# The movement pattern of horse and rider in different degrees of collection

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## Abstract

While some degree of collection is considered as basic schooling work for the riding horse, learning to perform the most collected movements, such as piaffe and passage, can be a performance limiting factor for dressage horses. The aim of this thesis was to study biomechanics of horse-rider interaction in varying degrees of collection.

Seven high level dressage horses were ridden on a force measuring treadmill while both kinematic and kinetic measurements were conducted. Horses were ridden in collected walk and trot, and six of seven horses were also ridden in passage.

In collected walk, the saddle rotated cranially, the rider's pelvis rotated caudally, and the rider's neck and feet moved backwards during the first half of each hind limb stance, and in opposite directions during the second half. In collected trot, the saddle rotated caudally, the rider's pelvis rotated cranially and the rider's lumbar back extended during the first half of stance, with reversed movements during the second half of stance and the suspension phase. The passage showed increased flexion of the hind limb joints and decreased hind limb retraction, and vertical impulse was shifted from the forehand to the hindquarters (-4.8%). Both at higher speed in collected trot and in passage, the rider's pelvis became more caudally rotated and the rider's lumbar back became more flexed. In free trot, the rider's position changed in opposite direction. The phase-shift between horse and rider was increased in free trot, and decreased in passage, compared to in collected trot.

The movement pattern of the rider in collected walk and trot can largely explained from the horse's movements. The higher degree of collection of the passage was characterised by increased hind limb engagement without increasing peak vertical load. With increasing degree of collection, the rider sat in a more upright position, with increased posterior pelvic tilt and showed a decrease phase-shift relative to the horse, suggesting that the rider used the seat more actively.



*Keywords:* horse, rider, equine dressage, kinematics



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# Hästens och ryttarens rörelser i olika grader av samling


## Abstract

En viss grad av samling är grundläggande i allt dressyrarbete, men förmågan att lära sig utföra övningar som piaff och passage som kräver mycket hög samlingsgrad kan vara begränsande för dressyrhästars prestation. Syftet med denna avhandling var att med biomekaniska metoder studera interaktion mellan häst och ryttare i olika grader av samling.

Sju högt utbildade dressyrhästar reds i samlad skritt och trav på en rullmatta med kraftmätning, samtidigt som deras rörelse också registrerades. Sex av hästarna reds även i passage.

I samlad skritt roterade sadeln framåt, ryttarens bäcken roterade bakåt, och ryttarens nacke och fötter rörde sig bakåt, under den första hälften av bakbenets understöd, och i motsatt riktning under andra hälften. I samlad trav roterade sadeln bakåt, ryttarens bäcken framåt och ryttarens ländrygg extenderades under första hälften av bakbenets understöd, medan motsatta rörelser sågs under påskjutfasen och i svävningsfasen. I passage sågs ökad flexion av bakbenets leder och en omfördelning av vertikal impuls från frambenen till bakbenen (-4.8%). Ryttaren satt med bäckenet mer roterat bakåt och med ökad flexion av ländryggen vid ökad hastighet i samlad trav, och i passage. I trav på lång tygel förändrades ryttarens position i motsatt riktning och fasförskjutningen mellan häst och ryttare ökade.

Sadelns och ryttarens rörelser följde ett gemensamt mönster hos alla de sju ekipagen. Ryttarens rörelse kunde tydligt relateras till hästens rörelse i både skritt och trav. Den högre graden av samling i passage karaktäriserades av ökad bärighet genom ökad bakbensaktivitet. Vid en ökad grad av samling satt ryttaren i en mer upprätt position med mer bakåtroterat bäcken, samtidigt som fasförskjutningen mellan häst och ryttare minskade, vilket kan indikera att ryttaren använder sätet mer aktivt.



*Nyckelord:* häst, ryttare, dressyr, kinematik



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# List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Byström, A.*, Rhodin, M., von Peinen, K., Weishaupt, M.A. and Roepstorff, L. (2010) Kinematics of saddle and rider in high-level dressage horses performing collected walk on a treadmill. *Equine Vet J*, 42, 340-345.

II. Byström, A.*, Rhodin, M., von Peinen, K., Weishaupt, M.A. and Roepstorff, L. (2009) Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. *Equine Vet J,* 41, 280-284.

III. Weishaupt, M.A.*, Byström, A., von Peinen, K., Wiestner, T., Meyers, H., Waldern, N., Johnston, C., van Weeren, R. and Roepstorff, L. (2009) Kinetics and kinematics of the passage. *Equine Vet J,* 41, 263-267.

IV. Byström, A.*, Rhodin, M., von Peinen, K., Weishaupt, M.A. and Roepstorff, L. (2015) Differences in rider movement pattern between different degrees of collection at the trot in high-level dressage horses ridden on a treadmill. *Human Movement Science,* 41, 1-8.



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The contribution of Anna Byström to the papers included in this thesis was as follows:

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# Abbreviations

| | |
|---|---|
| C7 | Seventh cervical vertebra |
| COM | Centre of mass |
| COP | Centre of pressure |
| EMG | Electromyography |
| FEI | Fédération Equestre Internationale |
| GRF | Ground reaction force |
| IMU | Inertial measurement unit |
| L3 | Third lumbar vertebra |
| L5 | Fifth lumbar vertebra |
| ROM | Range of motion |
| SD | Standard deviation |
| T6 | Sixth thoracic vertebra |
| ToT | Time of transition |

# 1 Introduction

Effective horse-rider interaction has been of interest to humans for as long as horses have been used for riding. The oldest documentation of horseback riding is from Spain in 3000 BC (Branderup, 2001; Dunlop & Williams, 1996). Historically, use of the horse in hunt and warfare has been the major drive for refining horse-rider communication (Branderup, 2001). Today performance in equestrian sports is a main motive, but pleasurable leisure riding is also a significant incentive for many riders. The process of perfecting the relationship and communication between rider and horse is termed schooling of the horse, or simply dressage: the objectives of equine dressage are, according to the Fédération Equestre Internationale (FEI) rules for dressage events, to make the horse "calm, supple, loose and flexible, but also confident, attentive and keen, thus achieving perfect understanding with the horse" (FEI, 2018). Dressage is thus not only a discipline for competition, but is, in its basic form, the very foundation for effective horse-rider communication. This thesis focuses on sports dressage, a term which denotes the Olympic discipline, but also describes a set of norms for the basic training of horses in all disciplines of English style riding. Riders commonly relate to these norms in their everyday riding, even riders without intention to ever compete in dressage (Zetterqvist Blokhuis & Lundgren 2017).

Within dressage, the concept of collection has been of central interest throughout the history of riding. The Rules for Dressage Events states that the aims of collection are to "develop and improve the balance and equilibrium of the horse, which has been more or less displaced by the additional weight of the rider", and to "make it more pleasurable to ride" (FEI, 2018). The aims of collection are thus both to improve the rider's experience and to improve the horse's ability to carry the rider's weight without a risk for overload injuries.

The topic of the rider's seat is as central in equestrian dressage as is collection. Practically all published equestrian works discuss the rider's seat. Modern texts typically describe the rider's ideal seat to be a position where the head, upper body and pelvis are vertically aligned, both viewed from the side and from in front or behind. Some authors expressively term this 'the vertical seat' (Kyrklund & Lemkow, 2008; Müseler, 1933), whereas others just describe it in words (Dietze, 2005; Hess et al., 2012; Swift et al., 2003). In historical texts, a similar position is described, though worded a bit differently: It is advised that the rider should maintain an erect body posture (de la Guérinière, 1729; Xenophon, 350BC) and that the position of the rider's pelvis should be similar to the position in standing, i.e. the pelvis should not be tilted backwards as if the rider was seated on a chair (Newcastle, 1658; Xenophon, 350BC). In addition to these descriptions of the ideal position, both modern and historical texts stress the importance of the rider's ability to follow the movements of the horse: The rider's seat should be relaxed and supple and the rider should be able to maintain balance at all times without getting tensed (de la Guérinière, 1729; Kyrklund & Lemkow, 2008; Hess et al., 2012; Müseler, 1933; Xenophon, 350BC). However, explicit recommendations how the rider should adapt to the horse's movements at the different gaits are scarce in the equestrian literature. This lack may reflect that riders and trainers generally do not have a detailed conscious perception of how the human body moves during riding.

In the last decades there has been a growing interest from the scientific community in various aspects of horse-rider interaction research. A number of studies addressing this topic are now available in the scientific literature, targeting biomechanical (Clayton & Hobbs 2017a) as well as ethological and welfare perspectives (Williams and Tabor 2017), and sometimes bridging these disciplines. To bring the knowledge one step further, a new scientific field, equitation science, has evolved. Equitation is the art or practice of horse riding or horsemanship. More specifically, it encompasses a rider's ability to ride correctly and with effective aids (Dyson 2017). The term equitation may, in practical terms, be defined as the difference between riding and just sitting on a horse. With the aim to put study findings into practice, advocates of equitation science suggest that the responsible rider should apply scientific principles when training and managing their horse to promote health, welfare and performance to achieve a positive horse-rider relationship. Equitation science is mainly focusing on dressage because it is the training basis of all the Olympic equestrian disciplines (McGreevy & McLean, 2007), though the principles are readily applicable in all disciplines.

The general incentive behind the studies in this thesis is in analogy with the two-fold objective of collection, to improve the rider's experience and the horse's ability to carry the rider's weight. Knowledge about horse-rider interaction is fundamental for understanding factors that influence the performance of riding horses, as well as a basis for understanding rider-related risk factors for equine orthopaedic injury.

## 1.1 Background

### 1.1.1 Measurement of rider movements

Many studies have addressed the movement pattern of humans during riding (Eckardt et al., 2014; Martin et al., 2016, 2017; Münz et al., 2014; Münz et al., 2013; van Beek et al., 2012; Kang et al., 2010; Peham et al., 2010; de Cocq et al., 2009; Symes & Ellis, 2009; Witte et al., 2009; von Peinen et al., 2009; Terada et al., 2006; Lagarde et al., 2005; Matsuura et al., 2005; Lovett et al., 2004; Terada et al., 2004; Matsuura et al., 2003; Peham et al., 2001; Terada, 2000; Schils et al., 1993). Of these studies, a majority have included kinematic measurements by use of skin markers (de Cocq et al., 2009; Symes & Ellis, 2009; von Peinen et al., 2009; Terada et al., 2006; Lagarde et al., 2005; Lovett et al., 2004; Matsuura et al., 2003; Peham et al., 2001; Schils et al., 1993), but saddle pressure measurements (Peham et al., 2010; von Peinen et al., 2009), stirrup force measurements (van Beek et al., 2012), inertial measurement unit (IMU) systems (Münz et al., 2014; Münz et al., 2013; Pfau et al., 2009), accelerometers (Viry et al., 2013; Wolframm et al., 2013; Matsuura et al., 2005; Terada, 2000) and electromyography (EMG) recordings (Terada et al., 2004; Terada, 2000) have also been utilised to document the movement pattern of riders. The gold standard for kinematic measurements has traditionally been considered to be 3-D optical systems, using reflective markers. However, these systems are not easily portable and the measurement volume is limited, making it difficult to collect data from a large number of consecutive strides without the use of a treadmill. Accelerometers and IMU systems are portable, and comparably affordable. These systems are, therefore, well-suited for collection of a large number of strides under field conditions. The downside is that the accuracy of the systems is often less good compared to optical systems, and that filtering is often needed to compensate for drift, which precludes the interpretation of the absolute values, particularly displacement values (whereas rotation angles are more accurate). Kinetics describes the forces behind movement. Kinetic data are therefore an important complement to kinematic measurements. For the horse, accurate kinetic data can be collected using force plates. The forces acting on the rider can be approximated through the saddle pressure measurements, pressure can be recalculated to force if summed over the loaded area. However, the accuracy of saddle pressure measurements are difficult to assess because there is no gold standard to which measurements during riding can be compared. Stirrup forces can also be measured but are low during sitting trot (van Beek et al., 2012).

### 1.1.2 Rider movement in relation to the horse's gait

A number of different studies have quantified the rider's movements in relation to the stride cycle of the horse. These studies have described rider position changes between different parts of the stride cycle, and made comparisons between different gaits: Matsuura et al. (2003) determined the frequency and amplitude of the rider's movements during riding in walk and trot on horses of two different breeds. They found that both frequency and amplitude differed significantly between horse breeds. In a later study Matsuura et al. (2005) compared the frequency and amplitude of the rider's movements in walk and in sitting and posting trot to the movements of the horse, as well as to the human walking or running at the same speed as the horse walked or trotted. It was found that the rider's movements had larger amplitudes compared to the horse's trunk in both sitting and posting trot, whereas in walk the amplitudes of the rider's movements were similar or smaller compared to the horse. The frequency of the rider's movements in walk and trot was similar to that of a walker and runner, respectively, but the amplitudes were generally lower for the rider.

Lovett et al. (2005) studied angles of the trunk, thigh and lower leg in five riders (in 2D from 25 Hz video) at first contact of each of the horse's four limbs in walk, posting trot and canter. They found that in walk the rider's trunk angle was significantly different between limb impacts, and in trot there was a significant difference between the impacts of the sitting and rising diagonals for angles of the trunk, thigh and lower leg. In canter, however, there were no significant differences in the rider's position between limb impacts.

Witte et al. (2009) applied principal component analysis to identify the major dynamic constituents of the horizontal velocities of 14 horse and rider markers in walk, trot and canter with an English saddle and a side saddle. From their analysis they concluded that only one compound variable (eigen mode) was necessary to characterise the trot, but two eigen modes were required for walk and canter. In a more detailed analysis of the trot variable, it was possible to identify separate patterns for the two saddle types.

Münz et al. (2013) performed a preliminary study on rotations of the rider's pelvis (n=2) and the horse's trunk (same horse for both riders) and found that anterioposterior rotations generally dominated over lateral rotations in all gaits. The same principle author (Münz et al., 2014) performed a second study including 10 professional and 10 amateur riders measured in walk, sitting trot and right-lead canter. In this larger group of riders, similar results were generally found as in the preliminary study.

Wolframm et al. (2013) used accelerometers to study the coordination dynamics of the vertical displacements of horse and rider in walk, sitting and posting trot and sitting canter. The analysis showed that canter had the highest horse-rider synchronicity, whereas in walk the phase difference between horse and rider movements was both larger and more variable compared to trot and canter.

Some studies on rider kinematics have focused particularly on posting versus sitting trot. De Cocq et al. (2009) measured rider kinematics with the aim to estimate the forces applied to the horse's back during sitting and posting trot. It was found that the peak forces were comparatively lower in posting trot. Van Beek et al. (2012) found that stirrups forces showed two peaks in every stride cycle, but that in posting trot the maximal force was three times higher when the riders was standing in the stirrups compared to the sitting diagonal. Several studies have shown that the asymmetry in rider movement between the sitting and the rising diagonals results in corresponding asymmetries of the horses' movements (Martin et al., 2016, 2017; Persson-Sjödin et al., 2018; Roepstorff et al., 2009; Robartes et al., 2013).

### 1.1.3 Movements of the saddle and effects on the horse's back

A number of studies have used saddle pressure measurements to study the influence of the saddle and rider on the horse's back. Pressure distribution has been investigated for different saddle types (Harman 1994; Meschan et al., 2007; Mönkemöller et al., 2005; Peham et al., 2004; Winkelmayr et al., 2006) and riding techniques (Geutjens et al., 2008; Peham et al., 2004). The saddle force, calculated from saddle pressure, has been investigated in different gaits, and it was found that the total force curve shows a characteristic, gait dependent pattern (Fruehwirth et al., 2004; Jeffcott et al., 1999; Pullin et al., 1996).

Galloux et al. (1994) measured saddle movements at the front part of the saddle in two horses on a treadmill without rider. They found that the vertical displacement was greatest in canter, and that at the walk, yaw (twisting rotation) was more dominant in comparison to the other gaits. Pitch range of motion (ROM) was relatively equal in walk and trot and slightly greater in the canter. Von Peinen et al. (2009) studied the relationship between horse, rider and saddle movements and saddle force pattern at walk. The authors concluded that the shape of the saddle force curve is mainly related to lateral flexion and axial rotation of the horse’s back and the activity of the back and shoulder muscles. The vertical movement of horse and rider had less influence compared to at the trot.

The presence of a saddle and rider influences the movements of the horse’s back. DeCocq et al. (2004) found increased extension of the horse’s back when a saddle was loaded with weight (75kg lead), compared to without and with an unloaded saddle. Martin et al. (2016; 2017) found that when the rider performed posting trot the ROM of the horse’s back increased in the standing phase compared to the sitting phase, using IMUs behind and under the saddle. The mean pressure from the saddle on the horse’s back increased significantly by 3.1 kPa during the sitting phase with respect to standing phase (Martin et al., 2016).

Recently a number of studies have investigated asymmetries in saddle movements during riding. It was found that the saddle slipped consistently to one side in 38 of 71 horses with hind limb lameness (Greve & Dyson 2013). In a population of 506 sport horses, which were in regular use and deemed sound by their owners, the saddle slipped consistently to one side in 62 horses (Greve & Dyson 2014). In both of these studies the saddle slipped to the (subclinically) lamer hind limb in all gaits. Apart from hind limb lameness, crookedness of the rider and the fit of the saddle were independently associated with saddle slip in lame and non-lame horses (Greve & Dyson 2013; Greve & Dyson 2014). Additional studied have confirmed the importance of saddle fit (Mackechnie-Guire et al., 2018) and rider movements (Byström et al., 2018) for saddle movement symmetry.

### 1.1.4 Rider skill level

Several studies have compared the kinematics of novice and expert riders (Lagarde et al., 2005; Münz et al., 2014; Kang et al., 2010; Peham et al., 2001; Schils et al., 1993). It has been found that experts position themselves on the horse with more extended hip joints in walk (Schils et al., 1993), more dorsi-flexed ankles in walk and posting trot (Kang et al., 2010), and a more upright upper body position in walk (Kang et al., 2010) as well as in sitting trot (Lagarde et al., 2005; Schils et al., 1993) and posting trot (Kang et al., 2010; Schils et al., 1993). Experienced riders have also been shown to sit with a more upright, less backwards tilted pelvis in walk, sitting trot and canter (Münz et al., 2014). Some of these differences in rider position may be related to, or influenced by, equipment choices and adjustment. Comparing static leg position and self-selected stirrup length between novice and experienced riders, on three horses and one mechanical horse, novice riders chose a shorter stirrup length compared to the more experienced riders (Andrews-Rudd et al., 2018).

The movements of experienced riders were found to be more consistent (Lagarde et al., 2005; Peham et al., 2001) and more synchronized with the horse (Lagarde et al., 2005) compared to less experienced riders. Münz et al. (2014) additionally found that amateurs showed greater pelvic roll ROM in sitting trot compared to professionals, and the same was true for the horse's trunk when ridden by the respective rider categories. In contrast, Eckardt and Witte (2017) compared 10 professional riders and 10 beginners in walk, sitting trot and canter, and found no difference in phase-shift relative to the horse between the two groups. However, the professional riders rode at higher speed in walk and trot.

Postural coordination has been shown to be influenced by expertise in many sports, for example gymnastics (Delignieres et al., 1998) and skiing (Nourrit et al., 2003). EMG recordings of two important postural muscles, *mm. erector spinae* and *m. rectus abdominis*, and the great adductor of the thigh, *m. adductor magnus*, showed differences in activity pattern between advanced and novice level riders in walk and sitting trot (Terada, 2000). There are a few studies that indicate that postural coordination is influenced by skill level also in riders. In trot, advanced level riders had a similar proportion of forceful contractions in both erector spinae and rectus abdominis while their adductor magnus were largely inactive. Novice level riders had proportionally more forceful contractions of *m. rectus abdominis* compared to *m. erector spinae* and their *m. adductor magnus* were markedly more active compared to the advanced level riders (Terada, 2000). Increased activity of the thigh adductors is likely an attempt to compensate for the unstable upper body position. In walk, advanced level riders had proportionally more concentric activity of these postural muscles while the novice showed a more static activity pattern (Terada, 2000).

Olivier et al. (2017) studied riders cantering on a horse simulator using an electromagnetic tracking system, and showed that skilled professional riders maintained a higher degree of postural stability and were less dependent on visual input compared to novice riders. There was also lower ROM for the vertical motion of the head and for the forwards-backwards motion for the head, neck and lumbar back in the expert riders. Baillet et al. (2017) compared experienced riders with experienced athletes from other sports riding a mechanical horse. The athletes lost their trunk coordination more readily than the riders and at a faster gait/higher frequency the rider's head motion tuned more readily with the gait frequency of the mount. Additionally, when the horse's oscillation frequency increased, non-rider athletes showed postural disorganization and increased energy expenditure with energetic change to a more anaerobic mode, whereas the riders maintained their posture, which required an increase in energy expenditure, but without energetic change (Baillet et al., 2017).

### 1.1.5 Rider asymmetries

A symmetric position is traditionally regarded as highly important for good riding skills and postural efficiency in riders. The topic of rider asymmetry has been researched more extensively in the last decade. Symes and Ellis (2009) studied rider shoulder rotation (around the vertical axis, n=17) in walk, trot and left and right lead canter. They found that most riders sat slightly turned to the left on average during the stride, except in right lead canter. Gandy et al. (2014) measured internal-external rotation of the hip in 12 rider-horse combinations (seven riders in total) and concluded that all horse-rider combinations were asymmetric. Ten of the 12 combinations showed greater external rotation on the right hip. Alexander et al. (2015) found that seven of 10 riders were laterally flexed to the left (collapsed in the left side) and kept the right shoulder and hip more backwards than the left counter-parts. Their data further suggest that taping to stabilise the shoulder region can improve rider movement symmetry and position.

Some studies have evaluated rider symmetry in the unmounted situation, isolating rider asymmetries from the symmetry of the horse. Nevison and Timmis (2013) measured the lateral symmetry in force distribution in six riders, when seated on a saddle placed on a saddle horse. Five of six riders had larger pressurized area readings to the right side of the mat. Guire et al. (2017) evaluated 30 right-handed riders' perception of symmetric pressure and rein contact when seated on a static platform. They found that the riders had significantly more pressure beneath the left ischial tuberosity compared to the right but no significant difference was observed between left and right rein tension. Hobbs et al. (2014) studied 127 right-handed riders seated in a saddle on a horse model and found that experienced riders were not less asymmetric compared to less experienced riders. The ROM for lateral bending to the left was reduced in advanced level riders with many years of experience. This may be related to asymmetry in shoulder height, suggesting that the riders were stronger on the right side of the body (Hobbs et al., 2014). Engell et al. (2018) found that all riders (n=20) in the study had asymmetric head, trunk and pelvic frontal plane rotations and translations while rocking a balance chair. There was no dominant pattern on group level, but individual asymmetries correlated with asymmetries in the same segments while riding in sitting trot (Engell et al., under review) as well as asymmetry in the degree of foot pronation (Engell et al., 2018). These findings suggest that a balance chair could be a useful tool to evaluate rider symmetry.

Rider position asymmetries can be related to asymmetries in the equipment. Novice riders were found to select shorter left, compared to right, stirrup lengths, whereas professional riders chose equal stirrup length (Andrews-Rudd et al., 2018). Also, an imbalanced saddle, positioned asymmetrically, can be a reason for an asymmetric rider position, with improvement in rider symmetry after correction of the saddle (Mackechnie-Guire, 2018).

### 1.1.6 The kinetics and kinematics of collection

Collection is described as a shortening of the horse’s stride length with retained energy and hind limb activity (FEI, 2018; Kyrklund & Lemkow, 2008; Dietze, 2005; Branderup, 2001; Hess et al., 2012; de la Guérinière, 1729), accompanied by an increased flexion of the hind limb joints resulting in a lowering of the hindquarters (FEI, 2018; Kyrklund & Lemkow, 2008; Branderup, 2001; Müseler, 1933; de la Guérinière, 1729). Most authors also state that the hind limbs should step further underneath the horse with increasing degree of collection (Branderup, 2001; Hess et al., 2012; Kyrklund & Lemkow, 2008; von Dietze, 2005). The lowering of the hindquarters and flexion of the hind limb joints is particularly emphasised in historical texts (de la Guérinière, 1729; Newcastle, 1658; Xenophon, 350BC). In the earliest works, this is described as ‘to put the horse on the haunches’, rather than using the term ‘collection’, to define this goal of dressage (Newcastle, 1658; Xenophon, 350 BC). In modern texts, the aspect most stressed is to maintain hind limb impulsion while shortening the horse’s stride length; it’s pointed out that in collection the horse should push off as strongly as in the extended gaits, only in a more vertical direction (Decarpentry, 1971; Hess et al., 2012; Müseler, 1933). So in summary, the hallmarks of collection as described in these equestrian texts are: a decrease in stride length with retained energy of the movement, increased flexion of the hind limb joints with a lowering of the hindquarters, and increased protraction of the hind limbs. These movement pattern changes are claimed to result in a shift of weight from the forelimbs to the hind limbs. Many, but not all, of these features have been confirmed in scientific studies, by kinetic and kinematic measurements.

Increasing degree of collection has been found to be associated with decreased stride length in walk (Clayton, 1995), trot (Clayton, 1994a) and in canter (Clayton, 1994b; Holmström et al., 1995a). In walk and trot the stride frequency also decreased but to a lesser degree (Clayton, 1994a, 1995;

Holmström et al., 1995a). In canter the stride frequency was not significantly altered (Clayton, 1994b). Increased hind limb protraction has not been found to be a feature of collection in any studies. However, Holmström et al. (1995a) found that the decrease in stride length from working trot to collected trot was entirely a result of decreased hind limb retraction, and Rhodin et al. (2009) found a decrease in hind limb retraction after lift-off in collected trot compared to trot on loose reins at the same speed. Thus, collection results in, not an absolute, but a relative increase in hind limb protraction, i.e. the hind limbs are more protracted on average during the stride cycle. Increased flexion of the hock and stifle was found in collected walk in one study (Rhodin et al., 2018), but studies on collection in trot found no significant increase (Clayton, 1994a; Holmström et al., 1995a; Rhodin et al., 2009). On the contrary, a study comparing collected and extended trot found that the hock had a smaller minimum joint angle in extended trot (Walker et al., 2013). Significant lowering of the croup has not been found to be a biomechanical feature of collection, neither in walk nor in trot (Rhodin et al., 2009; Rhodin et al., 2018). However, collection can be accompanied by increased angulation of the pelvis (Rhodin et al., 2009; Rhodin et al., 2018).

The effect of collection on fore vs. hind limb ground reaction force (GRF) distribution is relatively little studied. The data available suggest that changes are minor at free versus collected walk and trot (Weishaupt et al., 2006), though the study was conducted on a treadmill and included a limited number of horses (n=7). Piaffe and passage aim to demonstrate the highest degree of collection possible in a diagonal gait (FEI, 2018). In passage, the centre for the summed GRF of the diagonal limbs was shifted towards the hind limbs compared to collected trot (Clayton et al., 2017), i.e. there was a shift of weight from the forehand to the hindquarters, in line with equestrian theory. For piaffe only preliminary kinetic data have been published, but these indicate that piaffe displays an even greater shift of weight to the hindquarters (Clayton & van Weeren, 2013). There have been a number of studies on the kinematic features of piaffe and passage showing features generally similar to collected trot, only more pronounced (Clayton, 1997; Holmström & Drevemo, 1997; Holmström et al., 1995a, 1995b). In passage, increased protraction of the hind limbs, on average, during the stride cycle correlated with centre of mass (COM) position closer to the hind limbs and increase nose-up movements during propulsion, and also with decreased peak hind limb propulsive and braking forces (Clayton & Hobbs 2017b).

### 1.1.7 Horse-rider interaction studied by objective measurement techniques

Numerous biomechanical studies have been conducted aiming to investigate various aspects of horse-rider interactions (cf. Egenvall et al., 2013): It has been investigated how the horse's movement pattern is influenced by the rider's skill level, by the rider performing posting trot compared to sitting trot, by various auxiliary reins, and by different head-neck positions imposed by the rider. Further, rein tension have been measured during riding, including comparisons between different riding styles and exercises, and the saddle pressure pattern in different gaits and riding styles has been documented. However, only a few of these studies include simultaneous measurements of both rider kinematics and the horse's movement pattern responses (other than studies on conflict or distress behaviours): Lagarde et al. (2005) compared the movement pattern of the same horse when ridden by a novice and an expert rider in sitting trot and found that both the expert rider and the horse when ridden by the expert had less variable movements, compared to the novice rider condition. Münz et al. (2014) found that the horse's trunk had greater roll ROM when ridden by an amateur compared to a professional rider, and the same was found for the rider's pelvis. To learn more about the horse-rider interaction from a biomechanical perspective, simultaneous measurements of rider interventions and the horse's movement responses to such are likely to be the most informative.

### 1.1.8 Background summary and conclusions

From the above-mentioned studies, it's possible to gather quite a lot of information about the rider's movement pattern in different gaits, as well as the horse' s movement pattern in collection. However, the published studies provide pieces of the puzzle rather than a comprehensive picture. With regards to rider studies, most include only a limited set of kinematic variables or focus on specific time points rather than the whole gait cycle. With regards to collection, results from synchronised kinetic and kinematic measurements are scarce, which precludes conclusive elucidation of the question what kinematic changes are linked to a weight-shift to the hindquarters. Combining data together from several studies to develop a more complete picture isn't fully feasible, because of differences in methodology, measurement techniques, experimental conditions, etc., between studies. Further, there is an almost complete lack of studies that document biomechanical horse responses to rider aids, or rider movement pattern changes. This makes it difficult to distinguish between compensatory and intentional parts in the rider's movement pattern, which is necessary in order to understand how the horse and rider actually communicate.

## 1.2 Aims of thesis

The general aim of this thesis is to diminish the knowledge gaps that exist at the intersection between biomechanics on one hand, and traditional equestrian knowledge on the other; it is hoped that the studies included will increase our understanding of horse-rider interactions, for future benefits to both health and performance of riding horses.

### 1.2.1 Specific aims of thesis:

- To describe whole-body kinematics of high-level dressage riders, as well as the relationships between horse, saddle and rider movements at collected walk and trot (paper I and II).
- To describe the interrelationships between orientation of the horse's body, limb movements, inter-limb timing and loading of the limbs at the passage (paper III).
- To compare rider body position, and range and timing of movements relative to the horse in high-level dressage riders between free trot, collected trot, and passage (paper IV).

# 2 Materials and methods

## 2.1 Experimental set-up

The studies included in this thesis were conducted as a part of a larger experiment, which also evaluated the kinetic and kinematic effects of different (horse) head and neck positions (Gómez Álvarez et al., 2006; Weishaupt et al., 2006). The experimental protocol was approved by the Animal Health and Welfare Commission of the Canton of Zurich.

## 2.2 Horses and riders

Seven dressage horses competing at Grand Prix (n = 6) or FEI Intermediate (n = 1) level were used. Horses were of Warmblood breed, withers height (mean ± SD) 1.70 ± 0.07 m and were equipped with their own fitted saddle and a bridle with a normal snaffle bit. The horses were subjected to a thorough orthopaedic examination by an experienced clinician and judged to be free from lameness and pain or dysfunction of the neck and back. All horses were in active dressage training at the time of the study. The horses were ridden by their usual riders, 3 men and 4 women, weight 78 ± 17 kg. The riders had not been training with the same trainer together prior to the experiment.

The experiment was conducted on a high-speed treadmill (Mustang 2200) with an integrated force measuring system (Weishaupt et al., 2002). Horses and riders were measured at square stance and in collected walk (paper I), collected trot (a range of speeds, paper II-IV) and free trot (loose reins, unrestrained horse) (paper IV), and in passage (paper III). The correctness of execution of the collected walk, collected trot and passage was assessed by a qualified dressage judge. Each condition/speed was recorded in one measurement of 15 s.

## 2.3 Kinematic measurements

For the kinematic measurements, numerous spherical reflective markers were placed on the horse, rider and saddle. Marker positions were registered by 12 infrared cameras (ProReflex) at a frame rate of 240 Hz for three horses and 140 Hz for four horses. The laboratory coordinate system was oriented as follows: The X-axis horizontal and positive in the horse's direction of motion, the Y-axis horizontal and positive to the left and the Z-axis vertical and positive upwards (Figure 1). The reconstruction of the 3D position of each marker was based on a direct linear transformation algorithm (Q-Track). The raw X-, Y- and Z-coordinates were exported into Matlab for further processing.

Rigid body analysis as described by Söderkvist and Wedin (1993) was used to quantify the movements of the saddle and the rider's core body segments (head, upper body and pelvis) in paper I, II, and IV, and the horse's pelvis in paper III. Rotations of each segment around the X-, Y- and Z-axes were thereby described as roll, pitch and yaw angles, respectively. Except for the pelvis, rider segment rotations were calculated in relation to the next segment, e.g. upper body rotations were calculated relative to the position of the pelvis. Zero angles were defined according to the stance measurements, conducted with the riders sitting on their horses standing square on the treadmill. Angular changes were assigned positive values for clockwise rotation viewed along the direction of the respective axis (Figure 1). In the results section positive pitch will be termed cranial rotation, positive roll will be termed right and positive yaw will be termed left, for convenience.

3D angles and 2D plane projection angles between relevant markers were determined to represent horse and rider extremity joint angles, horse fore- and hind limb protraction-retraction and horse neck and trunk segment orientation angles. Rider plane projection angles were calculated after re-rotating marker data to the stance position using the rotation matrix of the upper body (arms) or pelvis (legs). In the results section, sagittal and frontal plane projection angles will be termed flexion-extension and adduction-abduction, respectively, for the rider's arms and legs.

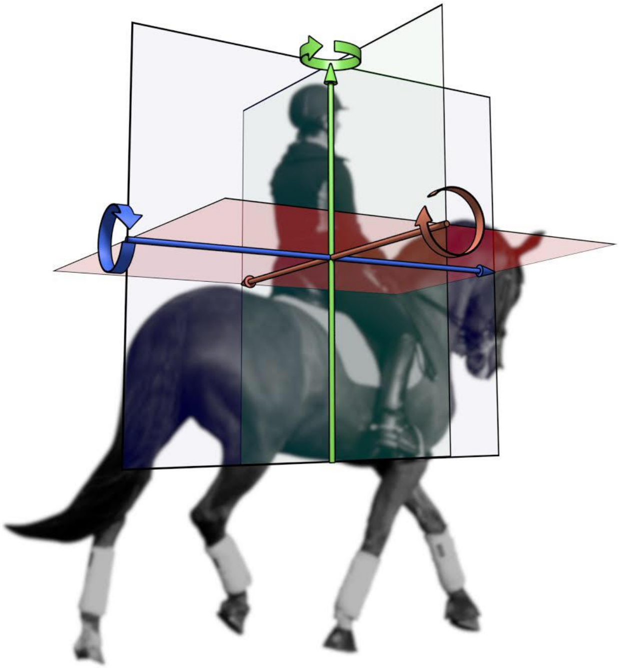

*Figure 1.* Illustration of the coordinate system and movement planes: the sagittal/longitudinal (green), horizontal/transverse (red) and frontal (blue) planes. Positive directions within these planes are defined by three axes, x (red), y (blue) and z (green). Rotations around these respective axes are termed roll, pitch and yaw, positive directions of rotations are indicated by arrows.

To define rider leg position and rider position relative to the horse, distances between selected horse and rider markers were calculated. These included: X-distance from rider's C7 to the spinous process of the third lumbar vertebrae (L3) of the horse; X and Z-distances from rider's seat (a mean of the left and right trochanter markers) to L3 of the horse; Z-distance from rider's seat to the front part of the saddle (a mean of the left and right pommel button markers); Y- and X-distances from rider's hip (trochanter) to the toe of the boot; Z-distance between the toe and heel of the rider's boot.

For each measurement, the data for all kinematic variables were split into strides based on left hind limb first contact times from the treadmill force measuring system, then normalised to 101 points (0–100%) and averaged over the available number of strides. Finally, group mean and SD were calculated from the individual mean curves. For the rider variables, stride mean was subtracted from each individual rider's mean curve before group mean was determined, to facilitate comparison between riders.

## 2.4 Kinetic and temporal measurements (paper III only)

Stride length, temporal variables and vertical ground reaction force variables of each limb were measured by a treadmill-integrated force measuring system capable of determining the vertical ground reaction forces and the hoof positions during stance of all limbs simultaneously (Weishaupt et al., 2002).

## 2.5 Statistics

### 2.5.1 Paper I and II

Time of transition (ToT) was defined as time of occurrence of a minimum or maximum value expressed in percent of stride time. Comparisons were made between the vertical displacement of the fifth lumbar vertebra (L5) of the horse and the rider movement variables. For rider extremity variables, ToT difference to L5, as well as variable values at ToT, were compared between the first and second half of the stride cycle. Variable ROM were compared between collected trot and collected walk. All comparisons were tested for significant differences by use of a paired, nonparametric test (Wilcoxon sign-rank test) with a significance level of $P<0.05$.

### 2.5.2 Paper III

Differences between collected trot and passage were tested for significance using a paired test, either a t-test or a Wilcoxon signed rank test depending the result of a Kolmogorov-Smirnov normality test. The significance level was set at $P<0.05$.

### 2.5.3 Paper IV

The mixed procedure in SAS (SAS Institute) was used to create multivariable models with horse, type of trot (collected, free or passage) and speed as independent variables and stride mean, stride range and ToTs for each variable as the dependent variable. Speed was modelled as a linear effect. The interaction between trot type and speed was included in the model if significant ($P<0.05$). Horse was modelled as a random factor and interactions between horse and speed, and horse and trot type were included if this improved the Akaike information criteria of the model. Passage and free trot were analysed in separate models. Model parameter estimates were used to assess significant differences between collected trot and passage or free trot, respectively, as well significant effects of speed in collected trot (assessed in the passage model). Model diagnostics plots were used to confirm normal distribution of model residuals.

# 3 Results

## 3.1 The rider's movements in walk (paper I)

During the first half of each hind limb stance, from the tripedal support with a single forelimb and both hind limbs to the tripedal support with both forelimbs and a single hind limb, the horse's trunk rotated cranially (clockwise viewed from the right) and the horse's neck extended. At the same time, the saddle rotated cranially in pitch and away from the newly placed hind limb in roll and in yaw (the pommel moved away from, and the cantle towards the hind limb). The rider's pelvis followed the rotation of the saddle in roll and in yaw, but rotated caudally (posteriorly) in pitch. i.e. in the opposite direction compared to the horse's trunk and the saddle. The rider's seat was displaced forwards in relation to the horse while the rider's neck (C7) and feet were displaced backwards. Flexion-extension of the rider's lumbar back varied between riders. Four riders had a consistent pattern but the time of maximal flexion and extension varied between riders. The remaining riders showed greater between-stride variability, precluding pattern description. At hind limb midstance, all variables changed direction of movement except in roll and in yaw. The saddle continued rotating away from the hind limb in roll and in yaw until or just before next hind limb ground contact, i.e. until forelimb midstance. Rider movements in roll and in yaw were variable within and between riders during the second half of hind limb stance. Significant phase-shifts between the vertical movement of horse L5 and other horse and rider movement variables, at the tripedal dual forelimb support and the tripedal dual hind limb support, are listed in Table 1.

Table 1: *Difference in % of stride time between the time of transition, i.e. min or max value time of occurrence, in the vertical displacement of the fifth lumbar vertebra (L5) of the horse, and other horse and rider movement variables, at the tripedal dual forelimb support and the tripedal dual hind limb support (rider contralateral hip is contralateral to the hind limb in support phase) in high-level dressage horses (n=7) ridden at collected walk on a treadmill. Values represent group mean ± SD. All listed differences were found to be significant (p<0.05) in a paired non-parametric test (Wilcoxon). Adapted from paper I.*

| Tripedal dual forelimb support | % stride |
|---|---|
| Horse neck pitch | -5.5 ± 3.6 % |
| Rider neck-horse L3 sagittal distance | -3.3 ± 3.3 % |
| Horse position L5 vertical displacement | 0% |
| Rider seat-horse L3 sagittal distance | +6.7 ± 3.6 % |
| **Tripedal dual hind limb support** | **% stride** |
| Saddle yaw | -12.4 ± 4.8 % |
| Saddle roll | -7.0 ± 4.1 % |
| Rider neck-horse L3 sagittal distance | -5.4 ± 1.5 % |
| Horse neck pitch | -3.1 ± 3.0 % |
| Horse position L5 vertical displacement | 0% |
| Rider seat-horse L3 sagittal distance | +2.3 ± 1.3 % |
| Rider seat-saddle front vertical distance | +2.9 ± 2.2 % |
| Rider contralateral hip flexion-extension | +3.9 ± 2.7 % |

## 3.2 The rider's movements in trot (paper II)

During the first half of stance the horse's trunk and the saddle rotated caudally in pitch. The rider's pelvis rotated cranially (anteriorly) in pitch and to the right in roll and yaw. The rider's lumbar back extended. The rider's seat was displaced downwards and forwards at first, and then backwards in relation to the horse. The rider's neck was displaced forwards in relation to the horse. The rider's hip joints flexed and abducted and the knees flexed. The rider's toes were displaced forwards and outwards and rider's heels were lowered in relation to the toe.

At midstance, all horse and rider variables changed direction of movement except for roll and yaw of the saddle and yaw of the rider's pelvis (for which changes of direction occurred only around first contact of a diagonal).

During the second half of stance and the suspension phase, reverse pitch rotations were observed for the saddle and rider pelvis, and the rider's lumbar back flexed. Rider-horse distances also showed reverse changes compared to the earlier part of stance. The rider's pelvis rotated more slowly in both roll and yaw, and in roll the direction of rotation varied between riders.

Significant phase-shifts between the vertical movement of horse L5 and other horse and rider movement variables at the midstance and first contact of a diagonal are listed in Table 2.

Table 2: *Group mean values ± SD for the difference in time of transition, i.e. min or max value time of occurrence, in % stride between peak vertical height of L5 of the horse, and other horse and rider movement variables, at midstance and first contact of a diagonal (rider ipsilateral thigh is ipsilateral to the hind limb in support phase) in collected trot. All listed differences were found to be significant ($p<0.05$) in a paired non-parametric test (Wilcoxon). Adapted from paper II.*

| Midstance | % stride |
|---|---|
| Rider thigh flexion/extension | +3.7±1.7 % |
| Rider ipsilateral thigh abduction | +4.3±2.8 % |
| Rider head pitch | +5.1±2.5 % |
| Rider pelvis pitch | +5.3±1.2 % |
| Rider neck-horse L3 sagittal distance | +5.8±3.8 % |
| Rider toe-heel vertical distance | +6.5±4.2 % |
| Rider toe-hip sagittal distance | +7.4±3.0 % |
| Rider seat-horse L3 sagittal distance | +12.1±2.9 % |
| First contact | % stride |
| Rider lumbar back flexion/extension | +4.6±4.0 % |
| Rider thigh flexion/extension | +5.2±2.4 % |
| Horse trunk pitch | +5.6±1.7 % |
| Rider head pitch | +6.1±3.2 % |
| Rider pelvis pitch | +7.0±2.1 % |
| Rider toe-heel vertical distance | +7.2±3.3 % |
| Rider upper arm flexion/extension | +7.8±5.3 % |
| Rider neck-horse L3 sagittal distance | +8.1±3.2 % |
| Rider thigh adduction | +8.1±3.8 % |
| Rider seat-horse L3 vertical distance | +9.1±2.2 % |
| Rider toe-hip sagittal distance | +10.2±4.6 % |
| Rider seat-horse L3 sagittal distance | +16.0±6.1 % |

## 3.3 Differences in saddle and rider movement between walk and trot (papers I and II)

Range of motion for horse, saddle and rider movements in walk and trot, as well as differences between gaits, are listed in Table 3. At the walk, ROM for yaw of the saddle was significantly larger compared to trot. With regards to the rider, ROMs for pitch of the pelvis, flexion-extension of the lumbar back, all head movements and the vertical displacement of the rider’s seat in relation to the front part of the saddle were all significantly smaller in walk compared to trot. With regards to the horse, the range of vertical displacement of L5 was significantly smaller in walk whereas ROM for pitch of the horse’s trunk was significantly larger compared to trot.

Table 3: *Stride range of motion (ROM) in degrees or mm for horse, saddle and rider variables measured in high-level dressage horses and riders (n=7) during collected walk (leftmost column, paper I) and collected trot (rightmost column, paper II) on a treadmill: rotations of the saddle and of the rider's pelvis around the transverse (pitch), longitudinal (roll) and vertical axes (yaw), pitch, roll and yaw of the rider's upper body in relation to the pelvis, pitch, roll and yaw of the rider's head-neck in relation to the upper body, pitch of the horse's neck and trunk, the vertical distance from the rider's seat to the front part of the saddle, the vertical and the sagittal distances from the rider's seat to the spinal process of the third lumbar vertebra (L3) of the horse, the sagittal distance from the rider's neck to L3 of the horse, and the vertical displacement of the fifth lumbar vertebra (L5) of the horse. The range of motion differences in percent from collected trot to collected walk are given in the middle column. Table values represent group mean ± SD. *significant difference (p<0.05) between gaits in a paired non-parametric test (Wilcoxon). Adapted from paper I.*

| | | Walk ROM (°/mm) | Diff trot - walk (%) | Trot ROM (°/mm) |
|---|---|---|---|---|
| Saddle | pitch | 6.1 ± 0.9 | 9 ± 13 | 5.6 ± 0.6 |
| | roll | 8.5 ± 2.7 | 53 ± 69 | 7.3 ± 5.2 |
| | yaw | 8.3 ± 1.5 | 49 ± 33* | 5.7 ± 1.0 |
| Rider pelvis | pitch | 9.7 ± 2.0 | -28 ± 20* | 13.9 ± 2.2 |
| | roll | 5.6 ± 0.6 | 18 ± 31 | 5.1 ± 1.1 |
| | yaw | 8.2 ± 1.9 | 9 ± 31 | 7.9 ± 2.1 |
| Rider upper body | pitch | 6.0 ± 2.0 | -42 ± 14* | 10.7 ± 3.4 |
| | roll | 5.0 ± 1.8 | 12 ± 42 | 4.9 ± 1.8 |
| | yaw | 5.0 ± 1.3 | -6 ± 21 | 5.5 ± 1.1 |
| Rider head-neck | pitch | 11.0 ± 4.8 | -30 ± 19* | 15.7 ± 4.5 |
| | roll | 4.0 ± 0.9 | -28 ± 22* | 5.9 ± 1.1 |
| | yaw | 4.1 ± 1.3 | -25 ± 22* | 5.7 ± 2.4 |
| Rider seat-saddle front vertical distance | | 25 ± 6 | -55 ± 14* | 58 ± 10 |
| Rider seat- horse L3 vertical distance | | 38 ± 9 | -5 ± 39 | 45 ± 13 |
| | sagittal distance | 41 ± 4 | -14 ± 24 | 50 ± 24 |
| Rider neck- horse L3 sagittal distance | | 53 ± 14 | 21 ± 33 | 45 ± 6 |
| Horse neck pitch | | 8.0 ± 1.6 | 43 ± 50 | 6.0 ± 1.4 |
| Horse trunk pitch | | 6.0 ± 0.7 | 53 ± 22* | 4.0 ± 0.7 |
| Horse L5 vertical displacement | | 62 ± 7 | -42 ± 8* | 106 ± 8 |

## 3.4 The horse's movement pattern in passage compared to collected trot (paper III)

Comparing the passage to collected trot, horses moved at a slower speed (1.84 ± 0.38 m/s vs 3.24 ± 0.04 m/s), with a shorter stride length (passage 1.96 ± 0.38 m vs. trot 2.66 ± 0.11 m) and with a lower stride frequency (56.0 ± 2.4 vs 73.3 ± 3.2 strides/min). Both stride and stance duration were longer at the passage compared to collected trot, but relative stance duration of fore- and hind limbs and suspension duration remained unchanged. Because of the prolonged stride duration, limb impulses were higher at the passage in the fore- as well as in the hind limbs (+24.8% and +39.9%, respectively). Within the diagonal limb pair, load was shifted from the forehand to the hind quarters: percentage stride impulse carried by the forelimb changed from 58.2 ± 0.8% in collected trot to 55.4 ± 1.1% in passage. Despite the higher impulses, peak vertical forces in the fore- and hind limbs remained unchanged. Advanced placement of the hind limb in relation to the diagonal forelimb increased from 36 ± 9 ms at collected trot to 62 ± 31 ms at the passage.

Compared to collected trot, the horse's movements in passage were characterised by an increase in peak vertical position of the head (C1) and trunk (T6 and L5) at the suspension phase, increased flexion of the lumbosacral junction throughout the entire stride and reduced protraction and retraction of the forelimbs and reduced retraction of the hind limbs. With regards to the limb joints, the passage displayed higher carpal lift during the swing phase, increased stride mean flexion angles for the stifle and the tarsus, and a higher maximal lift of the hind hoof during the swing phase. However, despite increased flexion of the hind limb joints, the horizontal orientation of the trunk (a line between T6 and L5) was unchanged compared to collected trot. Maximal extension of the fore- and hind fetlock joints during midstance also remained unchanged.

## 3.5 Changes in rider movements with increased collection (paper IV)

Collected trot was recorded in speeds ranging from 2.74 to 3.29 m/s. Group mean speed for free trot was 3.15±0.15 m/s and for passage 1.84±0.38 m/s. Differences in rider stride mean position between these conditions are illustrated in Figure 2.

Both at higher speed in collected trot and in passage, the rider's pelvis became more caudally rotated (increased posterior pelvic tilt) and the rider's lumbar back became more flexed. The ranges for the forwards-backwards (sagittal plane) movement of the rider's seat and neck relative to the horse both decreased as speed increased in collected trot. In passage, there were larger ranges for the vertical movement of the rider's seat and knees relative to the horse, but there was no significant difference for the rider's neck. The mean vertical distance between the rider's knees and horse L3 was smaller. The phase-shift between the vertical displacement of L5 of the horse and the forwards-backwards movement of the rider's neck relative to the horse was larger at higher speed in collected trot, both at first contact and at midstance. In passage compared to collected trot, the phase-shift relative to the vertical displacement of horse L5 was lower for pitch of the rider's pelvis at first contact, and for the forwards-backwards movement of the rider's seat relative to the horse both at first contact and at midstance.

In free trot, the rider's pelvis was more cranially rotated, the lumbar back was more extended and the rider's neck was further forward. The phase-shift between horse and rider was increased, compared to collected trot: the phase difference to the vertical displacement of L5 of the horse was larger for the forwards-backwards movement of the rider's neck relative to the horse at first contact, as well as for the vertical movement of the rider's seat relative to the horse both at first contact and at midstance, compared to collected trot.

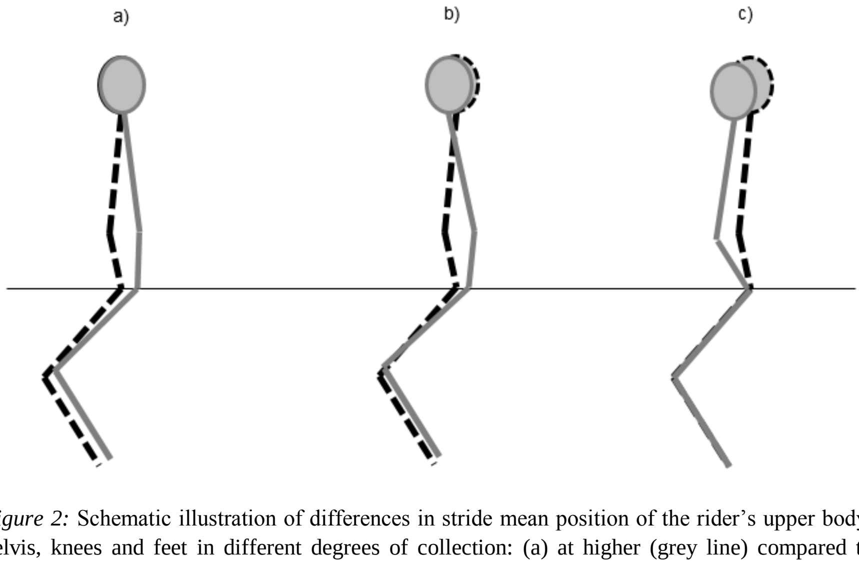


*Figure 2:* Schematic illustration of differences in stride mean position of the rider's upper body, pelvis, knees and feet in different degrees of collection: (a) at higher (grey line) compared to lower speed (black interrupted line) in collected trot, (b) in passage (grey line) compared to collected trot (black interrupted line) and (c) in trot on loose reins (grey line) compared to collected trot (black interrupted line).

# 4 Discussion

## 4.1 The rider’s movements at the different gaits

Horseback riding is a challenging task that requires regulating postural balance while sitting on a moving base of support. To control their balance, riders need to adapt their movements to those of the horse while picking up information both from the horse and the environment to direct the horse toward the intended goal (Olivier et al., 2017). From the results of papers I and II it can be concluded that it is possible to describe a general movement pattern for a group of high-level dressage riders in both walk and trot, at least for the rider’s core body segments. Even though individual differences were noted, these were usually variations of the general pattern rather than individually unique patterns. A plausible explanation for these similarities is that the basic movement pattern of the rider is, to a large extent, dictated by the movements of the horse, which generally are very similar between individuals for each gait, particularly for horses of a similar size and breed (Back et al., 1995a, 1995b; Cano et al., 2001). In order to seek a functional understanding of the rider’s movement pattern, it is therefore relevant to review the rider’s movement pattern in relation to the components of the horse’s movements that the rider needs to compensate for in order to maintain a balanced and effective position on the horse. In adapting to the horse’s movement, the rider’s pelvis is particularly important since it has direct contact with the saddle (Clayton & Hobbs 2017a). During trot, a rider can choose between three different riding techniques: sitting trot, posting trot and the two-point seat. The studies included in this thesis focus on sitting trot, which is the most commonly used technique in dressage. In the walk only the sitting technique is typically used.

In all gaits, horse locomotion as well as rider movements involve translations and rotations in three dimensions. To describe these movements they can be defined relative to three planes termed the sagittal (longitudinal), horizontal and frontal planes. The sagittal plane is vertical and oriented along the horse’s direction of motion. The frontal plane is vertical, and perpendicular to both the sagittal and horizontal planes (Figure 1). Positive directions within these planes are defined by three axes, x, y and z, known as the longitudinal, transverse and vertical axes. Rotations around these respective axes are called roll, pitch and yaw (Figure 1). With regards to human movement, cranial and caudal pitch of the pelvis are often termed anterior and posterior tilt.

## 4.2 Rider movements in sitting trot

The trot is a two-beat, symmetric, diagonal gait with a suspension phase. This creates a bouncing movement where each diagonal stance encompasses a braking phase, in which the horse’s body undergoes deceleration and its limbs are compressed by joint flexions, and a propulsive phase, where the horse’s body is accelerated forwards and upwards through active extension of its limbs (Farley et al., 1993). The horse’s movements in trot will thus be dominated by alternating impacts and push-offs. From a biomechanical perspective, the trot is frequently described by use of a spring mass model. The bouncing movement of the rider in sitting trot can be modeled with a similar approach (de Cocq et al., 2013). In these models, the term ‘spring’ or ‘leg spring’ is used to indicate the mechanical properties of the body, determined by the relationship between the GRF and the distance between the body’s COM and the centre of pressure (COP) on the contact surface (Bobbert and Casius, 2011). The COP is the point of application of the GRF vector. The GRF vector is the sum of all forces acting between the body and its supporting surface (https://en.m.wikipedia.org/wiki/Center_of_pressure_(terrestrial_locomotion)), in this case the ground for the horse and the saddle for the rider. The leg spring of the horse therefore not only refers to the biomechanical properties of the leg but represents the whole body. In sitting trot, when the rider stays seated in the saddle, the mechanical properties of the rider is mainly influenced by the saddle, and by the joints and ligaments of the rider’s lower back, and the back and abdominal muscles (de Cocq et al., 2013). To summarize, the vertical movements of the horse and rider in trot can in many ways be thought of as two coupled springs.

As can be expected, the rider’s movement pattern throughout the stride cycle in trot can largely be explained as being effects of and/or reactions to the vertical and horizontal deceleration and acceleration of the horse’s trunk during each diagonal stance (paper II, Eckardt et al., 2016). Following ground contact of a diagonal limb pair, both vertical and braking ground reaction forces increase rapidly (Barr et al., 1995) and the forwards movement of the horse's COM is rapidly decelerated (Buchner et al., 2000). At the same time the distance between rider and horse starts to decrease, causing the rider's seat to be pressed against the saddle. This is reflected in the pressure between the horse's back and the saddle, which increases rapidly (Figure 3). As the rider's seat is pressed against the saddle, the rider's pelvis starts to rotate cranially (paper II, Eckardt et al., 2016), the rider's lumbar back extends (hollows) and the rider's neck flexes (paper II). The rider's trunk tilts forwards (the rider's neck translates forwards in relation to the horse) and the rider's leg joints flex and the feet move laterally and forwards in relation to the rider's hips. Initially the rider's seat moves forwards in the saddle, but as the rider is pressed deeper and deeper into the saddle the forwards movement of the rider's seat ceases, and when midstance is approached the seat starts to slide backwards in the saddle (paper II). At midstance both horse and rider reach maximal downwards displacement. The rider sits most deeply into the saddle (Figure 4, paper II), and the saddle applies maximal pressure against the horse's back (Figure 3). From midstance, through push-off and into suspension these movements are reversed, such that the rider's back and legs are most extended and the rider's seat is the maximally lifted out of the saddle at first contact of the next diagonal (Figure 4, paper II).

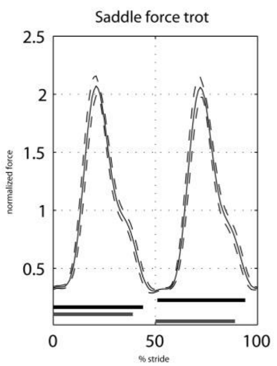


*Figure 3:* Illustration of a typical saddle force stride curve of one rider in sitting trot (stride-mean±SD) with bars indicating stance phases of the left and right forelimbs (upper and lower black bars) and left and right hind limbs (upper and lower grey bars).

*Figure 4.* Illustration of rider position in sitting trot at first contact (left picture) and at midstance (right picture).

From the rider's movement pattern in sitting trot, as described above, one can get the impression of the rider passively letting his or her body be moved by the horse. However, even though the movements of the horse seem to dictate the basic pattern of the rider's movements, the rider still needs to actively control these movements. Experienced riders anticipate the horse's movements and are able to moderate and compensate for perturbations resulting from the horse's movements (Terada et al., 2006). Several studies have also found differences in rider position and movements between skilled and less skilled riders, as summarized in the introduction. This suggests that the exact movement pattern of the high-level riders studied in this thesis reflects their many years of practice. A balanced, supple, and established position in the saddle is essential to communicate efficiently with the horse, to minimize interference with the horse's natural movements and to avoid aversive responses in the ridden horse (Meyners, 2004; Zetterqvist Blokhuis et al., 2008).

## 4.3 Rider movements in walk compared to trot

The walk is a symmetrical gait, in which the horse alternates between tripedal and bipedal supports. At the walk the horse's limbs function similar to rigid struts that raise the withers or croup, respectively, from first contact to the middle part of the stance phase. Because the fore- and hind limbs of a walking horse move out of phase by approximately 25% stride duration, the withers are raised when the croup is lowered and vice versa. This is opposite to the trot, in which the withers and the croup are lowered together during the first half of diagonal stance and then raised during the propulsion and suspension phases. As a result, vertical displacement of the saddle area of the horse's back in walk is only about half of that at the trot (Matsuura et al., 2003). The vertical movement and accelerations are much lower in walk compared to trot, while the lateral and forwards-backwards excursions of the horse's COM are approximately equal in range to the vertical excursion (Buchner et al., 2000). Further, the range of twisting movements (axial rotation) in the horse's back is almost twice as large in walk compared to in trot (Faber et al., 2000; Faber et al., 2001), and the range of yaw of the saddle is also significantly larger in walk (Table 3, paper I, Galloux et al., 1994). Taken together, the extra-sagittal movements constitute a proportionally larger part of the rider's experience of the horse's movements in walk compared to in trot. Therefore, the walk presents a more diverse task for the rider. The walk is also more variable. Approximate entropy values indicate that the horse's movements in walk is significantly less predictable than in trot or canter (Wolframm et al., 2013).

The biomechanical characteristics of the walk are reflected in the rider's movement pattern: The absence of impacts between rider and saddle results in a lower range of pelvic pitch, back flexion-extension and head-neck segment rotations in walk compared to trot (Table 3, paper I). Further, the range of vertical displacement of the rider's body is significantly smaller in walk compared to trot, both within space (Matsuura et al., 2003) and in relation to the front part of the saddle (Table 3, paper I). The rider's movement pattern in walk seems to be determined by the alternating difference in height between the horse's croup and withers: When the horse's trunk starts to rotate cranially the rider's seat begins to slide forwards. Simultaneously, the rider's pelvis rotates caudally (paper I, Munz et al., 2014), while the rider's neck and feet move backwards (paper I). After hind limb midstance, when the croup descends relative to the withers, these movements are reversed.

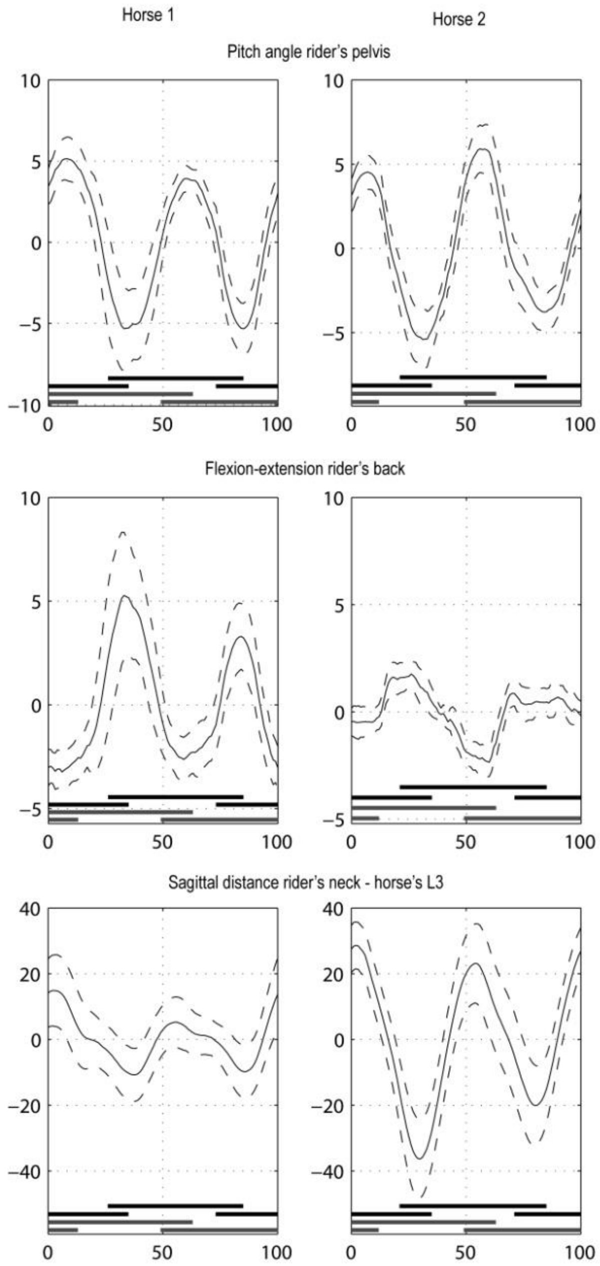


*Figure 5.* Stride curves for rider upper body pitch (positive for cranial rotation) and sagittal distance between rider neck and horse L3 (positive if the rider is further forward) of two horses and riders in walk (mean ± SD). Bars indicate stance phases of the left and right forelimbs (upper and lower black bars) and left and right hind limbs (upper and lower grey bars).

Similar to the horse, the rider's movements in walk appear to be more variable. The mean standard deviations of relative phase between horse and rider point towards unstable phase-coupling in the walk (Wolframm et al., 2013), i.e. more within-rider variation. Comparing the group of riders studied in this thesis between a walk and trot, there was also more between-rider variation in walk. The relative contribution of the rider's pelvis and lumbar back in accommodating to the alternating height differences between the withers and croup varied between the individual riders and affected the range of forwards-backwards movement of the rider's neck (Figure 5). All riders moved the neck caudally in relation to the horse when the horse's croup was raised, but particularly one rider used mainly flexion-extension of the lumbar back to compensate and had a low range of neck displacement, whereas the other riders used more their entire trunk to balance the movements of the horse. It is unclear if either of these strategies is superior. However, skill level dependency of the rider's upper body movements at walk is suggested by the finding that advanced level riders had a more regular pattern in their vertical head movements whereas novice level riders had greater between-stride variability (Terada, 2000).

While sagittal plane movements give a basic description of the rider's movement pattern in walk, a deeper understanding of the interplay between horse and rider movements in this gait requires that roll and yaw of the rider's body segments (i.e. rotations around the vertical and longitudinal axes) are considered as well. These movements seem to be related to the lateral flexion and axial rotation of the horse's back, in combination with the alternating rise and fall of the withers and the croup. When the hind limb makes ground contact, i.e. at the start of the tripedal dual hind limb support, the horse's withers are at its highest while the croup is at its lowest (paper I), and the horse's back has maximal lateral bending such that the back is hollow to the side of the hind limb in early stance (Faber et al., 2000). The rider's hip on this side is maximally lowered (in roll) and turned maximally backwards (in yaw). When the contralateral hind limb is lifted and protracted, the croup is raised while the horse's back reaches maximal axial rotation towards the hind limb in protraction, i.e. the side of the hind limb in stance is relatively higher (Faber et al., 2000; von Peinen et al., 2009). Simultaneously the saddle rolls towards the hind limb in protraction (paper I). Because the rider initially has the hip maximally lowered and backwards on the side of the supporting hind limb, the push from the horse's back through the saddle displaces the rider's hip upwards (in roll) and forwards (in yaw). This results in a distinct force peak between the horse and the saddle below the rider's seat bone, under the caudal third of the saddle on this side (von Peinen et al., 2009). During the second half of hind limb stance, roll and yaw of the rider are of lower range and sagittal plane movements dominate (paper I).

The discussion above illustrates that the results of paper I, together with studies on movements of the horse's back and saddle pressure, allow for a more complete understanding of the interaction between horse and rider in walk.

## 4.4 The horse in passage

According to the FEI Rules for Dressage Events the goal of the passage is to demonstrate the highest degree of collection, cadence and suspension in the trot. The passage is described as a measured, very collected, elevated and cadenced trot with a prolonged suspension, characterised by a pronounced engagement of the hindquarters, accentuated flexion of the stifles and hocks and a graceful elasticity of the movement (FEI, 2018). A standard equestrian work written in the 18th century gives a similar description (de la Guérinière, 1729); the only discrepancy is that a prolonged suspension phase is not mentioned, instead lowering of the hindquarters through increased flexion of the hind limb joints is more strongly emphasised. This indicates that equestrians for a long time have had a relatively consistent opinion on the characteristics of a good passage.

Objective measurements of the kinematics of high-level dressage horses performing passage support most of the features mentioned above: Elevated and cadenced movements can translate to the observed increase in maximal upwards excursion of the head, withers and croup at the suspension phase (paper III). The horse's stride length was shorter in passage compared to collected trot (Holmström et al., 1995a; paper III). With regards to the hind limbs, the decrease in stride length was predominantly (Holmström et al., 1995a) or only (paper III) related to decreased retraction. Consequently, the hind limbs were more protracted on average during the stride. Pronounced engagement of the hindquarters in passage, as described in equestrian texts, could be a visual interpretation of the increased average hind limb protraction. This feature is likely important for the impression of hind limb engagement, due to the influence on generation of GRFs that determine the horse's balance. When the hind limb is more protracted during stance, the moment arm of the vertical component of GRF is shorter so it produces a smaller nose-down torque (Clayton & Hobbs 2017b), which likely gives the visual appearance of a lighter forehand and more engaged hindquarters. Increased flexion of the hind limb joints was present; the hock and stifle had smaller joint angles in passage (Holmström et al., 1995a; paper III). However, despite the increased flexion of the hind limbs, the horizontal orientation of the trunk did not change, i.e. a relative lowering of the hindquarters did not take place (paper III). This finding is consistent with studies on collection in walk and trot (Rhodin et al., 2009; Rhodin et al., 2018). Similar to collection in trot, the passage did, however, feature increased flexion of the lumbosacral junction (Holmström et al., 1995a; paper III), that may be interpreted visually as a lowering of the croup because the root of the tail is lowered. A prolonged suspension (in percent of stride duration) could not be confirmed (Clayton, 1997; Holmström et al., 1995a; paper III). However, the increase in vertical excursion of the horse's body (Clayton et al., 2017; paper III) together with a higher carpal lift (paper III) and higher hind hoof lift during the swing phase (Holmström et al., 1995a; paper III) may give the impression of a prolonged suspension phase. Taken together, there is reasonable agreement between equestrian texts and horses' actual movements in passage.

The horse's movement pattern in passage resulted in a shift of a vertical impulses from the forelimbs to the hind limbs of about 5% compared to collected trot (paper III). There are three basic ways how the horse can shift vertical GRF impulse from the forelimbs to the hind limbs. These are: (i) adjustment of relative fore-hind contact timing, i.e. diagonal dissociation; (ii) adjustment of limb protraction–retraction, i.e. shifting the base of support position relative to body COM; and (iii) shifting fore-hind vertical force distribution, i.e. COP location within the base of support (Clayton & Hobbs 2017b). Forelimb and hind limb protraction-retraction angles throughout stance affect the horse's balance by changing the relative lever arms for the fore- and hind limb. Principally the same effect (ii) can be achieved if the horse changes body posture, most effectively the head and neck position, such that the COM is shifted within the body. The difference in head and neck position is, however, rather minor between passage and collected trot, and therefore not a likely explanation for the weight shift in passage. The shift of weight from forelimbs to hind limbs in passage was approximately 3-fold greater than that observed in the same horses when trotted with a high elevated head-neck position (Weishaupt et al., 2006). The COP can be shifted towards the hind limb within the base of support (iii) if hind limb vertical force application is increased through muscular effort. This has the same effect on the vertical impulse distribution as does shifting the base of support relative to COM (ii). The redistribution of diagonal vertical impulse to the hindquarters in passage, compared to collected trot (paper III; Clayton et al., 2017), seems to be accomplished by shifting the COP (not the COM) towards the hind limbs (Clayton et al., 2017). In other words, increased hind limb force application through increased muscular effort seems to be more important than decreased hind limb retraction for the shift of vertical impulse.

In passage, there was also a change in the distribution of horizontal forces compared to collected trot: hind limb propulsive impulse was significantly increased in passage (Clayton et al., 2017). The higher hind limb propulsive impulse could contribute to a nose-up moment around the COM that would lift the forehand (Hobbs et al., 2016). This combined with the increased hind limb diagonal advanced placement (paper III) results in that the forelimb exerts a braking force while the hind limb simultaneously exerts a propulsive force through much of stance (Clayton et al., 2017), which facilitates the elevation of the forehand similar to the take off in a pole vaulter.

To summarize, the kinetic and kinematic measurements of paper III contribute to the understanding of how the perceptions of a dressage judge or trainer can be interpreted in terms of biomechanics, and how the horse uses its body to produce the graceful movements of the passage.

## 4.5 The rider’s seat and aids in collection

The collected gaits are created and shaped by the interplay between horse and rider. This means that a horse’s ability to collect is, apart from its bodily constitution, dependent on the skills of its rider, i.e. the rider’s ability to provide the horse with appropriate cues in order to shape the horse’s movements in the appropriate fashion. In trying to understand the cues used by a skilled rider to collect the horse, evaluating changes in the rider’s position and/or movements between different degrees of collection could be useful. Many rider cues for collection are likely transient and therefore difficult to capture. However, it is also possible that the rider uses positional cues that are maintained throughout a movement, for example a sequence of collected trot or passage. Changes in the rider’s movements or position that appear unexplainable from any changes in the horse’s movement pattern are most likely to represent rider cues.

The effects of varying the mechanical properties of the rider’s trunk and legs on the rider’s movements in trot have been explored in a modeling study (de Cocq et al., 2013). When the body spring is loaded, this energy can either be stored through stretching of tendons and other elastic structures, and then later returned through elastic recoil, or dampened (dissipated to the environment as heat) through eccentric muscle contractions (Konow et al., 2012). A wide range of combinations of rider spring stiffness and damping coefficients resulted in a sitting trot. However, an increase in damping increases the work required from the horse and an increase in spring stiffness increases the peak forces that the rider applies onto the horse's back (de Cocq et al., 2013). It is possible that riders modify these parameters to give seat aids. The muscle tone in various postural muscles and also the rider's posture theoretically have an influence on the rider's spring stiffness and damping coefficients. The rider's lower back is likely the dominant factor for the mechanical properties of the rider during sitting trot (de Cocq et al., 2013) because the forces on the stirrups are low under this condition (van Beek et al., 2011).

When moving at higher speed in collected trot, the rider's pelvis tilted posteriorly and the rider's lumbar back became more flexed. At the same time the ranges for the forwards-backwards displacement of the rider's seat and neck relative to the horse decreased as speed increased (paper IV). In the same horses and riders, it was found that peak saddle force, i.e. the force between horse and rider, increased markedly with increasing velocity in collected trot (+44.9% rider weight/[m/s]), more than double the increase in peak vertical GRF of the horse (+17.2% horse weight/[m/s] for the fore and hind limbs combined, Bogisch et al., 2014). This marked increase could suggest increased rider stiffness with increasing speed, possibly related to the postural changes observed, and/or increased muscle tone. In part this could also be related to increased back stiffness of the horse. The EMG activities in *m. longissimus dorsi* and *m. rectus abdominis* increased and back flexion-extension decreased at higher velocities within a speed range of 3.5-6.0 m/s (Robert et al., 2001a, b). In a study comparing active and more-passive riding, the pelvis had increased posterior pitch and pitch ROM when the riders were actively influencing the horse (Engell et al., 2016). This is described by equestrians as a 'driving seat'. Together with these changes in rider pelvic movements when actively influencing the horse, the rider's seat bones (ischial tuberosities) moved anteriorly in the saddle, with an increased ROM of the COP of the force applied by the saddle to the horse's back. Taken together, there is evidence to support that changes in the rider's posture or movements are reflected in the saddle force (or pressure) pattern. These changes are likely perceived by the horse and could be used as cues. From the above it seems that increased rider stiffness might ask the horse for more cadence or impulsion in the trot, but further research is needed to confirm this.

It seems that a more active or purposive rider influence correlates with a decrease in phase-shift between horse and rider when speed is accounted for. Both pitch of the rider's pelvis and the forwards-backwards displacement of the rider's seat were significantly less phase-shifted relative to the vertical movement of the horse in passage compared to collected trot (paper IV). In free trot, on the other hand, the phase-shift between rider and horse was increased for the vertical displacement of the rider's seat and the forwards-backwards displacement of the rider's neck compared to collected trot (paper IV). It has previously been found that an expert rider's movements are less phase-shifted in relation to the horse compared to a novice rider riding the same horse (Lagarde et al., 2005). It has also been shown that an expert rider has a more specific effect (i.e. uniform across horses) on the horse's head movements compared to a novice (Schöllhorn et al., 2006), and that the regularity of the horse's movements increases when ridden by an expert rider, both compared to a novice rider (Lagarde et al., 2005) and compared to trot in hand (Peham et al., 2004). This suggest that an expert rider has a more active, intentional influence on the horse's movements.

Collection is achieved through a fine tuning of driving and restraining aids (Decarpentry, 1971; FEI, 2018; von Dietze, 2005), i.e. collected gaits are the result of active rider interventions. This likely includes a more active use of the seat. In the equestrian literature, two forms of more active seat aids are described. One is the driving seat as mentioned above, a posture with increased posterior pelvic tilt, which is used to ask the horse to push off more with the hind limbs. The other is the seat aid applied in a half-halt. In a half-halt the rider is instructed to momentarily sit deeper into the saddle, placing increased weight on the seat bones by increasing the tension in the lower back and abdominal muscles (Decarpentry, 1971; Hess, 2012; von Dietze, 2005). If this increased muscle tension is to have the described effect in trot, it must likely be applied to counteract the lumbar back extension and cranial rotation of the pelvis that occurs as the rider moves downwards relative to the horse during the first half of stance (paper II). Doing so will increase the rider's lumbar back stiffness, likely resulting in a higher peak saddle force (cf. de Cocq et al., 2013). Resisting lumbar back extension will likely lead to an increased posterior pelvic tilt on average during the step in which the half-halt is performed, similar to the driving seat. Increased posterior pelvic tilt was observed for passage compared to collected trot, and in collected trot compared to free trot in paper IV. This was accompanied by a decrease in phase-shift between the movement of the rider's seat and those of the horse, suggesting a more active use of the seat by the rider. So, in agreement with the equestrian literature, the results from paper IV suggest that changes in pelvic tilt with increasing degree of collection at the trot is a result of active rider interventions, i.e. seat aids, rather than a passive adaptation to the horse's movement pattern.

## 4.6 Limitations

All four studies included in this thesis were conducted within the same experiment, including the same seven high-level dressage horses and riders. This is a limitation to the general applicability of the findings.

All studies were conducted on a treadmill. There are differences between horse locomotion on treadmill and over ground. Some of these differences may be related to differences in surface comparing treadmill locomotion on a rubber belt with locomotion on for example asphalt or sand (Buchner et al., 1994). However, even comparing a similar surface differences have been confirmed. These include increased stance duration, increased retraction of the forelimbs and hind limbs and decreased vertical excursion of the horse's body during locomotion on treadmill (Buchner et al., 1994). However, back movements in trot have been shown not to differ comparing treadmill to over ground locomotion (Gomez-Alvarez et al., 2009).

When riding on a treadmill, speed is determined by the operator and not directly by the rider. This could present an extra challenge when collecting the horse and may have affected the horse's quality of movements, even though the riders as well as the dressage judge present during the experiment were pleased with the horses' performance.

For rigid body rotations, interpretation of actual angular values was not possible because the reference measurements were conducted with the riders sitting on their horses at square stance, rather than in a defined anatomical position. Because of this limitation, asymmetries in rider movement patterns were not analysed other than a visual assessment of the curve shapes.

The current studies used a custom marker set-up for the riders. Since the calculated rigid body rotations are invariant to the location of the base point (Söderkvist and Wedin, 1993), this is not a source of errors for rotations but results in erroneous translations, and these data were therefore discarded. Instead distances between selected horse and rider markers were used to indicate rider translations. In human kinematics, it is common to use a standard full body marker set-up for model building in biomechanics software such as Visual3D or OpenSim. This would have allowed correct calculations of segment translations.

Although the riders were performing at a high-level, and their performance was evaluated by a qualified dressage judge, it was not within the scope of the included studies to evaluate the optimal way to communicate with the horse in order to achieve collection.

# 5 Conclusions

Based on the results of the studies included in this thesis, it can be concluded that:

- The saddles and riders of high-level dressage horses generally follow common movement patterns, at collected walk and trot (papers I, II).
- The basic movement pattern of the studied riders appears to be predominately induced by, or reactions to, forces applied to the rider's body from the movements of the horse. The basic characteristics of the equine gait present plausible explanations of the rider's movement pattern, both at the walk and at the trot (papers I, II).
- Saddle movements in walk and trot mainly reflect the movements of the horse's back and shoulders but are likely also to be influenced by the rider's movements (papers I, II).
- The higher degree of collection of the passage was characterised by increased hind limb engagement, with increased flexion of the hind limb joints, decreased retraction of the hind limbs, and redistribution of the vertical impulse from the forelimbs to the hind limbs, without increasing hind limb peak vertical forces (paper III).
- As the degree of collection increased, the rider sat in a more upright position with increased posterior pelvic tilt, and the phase-shift between horse and rider decreased. This likely reflects a more active use of the seat, in order to engage the horse into collection, since these changes appear to be unrelated to changes in the horse's movement pattern (paper IV).

# 6 Practical implications for the equestrian

When learning how to ride a horse, the first challenge for the rider is how to maintain balance while seated on a moving object. Particularly the sitting trot will be challenging to most riders to sit in balance and harmony. As the rider's education progresses, the next challenge is to deliver clear and timely cues to the horse, in order to shape the horse's movement pattern in the desired way. The desired way for a horse to move does not only include the speed, gait, and direction, but also posture, head carriage, step frequency, engagement of the hind limbs, and movement symmetry. The correctness of this movement pattern is based on empirical combinations of functional movement and aesthetics. One characteristic of dressage as a sport is subjectivity in evaluation of competition performance (Hawson et al., 2010).

The equestrian literature typically provides guidance in the form descriptions of the general appearance of the horse, the visual impression and the rider's feel. These descriptions guide the rider how the horse should move, how the rider should sit on the moving horse, and how cues should be given to the horse. This is often accompanied by some more biomechanical statements: for example, keeping the bridge of the nose close to the vertical while maintaining the poll the highest point is described as the desired head posture for the horse, and the rider should sit with the shoulder, the hip and the heel in vertical alignment. In practice, learning how to ride typically includes many hours of tuition with an instructor. Perhaps rider education could become more efficient if instructions were based on scientific data describing how a rider moves, or should move, when sitting on a horse. This is likely most useful when teaching the appropriate timing of the aids. Based on the work included in this thesis some practical advice can be given:

- In trot, the seat aid for a half-halt, which involves placing increased weight on the seat bones, is only efficient if applied during the first half of hind limb stance. At this time the rider’s lumbar back extends and the pelvis tilts forwards, as the rider moves downwards relative to the horse (paper II).

- In walk, the corresponding moment for the half-halt encompasses the forward reach and early stance of the hind limb, when the rider’s pelvis and upper body tilt forward while the rider seat moves backwards in the saddle.
- The timing of the half-halts suggested from the rider’s movement pattern is also logical from a horse-rider communication perspective, because the timing corresponds to the braking phase of the hind limb.
- For the rider to learn the appropriate timing of the half-halt, keeping track of hind limb movements appears to be a good start.
- At the walk, the rider’s hip is lowered and the seat bone sinks down on the same side, when the hind limb swings forward. The seat bone is then lifted again as the hind hoof lands and the hind limb starts to bear weight. Simultaneously, the thigh on the side of the forward swinging hind limb is brought closer to the horse, and the rider’s foot has more forwards movement compared to the rider’s other leg.
- At the trot, the timing between movements of the horse’s hind limb and movements of the rider’s hip and seat bone is practically the same as in walk, but increased contact of the thigh on the side of the forward swinging hind limb is less obvious.

The study on the horse’s movements in passage, together with previous research, has highlighted some important discrepancies, or differences in wording, between descriptions in the equestrian literature and how a high-level dressage horse moves in collection:

- The croup is not lowered in passage. Increased flexion of the hind limb joints is outweighed by increased pelvic tilt through lumbosacral flexion. However, the root of the tail is lowered. When evaluating the horse’s posture and hind limb engagement in collection, lowering of the croup should only be expected at a very high degree of collection, such as in piaffe or in a canter pirouette.
- The hind limbs do not step further forward in collection, rather they are less retracted. This is again important to know when evaluating the horse‘s performance.
- Comparing movement characteristics of collection as measured in the biomechanical studies to changes in the horse’s movement pattern under other circumstances, such as changing head and neck position or

> decreasing the speed, it is clear that no single variable can be used alone to measure (good) collection. Evaluating the degree and quality of collection requires assessment of the whole horse.

Training aids that measure dressage performances in real time may become reality in the near future (cf. Clayton 2014), given the devices we presently are surrounded by, e.g. accelerometers and high-speed video options in modern smartphones. But the more we are able to measure, the more important it becomes to know with greater detail which measurements are likely to be most useful. This thesis provides some pieces of knowledge that are steps towards evidence-based training in dressage, though significant further work is needed before this is reality.

# 7 Future studies

The studies included in this thesis focus on general kinematic patterns in horses and riders who have already reached a high level in dressage. This approach ignores individual differences and asymmetries, and does not reveal anything about the path of training taken by these horses and riders to reach their current level. Dressage horses and riders typically undergo many years of training to achieve a level of excellence in the sport. For the training to be successful, the communication between horse and rider needs to be perfected at each level of training, the horse's the physical abilities must be developed appropriately, and it is vital that the horse is kept sound. Straightness of the horse, with equal activity, protraction and weight carrying of both hind limbs, is a prerequisite for high-quality collection. On the other hand, any sidedness, or handedness, of the horse and rider, is likely to become more evident in the most demanding exercises, such as all highly collected movements, the extended gaits, and advanced lateral movements. High loading, especially if it is applied unequally to the limbs, may ultimately result in overload injuries. Straightness is therefore of great importance throughout the training, both for the preservation of orthopaedic health and as an integral part of the development of collection.

- In future studies it would be valuable to try to understand how the horse learns to interpret the rider's aids, including the rider's posture or position, and how the rider can present new aids to the horse in a way that is easily understandable, to reduce miscommunication and conflict behaviors in the horse during dressage training.
- In future studies it would be interesting to investigate the interrelationship between straightness and collection. This would include influence of the symmetry of the rider's seat, and the effectiveness of the rider's aids in this regard.

- In future studies it would be valuable to seek useful indicators of progression towards a specific goal in dressage, for example advanced level movements, both during a single training session, and long-term.
- Future studies may also investigate what we can learn from studying the horse without the rider, and the rider without the horse. Can working the horse in hand or on the lunge, or objective measurements of the horse’s symmetry, provide useful information about things that the rider should focus on in the ridden training? And can unmounted evaluation of the rider reveal weaknesses that can be addressed through unmounted training?

It is an ongoing challenge for us as researchers to perform studies and analyse our data to gain new knowledge and insights that are relevant for those that we are aiming to study, riders who are performing in equestrian sports, or just enjoy riding, and equally their horses.

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# Popular science summary

Improving the horse's ability to collect is a fundamental part of dressage training and is a goal during most dressage exercises. The goal of collection according to the international rules for dressage events is to develop and improve the horse's balance and ability to engage its hindquarters. This improves the horse's self-carriage for the benefit of the lightness and mobility of the forehand, making it more pleasurable to ride. Some degree of collection is considered as basic schooling work for all riding horses. More collected dressage movements, such as piaffe and passage, requires many years of training and is a performance limiting factor for many dressage horses.

Knowledge about the movements of the rider and saddle in relation to the movements of the horse provides an important link for understanding the interaction between horse and rider. By studying how this interaction changes between varying degrees of collection, further insight can be gained on the interplay between horse and rider.

The studies in this thesis involved seven high level dressage horses, that were ridden in collected walk and trot by their usual riders on a treadmill, while limb loading and movements were measured. Six of the seven horses were also measured when ridden in passage, a highly collected dressage movement which is part of the Grand Prix test.

Study I. Rider and saddle movements in collected walk

In walk, movements of the horse's back, the saddle and the rider were driven by the rhythmic vertical motion of the croup and withers during the stance phases of the hind and forelimbs, respectively. During the first half of hind limb stance, the croup was raised and, at the same time, the withers were lowered, so the horse's trunk rotated forwards, and the horse's neck extended. The saddle followed the movements of the trunk and tilted in a pommel-down direction, while the rider's pelvis was tilted backwards, i.e. in the opposite direction. The rider's seat moved forwards while the rider's shoulders and feet

moved backwards. However, it varied how much the riders moved the shoulders. Some riders flexed the lumbar spine more and kept the shoulders relatively still. During the second half of hind limb stance, movements of the horse's back, the saddle and the rider were reversed. The croup became lower relative to the withers, so the horse's back and the saddle tilted backwards, while the rider's pelvis tilted forwards.

Study II. Rider and saddle movements in collected trot

During the first half of diagonal stance, the horse's trunk as a whole moved downwards but the croup was lowered more than the withers. The saddle followed the movement of the trunk and tilted backwards. The rider's pelvis tilted forwards which hollowed the rider's lumbar back. The rider's seat moved downwards and forwards, the shoulders moved forwards and the toes moved forwards and outwards. As the diagonal limbs pushed off into the suspension phase the horse's trunk moved upwards, the saddle tilted forwards and the rider's pelvis tilted backwards, which rounded the rider's lumbar spine. Simultaneously the rider's seat was lifted slightly out of the saddle.

Study III: Movements and limb loading at the passage

In passage the horse moved at a slower speed (1.84 m/s) compared to at collected trot (3.24 m/s), with a shorter stride length (passage 1.96 m, trot 2.66 m) and in a slower tempo (fewer strides per minute). Within the diagonal limb pair, load was shifted from the forehand to the hindquarters. Compared to collected trot, the horse's movements in passage were characterised by increased upwards movement of the head and trunk at the suspension phase, increased pelvic tilt (lumbosacral joint flexion) throughout the entire stride, reduced retraction of all limbs and reduced forelimb protraction, a higher carpal lift during the entire swing phase and a higher trajectory of the hind hoof during the swing phase.

Study IV: The rider in different degrees of collection

The rider's average position during the stride was compared between trot on loose reins (3.15 m/s), collected trot at a range of speeds (2.74 to 3.29 m/s), and passage (1.84 m/s). Both at higher speed in collected trot and in passage, the rider's pelvis was tilted more backwards and the rider's lumbar back became more rounded. The phase-shift between horse and rider increased with speed in collected trot, and was lower in passage compared to at collected trot. In free trot, the rider's pelvis was tilted more forwards, the lumbar back was more extended and the rider's body inclined more forwards. The phase-shift between horse and rider was increased compared to collected trot.

Based on the results of the studies it can be concluded that:

- Among high-level horse-rider combinations, the riders show similar movement patterns, at collected walk and trot, and this is driven by the horse's movements.
- Saddle movements in walk and trot mainly reflect the relative vertical motion of the horse's croup, and the movements of the back and shoulders, but the movements of the rider likely also has some influence on the movements of the saddle.
- The higher degree of collection of the passage is characterised by increased hind limb engagement with greater flexion of the hind limb joints and a redistribution of the weight towards the hindquarters without increasing hind limb maximal loading.
- As the degree of collection increased, the rider sat in a more upright position and with increased posterior pelvic tilt and the rider's movements became more closely synchronised to those of the horse. This likely reflects a more active use of the seat, in order to engage the horse into collection, since these changes appear to be unrelated to changes in the horse's movement pattern.

The 'feel' in riding is important and cannot be replaced by descriptions of how the horse and rider should move. However, knowledge about the horse and rider's movement patterns in relation to the stride can guide the rider to a better understanding of how to influence the horse, for example, by indicating the optimal moment during the stride to apply the half halt so that it will have maximal effect. Further, the more focus that is given to details, the more knowledge is needed regarding what is accurate and what is important. Descriptions of collection in the equestrian literature are not in full agreement with how the horse really moves. For example, it is correct that at a high degree of collection the horse will transfer load from the forehand to the hind quarters, but it is not true that the horse's hind limbs step further forward, it is more about stepping out less behind. Such misconceptions illustrate how modern technology can be applied to improve learning and performance in equestrian sports.

# Populärvetenskaplig sammanfattning

**Hästens och ryttarens rörelsemönster vid olika grad av samling i ridning.**

Att förbättra hästens förmåga till samling är en viktig del i utbildningen av dressyrhästar och ett mål i de flesta dressyrövningar. Målet med samling enligt det internationella dressyrreglementet är att förbättra hästens balans samt att utveckla och öka hästens bakbensaktivitet. Det ska leda till en bättre bärighet med en ”lättare” och rörligare framdel, vilket gör hästen trevligare att rida. En viss grad av samling är grundläggande i all dressyrträning. Hög grad av samling, som t ex i piaff och passage, kräver många års utbildning och kan vara en begränsande faktor i tävlingssammanhang för många dressyrhästar.

För att förstå den komplexa interaktionen mellan häst och ryttare är det viktigt med kunskap om hur hästen, sadeln och ryttaren rör sig i förhållande till varandra. Genom att studera detta i olika grad av samling kan vi öka förståelsen för samspelet mellan häst och ryttare.

Sju dressyrhästar på elitnivå reds av sina ordinarie ryttare på en rullmatta samtidigt som det gjordes mätningar av hästens rörelsemönster och kraftbelastningen på benen. Hästarna reds i samlad skritt och i samlad trav i några olika hastigheter, samt på hängande tygel för jämförelse. Sex av hästarna reds också i passage som är en dressyrövning som ingår i de högsta dressyrklasserna.

Studie I. Ryttare och sadelns rörelse i samlad skritt

Under den första hälften av bakbenens understödsfas roterar hästens bål framåt så att den främre delen av ryggen blir lägre och hästen sträcker halsen. Sadeln följer bålens rotation och tippar framåt. Ryttaren kompenserar genom att rotera bäckenet bakåt. Ryttarens säte rör sig framåt medan axelpartiet och skänklarna rör sig bakåt. Det varierade hur mycket de olika ryttarna förflyttade axelpartiet. Vissa ryttare böjde (krummade) ryggen mer och höll axlarna mera stilla. När hästens bakben förs bakåt (bakom hästen) börjar både hästens rygg och sadeln tippa bakåt. Ryttaren följer då hästen genom motsatta rörelser, dvs bäckenet roterar framåt etc.

Studie II. Ryttare och sadelns rörelse i samlad trav

Under den första hälften av det diagonala benparets understödsfas rör sig hästens bål nedåt och sadeln tippar lite bakåt. Ryttarens bäcken tippar framåt och ryttaren svankar i ländryggen. Sätet trycks nedåt och framåt i sadeln. Ryttarens axelparti rör sig framåt, och skänklarna rör sig framåt och utåt. Under påskjutet och svävningsmomentet rör sig hästens bål uppåt och sadeln tippar lite framåt. Ryttarens bäcken tippar bakåt medan ryttarens svank rätas ut. Samtidigt lyfts ryttaren något ur sadeln. Ryttarens axelparti rör sig bakåt, och skänklarna rör sig bakåt och inåt mot hästen.

Studie III: Kinetik (belastning) och kinematik (rörelser) vid passage

I passage rörde sig hästarna långsammare framåt (1,84 m/s) jämfört med i samlad trav (3,24 m/s), och med en kortare steglängd (passage 1,96 m, trav 2,66 m) och i lägre tempo (färre steg per minut). Delar av belastningen överfördes från framdelen till bakbenen, från 58 % på frambenen i samlad trav till 55 % vid passage. Bakbenet landade också lite tidigare i förhållande till det diagonala frambenet jämfört med i samlad trav. Hästen fick en större rörelse uppåt och ett mer vinklat kors och mer vinklade has och knäleder. Hästarna hade även minskad bakåtrörelse av fram- och bakben och en minskad framåtrörelse av frambenen, samt högre lyft av framknän och bakhovar i passage jämfört med samlad trav.

Studie IV: Ryttaren i olika grad av samling

Ryttarens medelposition under steget jämfördes mellan samlad trav i olika hastigheter, passage och trav på lång tygel. Samlad trav reds i hastigheter mellan 2,74 till 3,29 m/s, och för passage var medelhastigheten 1,84 m/s och för trav på lång tygel 3,15 m/s. Både i passage jämfört med samlad trav och vid en högre hastighet i samlad trav satt ryttaren med bäckenet mer tippat bakåt och en mer krummad ländrygg. I passage hade ryttarens säte och överskänklar större rörelse uppåt relativt hästen jämfört med i samlad trav. Den tidsmässiga fasförskjutningen mellan häst och ryttare tenderade att öka med ökad hastighet i samlad trav och var lägst i passage. I trav på lång tygel var ryttarens bäcken mer framåtlutat och ryggen svankade mer, samtidigt som ryttaren lutade sig mer framåt. Fasförskjutningen mellan häst och ryttare blev också större jämfört med i samlad trav.

Baserat på resultaten i studierna kan man dra följande slutsatser:

- Hos högutbildade dressyrekipage följer ryttarna sinsemellan likartade rörelsemönster i samlad skritt respektive trav. Ryttarens grundläggande rörelsemönster speglar hästens rörelser.
- Sadelns rörelse i skritt och trav beror sannolikt främst av rörelserna i hästens rygg och bogar men sannolikt även till viss del av ryttarens egna rörelser.
- Den högre grad av samling, som ses i passage, karaktäriseras av ökad bärighet genom ökad bakbensaktivitet, med ökad vinkling av bakbenen och förflyttning av tyngdpunkten bakåt utan att maxbelastningen av bakbenen ökar eller att hästen trampar under sig mer.
- Vid ökad grad av samling har ryttaren en mer upprätt position med ökad bakåtlutning av bäckenet och sitsen rör sig mer synkront med hästen. Denna sits representerar sannolikt ett mer aktivt säte som ryttaren använder för att få hästen att samla sig då dessa förändringar i ryttaren sits inte går att relaterat till förändringar i hästens rörelser.

Även om ridning har mycket med känsla att göra så kan kunskap om hästens och ryttarens rörelsemönster i förhållande till steget guida ryttaren till en bättre förståelse av olika instruktioner, t ex när under steget en halvhalt bör ske. Men ju mer träningen fokuseras på detaljer desto mer kunskap behövs om vad som är viktigt och riktigt. Ridlitteraturens beskrivningar av samling stämmer inte helt överens med hur hästen verkligen rör sig. Till exempel är det korrekt att hästen i en hög grad av samling överför vikt från framdelen till bakdelen, men det stämmer inte att hästen trampar under sig mer. Sådana missförstånd är viktiga att känna till särskilt om vi vill använda modern teknologi för att förbättra inlärning och prestation.

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