Icelandic horses (Waldern et al., 2013; Weishaupt et al., 2013).

Weight and size of the front hooves differed significantly between shoeing styles. In S_H, the dorsal hoof walls of the front hooves were 21.3 ± 5 mm longer than in S_N and the total difference in weight of shoeing material and horn removed was 273 ± 50 g. This 'intrinsic' increase in weight is more than what is allowed in the current regulations of Icelandic sport competitions which preclude 'extrinsic' protective equipment exceeding 250 g per leg in sport and 120 g in breeding competitions (Anonymous, 2013).

In all three gaits and comparing S_H to S_N, gait quality as it is currently judged was improved due to a lower stride rate, longer stride length and a higher, but not wider, forelimb protraction arc which were positively associated with speed. At the tölt, the footfall rhythm became less 'pacey', which is desirable in competition; however, stride-to-stride variability increased. Forelimb-hindlimb balance remained unchanged, but limb impulses were higher due to the longer stride durations. S_H had little influence on Fz_{peak}, apart from increasing in the forelimbs at the faster speed of both tölt and trot. However, breakover durations were prolonged and calculated breakover torques were increased up to 20% at all three gaits (Weishaupt et al., 2014). A shoeing with high, long hooves may improve gait performance, but in the long term might induce adverse effects on limb loading and compromise the soundness of the locomotor system.

As a shoeing change from S_N to S_H as described by Waldern et al. (2013) always resulted in both an increase in toe length but also in a weight gain at the level of the distal limb, it was impossible to distinguish the influence of each of these factors separately. The application of weighted boots of 240 g (WB_{240}) in the same horses (Waldern et al., 2014a) allowed determining the effects of only additional weight for both of the shoeing styles. The comparison of S_N in combination with weighted boots (+ 240 g) with S_H (+273 ± 50 g) made it possible to describe the effect of the longer lever arm of the toe alone.

A comprehensive analysis of all conditions, namely S_N and S_H without and with weighted boots of 240g each (Waldern et al., 2014a), showed that the biomechanical consequences induced by weight and/or dorsal hoof length were similar at all gaits and speeds, but most obvious at the tölt. This might explain why special shoeing methods were developed mainly for gaited breeds as the Icelandic horse and not for 3-gaited breeds. At the tölt, in both shoeing styles, WB_{240} increased protraction height of the forelimbs by about 13%. The weight gain of 273 g at the distal limb induced by changing the shoeing from S_N to S_H had a similar and cumulative effect. Hoof length was also positively, but not significantly associated with protraction height and additionally enhanced the effect of weight, resulting in an increase of up to 35% with S_H and weighted boots. Lateral coupling (pace-like rhythm) in tölt was reduced only with additional weight when horses were already shod with S_H and with a combination of longer hoof length and weight. Stride impulse increased with a change of hoof conformation to S_H alone at tölt only, and combined with weight at all three gaits. Relative stance durations in the forelimbs were shorter at the tölt when comparing S_N with S_H in combination with WB_{240} and vertical peak forces had a tendency to increase, but this was not significant due to an impulse shift to the hindlimbs. However, particularly in combination with weighted boots, the long, high hoof conformation increased limb loading in form of higher limb impulses and increased torques during breakover (Weishaupt et al., 2014). The longer medio-lateral lever arms due to the larger hoof size may enforce the consequences of hoof imbalances and increase lateral joint moments in turns and on uneven ground. Moreover, further increases of limb loading are to be expected due to the higher inertial forces because of the increased mass at the level of the hooves and the steeper attack angle of the hoof approaching the ground before impact (Waldern et al., 2013).

Association of the shoeing style with hoof pathologies

Beside these biomechanical effects, it is known that high hooves reduce the damping and vascular pumping function of the hoof mechanism and long hooves increase the prevalence of hoof pathologies and deformations of the hoof capsule (O'Grady and Poupard, 2003). The latter could be demonstrated in a recent study for the FEIF, describing the hoof dimensions of 134 Icelandic sport and breeding horses in competition by manual und radiographic measurements. The horses were randomly selected at one international event in Iceland and three competitions in Europe. It was found that hoof dimensions of the front hooves in those horses were generally larger than those of the hind hooves which might be the reason for the more frequent occurrence of asymmetries between contralateral front hooves (38%) compared to the hind hooves (8%). Particularly long toes and to a lesser extent high hooves were associated with the occurrence of hoof pathologies. In the front hooves, a long dorsal hoof wall led to a significant increase in the prevalence of a broken hoof pastern axis, uneven height of quarter walls and flares at the toe. The same hoof problems were found with a high prevalence in horses with a longer cranial balance length in relation to total balance length (**Figure 5**). This variable was additionally associated with an increased occurrence of asymmetric hooves and atrophies of the frog.

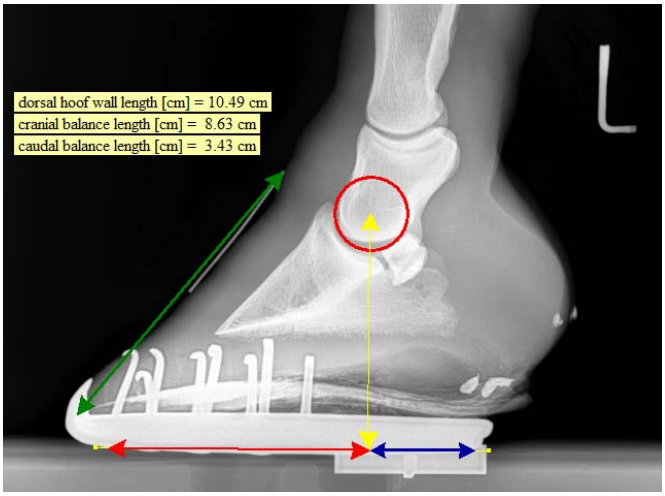

Figure 5: Lateral radiograph of a left front hoof with long, flared dorsal hoof wall and broken back hoof-pastern axis. High ratio of cranial balance length in relation to total balnce length. Green: dorsal hoof length; red line: cranial balnance length; blue: caudal balance length, yellow: height of the centre of rotation of the coffin joint; centre of red circle: centre of rotation of the coffin joint.

A receiver operating characteristic (ROC) analysis revealed that a dorsal hoof wall length of 100 mm was associated with an occurrence of some of the above mentioned pathologies in almost 100% of the measured horses (high specifity) (**Table 1**). Also in horses with a hoof length of 95 mm, prevalence of hoof pathologies was obviously increased. In contrast, when a hoof length of 80 mm was measured, almost all horses were sound in regard to the respective pathologies (high sensitivity). In the intermediate range (85 mm to 90 mm), the classification into diseased and non-diseased horses was less distinct. In the hind hooves, a longer dorsal hoof wall was significantly associated with asymmetry between contralateral hooves, flares at the toe, hoof rings and an atrophied frog.

Table 1: Occurrence of specific hoof pathologies in relation to the length of the dorsal hoof wall of the front left hoof (80 mm; 85 mm; 90mm; 95 mm; 100mm) based on ROC analysis.

Dorsal hoof length	***80 mm***		***85 mm***		***90 mm***		***95 mm***		***100 mm***	
Statistic measure	**Sens.**	**Spec.**	**Sens.**	**Spec.**	**Sens.**	**Spec.**	**Sens.**	**Spec.**	**Sens.**	**Spec.**
Flare	92.1	14.3	75.0	28.6	49.6	64.3	20.0	92.9	5.6	100.0
Flare toe	92.6	13.5	76.4	32.7	51.4	65.4	21.3	92.3	6.2	100.0
Uneven quarter walls	93.2	13.2	82.3	44.7	54.7	68.4	21.9	89.5	5.9	97.4
Broken hp axis	94.6	23.9	77.9	41.3	51.7	69.6	22.5	100.0	6.0	100.0
Atrophied frog	100.0	11.5	80.0	29.5	70.0	55.1	40.0	84.6	26.7	96.2

Sens.: Sensitivity; **Spec.**: Specificity; **unit**: Percent.

Influence of the saddle type on the pressure distributions under the saddle and on gait mechanics

In the present study, the saddle type seemed to have less influence on the gait pattern of the Icelandic horse than shoeing manipulations. Neither limb movements, including footfall rhythm and protraction height of the forelimbs, nor peak vertical forces were influenced by the saddle type. The three saddles used in this study exhibited different pressure patterns, but in contrast to our hypothesis, the back was not loaded more caudally with S_{Icel} compared to S_{Dres}. Only with S_{Cush}, riders were sitting further caudally relative to the horse's back which led to a slight weight shift to the hindlimbs. It therefore seemed to be this change of rider position in relation to the horse's back which had an influence on forelimb-hindlimb balance of the horse. Considering this, it can be expected that placing the saddles more caudally, as practiced in traditional Icelandic horse riding, does have an influence on the horse's balance and thus very likely also on limb movements and forces of the horse.

With S_{Cush}, high pressures were frequently measured very closely to the vertebral spine, particularly in horses with prominent withers which precludes the use of these saddles in individuals with such a back conformation. Unfortunately, the pressures directly over the spinous processes could not be assessed, because the standard placement of the pressure sensitive mat always left a small gap along the spine. In the saddles with trees, areas of high pressure were observed laterally to the vertebral spine caudally to the withers, caused by the head plates being slightly too wide for all horses with S_{Icel} and in some of the horses with the S_{Dres}. Even with the availability of four head plates of different sizes in the S_{Dres}, it was not possible to find a perfect fit for each horse. This emphasises that, even if the majority of horses of the same breed have a similar back shape, the saddle still needs to be fitted individually (Harman, 2004).

Propositions with regard to horse welfare

As high forelimb action is currently rewarded with high marks in competition, it has been adopted as an important breeding aim for Icelandic horses. However, particularly in combination with concurrently used additional weights and high, long hooves, horses frequently injure themselves during protraction in the region of the elbows showing that this development has to be re-discussed in relation to horse welfare. The fact that shoeing manipulation can improve gait performance particularly of the tölt as it is currently judged in competition on one hand but on the other increases loading of the locomotor system has the potential to lead to a difficult situation. Both beneficial effects on gait quality and detrimental effects on limb loading of additional weights and longer dorsal hoof length were additive. Therefore neither method could be replaced by the other in order to minimise limb loading and at the same time achieve maximal performance. The FEIF has recognised this problem by limiting dorsal hoof length and restricting the use additional shoeing material. These regulations for hoof size in Icelandic horses were so far based on empiric estimations, but did not have a scientific background. From the results of the current study series, it can be concluded that dorsal hoof wall length as it is currently used in the regulations appears to be a suitable parameter to control hoof size considering that it was both related to the prevalence of hoof pathologies and had profound influences on limb loading and movement. However, both biomechanical data of the treadmill study (Waldern et al., 2013; Weishaupt et al., 2013) and assessments of pathological changes of the hoof capsule (Waldern et al., 2014c) were pointing towards the necessity of further reduction of its maximal length. Based on the recommendations of O'Grady and Poupard (2003), length of the dorsal hoof wall in Icelandic horses should be between 76 mm and 86 mm. The tolerance interval of dorsal hoof length for a standard shoeing which could be determined based on the data of S_N of the presented thesis (Waldern et al., 2014a) suggested a similar value of 81 ± 7 mm. The length of the dorsal hoof wall of the Icelandic horses shod with S_N was neither associated with body weight ($r^2 = 0$; p = 0.85), leg length (height of the shoulder: $r^2 = 0.3$; p = 0.04 and height of the elbow: $r^2 = 0.11$; p = 0.14) nor height at the withers ($r^2 = 0.3$; p = 0.03); most likely due to the similar body dimensions within this horse breed. Conversely, a regression analysis plotting dorsal hoof length versus withers height of Icelandic and Warmblood horses ($r^2 = 0.82$; $P<0.0001$) allowed further specification of this relationship; indicating a dorsal hoof length of 95 mm as currently permitted in Icelandic horses as normal in horses with a height at the withers of at least 160 cm (**Figure 6**). Dorsal hoof wall lengths in those Warmblood horses shod with a standard shoeing were as low as 92 (± 0.4) and 107 (± 0.4) mm at the end of the shoeing period.

In order to relate dimensions of the hoof capsule with a fix bony structure, the estimated mass (height x length x width) of the hoof capsule standardised to the mass of the coffin bone was calculated. Mean values of this index in Warmblood horses were 4.0 (± 0.3) at the beginning and 4.5 (± 0.4) at the end of a shoeing period of 7-8 weeks. The mean value of this variable measured in the Icelandic horses with S_N was with 4.1 (± 0.9) slightly higher than that of Warmbloods. Icelandic horses shod with S_H lay with values about 5.1 (± 0.5) clearly higher than Warmblood horses at the end of a shoeing period, but were comparable to competition horses in Iceland 5.0 (± 0.6; P = 0.70). These estimations together with the ROC analysis shown above (**Table 1**) suggest a reduction of dorsal hoof length to 85 mm. This maximal limit of dorsal hoof wall length was proposed by the study group at the 2014 general meeting of the FEIF to be adopted in the current sports and breeding regulations.

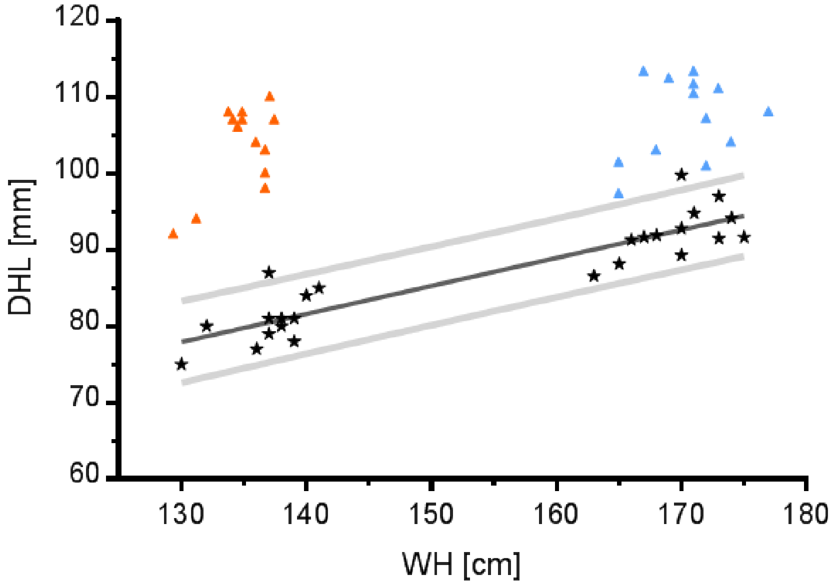

Figure 6: Linear regression analysis of dorsal hoof length (DHL) versus height at the withers (WH) of Icelandic horses (n = 12) and Warmblood horses (n = 13) shod with a standard shoeing (S_N). Gray lines indicate the upper and lower 99% confidence interval. Values of Icelandic horses shod with S_H are indicated as orange triangles; values of Warmblood horses at the end of one shoeing period are given as blue triangles.

In contrast to the shoeing style, the three saddle types tested in the current study had no influence on gait performance. However, it could be shown that slight changes in rider position on the horse`s back lead to changes in forelimb-hindlimb balance. With this finding, it can be expected that changes in the positioning of the saddle are likely to have a considerable effect on gait mechanics. This would be an important topic for further study related to horse welfare bearing in mind that in other breeds the lumbar region is particularly sensitive to load (Nyikos et al., 2005). In addition, extreme caudal placement of the saddle also requires placing the girth caudally to the sternum which might interfere with normal breathing of the horse.

Saddle fit and riding style play a major role in back health and well-being of a riding horse. The present data underline the necessity for proper saddle fitting also in Icelandic horses as these animals are frequently ridden by adult riders of heavy body weights in relation to the weight of the horses. Badly fitting saddles might not result in directly palpable back pain in this breed because of their stoic nature, but might rather result in gait problems (e.g. pace-like tendency at tölt) due to increased stress and muscle tension. New forms of training as described by Schwörer-Haag and Haag (2013) should be evaluated scientifically to exclude adverse effects of the traditional training methods on back health as described in other breeds.

The results of the presented PhD project may help to elaborate a more exact definition of the gait pattern of the tölt and for the first time provided a scientific basis for shoeing guidelines in Icelandic competition horses. From the veterinary perspective, the currently permitted dorsal hoof length should be further reduced as it still increases limb loading particularly at faster speeds compared to a standard shoeing. However, acceptance among the riding community might be difficult as traditional shoeing techniques do improve performance as it is currently demanded in competition. In order to guarantee horse welfare, the public but also the judges will have to reduce their expectations in regard to forelimb action. For the future, there are still important points requiring scientific investigation such as saddling the horses caudally which might potentially alter back health and their capacity to carry heavy riders; particularly together with the new breeding aim towards light-weight and elegant Icelandic horse type. New training techniques aiming at achieving the tölt by educating Icelandic horses according to classical dressage principles have to be evaluated in regard to gait quality and limb loading

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