THE BIOMECHANICAL INTERACTION BETWEEN SADDLE, RIDER, AND THE HORSE'S BACK

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A thesis submitted in partial fulfilment of the requirements of the University of the West of England, Bristol for the degree of Doctor of Philosophy

College of Health, Science, and Society/ Hartpury University

August, 2024

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Abstract

INTRODUCTION Understanding the horse-saddle-rider interaction plays a key role in promoting equine welfare and athletic performance. This thesis aimed to advance our understanding of the biomechanical interaction between saddle, rider, and the horse's back during straight-line walk and trot locomotion, in relation to the horse's back functioning.

METHODS (1) A systematic review study identified, evaluated, and synthesized the literature about the effect of saddle and rider on the horse's back biomechanics. (2a-b) Novel research methods were explored, facilitating optical motion capture of the horse's back in ridden and in-field conditions, including the development of a (loaded) experimental saddle with an open seat and the use of hybrid motion capture. (3a-b) Observational studies were conducted, evaluating the effect of saddle and rider on the horse's back movement at walk and (rising) trot and posture at halt, and how these effects relate to functional measures of the horse's back, in ridden competition horses (n=8-20).

RESULTS (1) The systematic review revealed postural and movement adaptations in the horse's back when loaded with a saddle and rider, which are associated with the forces acting upon the horse's back and influenced by saddle fit and the rider's body mass, seating style, riding skills and asymmetries. (2a) An experimental saddle enabling optical motion capture of the horse's thoracic region when loaded with a saddle was successfully developed, though loading the saddle with a rider-equivalent mass caused excessive saddle movements at trot. (2b) The proposed hybrid optical-inertial motion capture approach is compatible with optical motion capture in measuring a horse's back posture and movement at walk and trot on a treadmill (R=0.90-0.99), but has limitations for in-field settings. (3a) A saddle, without rider, induces comparative movement adaptations in the horse's back to when being ridden at walk and trot. (3b) The effect of saddle and rider on the horse's back posture at halt and movement at walk and in rising trot relates to the horse's postural type, thoracolumbar epaxial muscle tone, reactivity, and dimensions, and dorsoventral thoracolumbosacral flexibility and coordination.

CONCLUSION This thesis highlights that the effect of saddle and rider on the horse's back biomechanics should be evaluated for the individual horse-saddle-rider combination, considering the reported factors related to the saddle, rider, and the horse's back functioning. The study findings can support clinical decision-making when managing back health in the ridden horse. This thesis also introduces novel research methods which can support future research studying the biomechanical interaction between saddle, rider, and the horse's back.

Acknowledgements

I would like to dedicate this thesis to my father, Renaat Deckers, who taught me to believe in myself and, perhaps more importantly, my dreams.

I am extremely grateful for having been able to complete my doctoral research course despite the global COVID-19 pandemic overlapping with the majority of my time as a PhD-student and challenging many practical aspects of developing my research methods and organising my data collections, as well as my personal environment – for which many are to thank.

This thesis would not have been possible without the support of my brilliant supervisors. Dr Kathryn Nankervis, Dr Russell MacKechnie-Guire, and Dr Celeste Wilkins, I cannot thank you enough for your contributions to my development as a Researcher and a person. It has been an honour to be your student, and I will be forever grateful for the memorable times we had doing research together.

A special thanks goes to the Worshipful Company of Saddlers for funding and supporting this thesis, and to Patrick Burns and Keith Bryan for their expertise and help in developing the experimental saddle used in this thesis. To all the horses and owners who participated in the studies presented in this thesis, the outstanding students at Hartpury University, and Hartpury's wonderful Equine Therapy Centre team, thank you for helping me out with my data collections and realise my research goals.

Emma Timms, thank you for your ongoing support of my research as a Physiotherapist, co-researcher, and dear friend. Alesha Christian, thank you for being such a good friend and roommate throughout my time in the UK as a PhD student, and for the very precious photographs you took of my data collections. Vicki and Christy, there is a lot to thank you two for, but I'd like to especially thank you for always turning the research set-ups into a (Disney) celebration, brainstorming with me relentlessly about equine biomechanics, and for the motivational speeches and warm hugs when needed.

I would also like to thank my sisters, Lisa and Annakin, and my mum for cheering me on through every part of my journey and for standing by my side no matter the physical distance. Koen, my love, thank you for putting a smile on my face every day again and again. Zazu, my four-legged little angel, thank you for being the best travel, study, and cuddle buddy. Another thank you goes to my friends at home for all the love and laughter and to those of you who visited me in the UK, styled me at conferences, or proofread sections of my thesis. You all contributed to this thesis in an unneglectable way.

I owe my motivation and inspiration for this thesis to the horses I have been so lucky to meet and work with since I was a little child. Evita, Zico, Elias, and Espiritu, to name a few, you have made me the person and professional I am today. It is in honour of the horse that I endeavour to contribute to the welfare of the ridden horse, as a Researcher and Physiotherapist.

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Nankervis, K., Tranquille, C., Chojnacka, K., Tacey, J., Deckers, I., Netwon, R., Murray, R. (2023) 'Effect of speed and water depth on limb and back kinematics in Thoroughbred horses walking on a water treadmill', *The Veterinary Journal,* 300–302, p. 106033. doi:10.1016/j.tvjl.2023.106033.

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List of abbreviations

CoG = centre of gravity

IMU = inertial measurement unit

ROM = ranges of motion

CPGs = central pattern generators

EMG = electromyography

CoM = centre of mass

FEI = Fédération International Equestre

2D = two-dimensional

3D = three-dimensional

PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PICO = study criteria 'population', 'intervention', 'control', and 'outcome'

MeSH = medical subject headings

SWiM = synthesis without meta-analysis

SMS QSF = Society of Master Saddlers qualified Saddle Fitter

LTC = left *tuber coxae*

RTC = right *tuber coxae*

P25-P75/ROM = the ratio between the 25^{th}-75^{th} percentile range and the range of motion

TS = *tuber sacrale*

ACPAT = Association of Chartered Physiotherapists in Animal Therapy

BHSI Coach = international British Horse Society registered Coach

TLS = thoracolumbosacral

CHAPTER ONE

1 Introduction

Scientifically classified as the 'Equus Ferus Caballus', the modern horse is part of the Equidae family, which represents herbivorous browsers and intelligent animals adapted for long-distance running (Janis, 1976). The horse has adapted some extraordinary physiological and biomechanical features in order to efficiently function in nature as a cursorial quadruped, which is manifested in an impressive scope in stamina, agility, and speed (Hodgson, McKeever and McGowan, 2013). Regardless of the horse originally not being destined to be ridden, the horse's athletic features, alongside its broad and relatively rigid back (Jeffcott and Dalin, 1980), willing nature and favourable learning abilities (Budiansky, 1998), made it a suitable riding subject. Humans have been riding horses for thousands of years already, with the oldest written source about horsemanship dating back to two and a half thousand years ago (Xenophon, 431 B.C.). Throughout history, the horse's behavioural, morphological and biomechanical features have evolved in favour of the horse's purpose in society, steered by selective breeding by humankind (Budiansky, 1998). The modern horse stars in the sports industry, including at the Olympics. Nowadays, equestrian sport includes a wide variety of disciplines, most of which involve loading the horse's back with a saddle and rider.

The interaction between the saddle, rider, and the horse's back is complex to study, given that it involves two dynamic forms with the saddle as an interface and knows an inexhaustive list of confounding factors (Greve and Dyson, 2013a; Williams and Tabor, 2017). Technological advances have enabled biomechanical measurements of the interaction between saddle, rider, and the horse's back (Greve and Dyson, 2013a; de Cocq and van Weeren, 2014), which can advance our understanding of the effect of saddle and rider on the horse's back biomechanics and thereby, the biomechanical demands of the horse's back when loaded with a saddle and rider. Quantitative research is now available to support that saddle and rider can act as predisposing factors to back problems in the ridden horse (de Cocq, van Weeren and Back, 2004; de Cocq *et al.*, 2009a; Quiney, Ellis and Dyson, 2018; Dittmann *et al.*, 2021). Back problems in the ridden horse range from subtle subclinical dysfunctions, such as abnormal paraspinal muscle tension or joint movement restrictions (Haussler, 1999b), to clinical dysfunctions, including osseous and soft tissue spinal lesions (Jeffcott, 1980). Back problems are common in this population and are of concern to the equine industry, both for welfare and performance-related motivations (Jeffcott, 1979; Wennerstrand, 2008; de Cocq, 2012). To fully understand how back problems in the ridden horse develop and how we should manage them, profound knowledge is required about how the horse's back functions as well as about the biomechanical demands of the horse's back when loaded with a saddle and rider.

As previously established in human medicine (McGill, 1997; Heneweer, Vanhees and Picavet, 2009), the relationship between the biomechanical demands of the back and the risk of developing back dysfunctions follows a U-shape (see Figure 1.1). Deprivation of mechanical loading results in muscle atrophy and alterations in neuromuscular control, compromising back function in providing spinal stability (Lotz, 2011) and its load-bearing capacities (Jull et al., 2015). Overloading the back can also compromise its function, occurring when the involved structures fail to adapt to increased mechanical stresses (Bustos et al., 2021). Between the zones of under- and overloading, mechanical loading can improve back functioning by cumulative adaptive responses, gradually leading to the strengthening of the musculoskeletal structures (Roman-Liu, 2013). To manage back health, one must thus find the optimal level of loading in order to minimise the risk for back dysfunctions, tailoring the applied load in function of the spinal physical capacities, known as the load-capacity principle within clinical practice (Boucher et al., 2005).

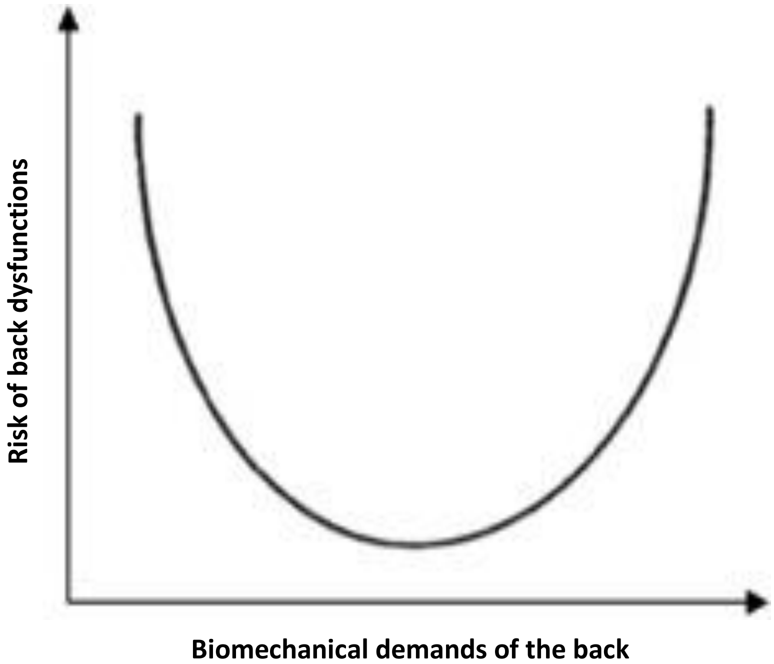


Figure 1.1 | The U-shaped relationship between the biomechanical demands of the back and the risk of back dysfunctions, adapted from Heneweer, Vanhees and Picavet (2009) and McGill (1997).

Regardless of the horizontal orientation of the quadrupedal spine in contrast to the bipeds' upward spinal orientation, the concept of back functioning in the horse is considered comparative to this in the human due to the similarities in the structure and function of the anatomical structures of the back (Stubbs *et al.*, 2006, 2010; Stubbs, 2011). Therefore, principles established in human clinical practice regarding back functioning are considered relevant for the horse as well (van Weeren, McGowan and Haussler, 2010; Clayton, 2012; McGowan and Hyytiäinen, 2017). Applying the load-capacity principle to the ridden horse, it can be inferred that loading the horse's back with a saddle and rider promotes the horse's back functioning when it is tailored to the physical capacities of the horse's back, while it will compromise the horse's back functioning when it under- or overloads the horse's back. Therefore, evaluating the biomechanical demands of the horse's back when loaded with a saddle and rider and how those can be monitored according to the horse's back functioning can steer the management of back problems in ridden horses.

The overarching purpose of this thesis is to advance our understanding of the biomechanical interaction between saddle, rider, and the horse's back and how this relates to the horse's back functioning. Therefore, this thesis aimed to investigate the effect of saddle and rider, and related characteristics, on the horse's back biomechanics and how these biomechanical responses are associated with the horse's back functioning. To narrow the complexity of the biomechanical interaction between saddle, rider, and the horse's back, this thesis only considers straight-line walk and trot locomotion, serving as a baseline for comparison with other types of movement. Furthermore, this thesis only considers an equine population that is in active ridden work and without clinical back problems or lameness to evaluate the 'normal' biomechanical response to the effect of saddle and rider in the horse. However, subclinical back dysfunctions are common in this population (Haussler, 1999b; Wennerstrand, 2008; Wolschrijn *et al.*, 2013). A certain variation in the presentation of back functioning is thus anticipated in this population, which enables evaluating the relevance of the horse's back functioning in the biomechanical interaction between saddle, rider, and the horse's back.

The first study objective was to conduct a literature review evaluating how the horse's back functions and how we can evaluate this, including the evaluation of the anatomy, functional assessments, biomechanics, and movement analysis of the horse's back. The second study objective was to systematically review the literature providing quantitative evidence of the effect of saddle and rider, and related characteristics, on the horse's back biomechanics and establish how these biomechanical responses relate to the horse's back functioning. Those review studies served as a platform to formulate the research methods and methodologies of the sequential studies and facilitate the clinical interpretation of the study findings.

The third study objective was to develop novel research methods overcoming some of the limitations of current methods used for the movement analysis of the ridden horse's back and facilitating biomechanical measurements of the ridden horse's back that are considered clinically relevant. More specifically, research methods facilitating postural measures of the back, including the back region covered by the saddle when loaded with a saddle and rider and in the field, were investigated.

Another study objective was to investigate the effect of a saddle without a rider on the horse's back movement at walk and trot. While the saddle is considered to play a central role in the horse-saddle-rider interaction (Greve and Dyson, 2013a), the effect a saddle has on the horse's back movements is not yet fully understood. Therefore, this investigation was considered another substantial step in advancing our understanding of the biomechanical demands of the horse's back when loaded with a saddle and rider.

The final study objective of this thesis was to investigate the effect of a saddle and rider on the horse's posture at halt and movement at walk and in rising trot, and how these effects relate to functional measures of the horse's back. Adhering to the load-capacity principle used in clinical practice (Boucher *et al.*, 2005), it is evident that how saddle and rider alter a horse's back biomechanics relates to the physical capacities, or functioning, of the horse's back. However, more quantitative evidence to support this relation in the horse is still warranted.

Adhering to these study objectives, the hypotheses of this thesis were that: (1) the effect of a saddle and rider on the horse's back biomechanics cannot be generalised, but there would be significant associations between these effects and factors related to the saddle, rider, and the horse's back functioning, (2) novel research tools could be developed facilitating optical motion capture of the horse's entire back, including the region covered by the saddle, when ridden and in the field, (3) there would be significant differences in the horse's back movement when walking and trotting without and with a saddle, and (4) there would be significant differences in the horse's back posture at halt without and with a saddle and rider and in the horse's back movement when walking and trotting unridden and ridden, and that significant associations would be found between these differences and functional measures of the horse's back. The evaluation of these study hypotheses will provide novel insights into the biomechanical interaction between saddle, rider, and the horse's back and how it relates to the horse's back functioning.

CHAPTER TWO

2 Literature review

Optimal functioning of the equine thoracolumbosacral spine, from here on referred to as the back, is integral to the horse's locomotor apparatus and ridden performance (van Weeren, McGowan and Haussler, 2010). In this Chapter, the concept of optimal functioning of the horse's back is honed by reviewing the functional anatomy and functional assessments of the horse's back. The Chapter continues with discussing the biomechanics and movement analysis of the horse's back. This literature review will facilitate the interpretation of the effect of saddle and rider on the horse's back biomechanics and how those effects relate to the horse's back functioning throughout the following thesis chapters.

2.1 Functional anatomy of the horse's back

The primary function of the back, part of the musculoskeletal system, is to enable movement while providing stability and support to the body (Watkins, 2010). Being horizontally orientated and located between the thoracic and pelvic limbs, the horse's back transmits forces between the appendicular and axial skeleton while accommodating a saddle and rider's weight (van Weeren, McGowan and Haussler, 2010). As originally established in human medicine (Panjabi, 1992a) and integrated in the equine literature, optimal functioning of the spinal musculoskeletal system is regulated by the condition of, and the interaction between, the anatomical structures of the passive, active, and control systems (Tabor, 2015; McGowan and Hyytiäinen, 2017). The anatomical structures of the passive system represent the skeletal structures, intervertebral discs, ligaments, joint capsules, and the passive or viscoelastic component of a muscle, while the active system refers to the muscular and tendinous structures (Panjabi, 1992a). The passive system provides passive stability to the movement, and the active structures move and actively stabilise the body segments. The ability to time and coordinate the movement is referred to as neuromotor control, which is regulated by the neural or 'control' system. The anatomical structures of the control system include the central and peripheral nervous system and the mechanoreceptors within the active and passive musculoskeletal structures (Panjabi, 1992a). The control system receives proprioceptive feedback (i.e. information about the tension in and position of the musculoskeletal structures) by afferent signals, based on which it sends out efferent signals to the active subsystem, which is also called the neural drive. Together, the passive, active, and control systems act to provide stability to the spine when subject to static and dynamic loads (Tabor, 2015), such as those induced by a saddle and rider. The interaction between the three systems regulating spinal function is illustrated in Figure 2.1, and each system's anatomical structures and their function within the horse's back are described.

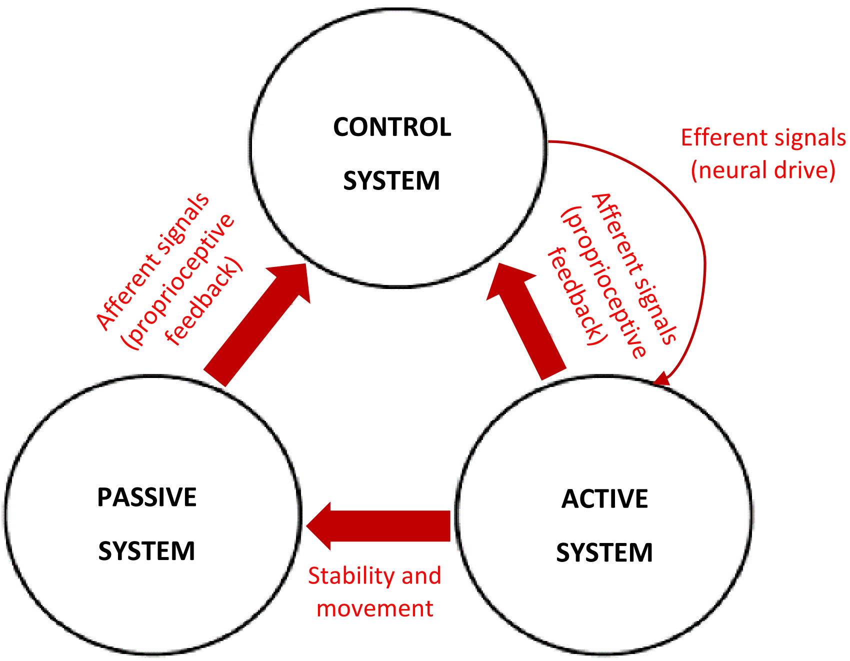


Figure 2.1 | The three systems regulating spinal function, adapted from Panjabi (1992a).

2.1.1 The passive system

2.1.1.1 Skeletal structures of the horse's back

The skeletal structures function to support the body structures, provide a stable attachment and insertion basis for the ligamentous and myofascial structures, and protect vital structures such as the spinal cord (Dyce, Sack and Wensing, 2002). The horse's back consists of 18 thoracic vertebrae, six lumbar vertebrae, and five fused sacral vertebrae, although individual anatomical variations have been reported (Jeffcott and Dalin, 1980; Spoormakers *et al.*, 2021). The 24 thoracolumbar vertebrae and the sacrum are connected by intervertebral discs and facet joints, which are held together by joint capsules, ligaments and myofascial structures. The back connects with the thoracic limbs via a synsarcosis, an articulation via muscular attachments only, and the pelvic limbs via the *sacroiliac* articulations. The thoracic limbs naturally carry more weight than the pelvic limbs – approximately 57% versus 43% at trot on a level surface, which is similar at halt (Dutto *et al.*, 2004) – and can be compared with a strut structure, being efficient in resisting compression, while the pelvic limb acts like a spring, being efficient in generating the locomotory impulsion (Clayton and Hobbs, 2019). Furthermore, the thoracic vertebrae articulate bilaterally with the 18 ribs, with the eight most cranial ribs having direct cartilage attachments to the horse's sternum, the 'true ribs', and ribs 9-18 being connected to the sternum via the costal arch, the 'false ribs', bilaterally. Together with the ribcage and the pelvis, the horse's back forms the horse's trunk (see Figure 2.2), which continues into the cervical spine at cervicothoracic levels C7 and T1 via facet joints and an intervertebral disc. An overview of the articulations of the back is given in Table 2.1.

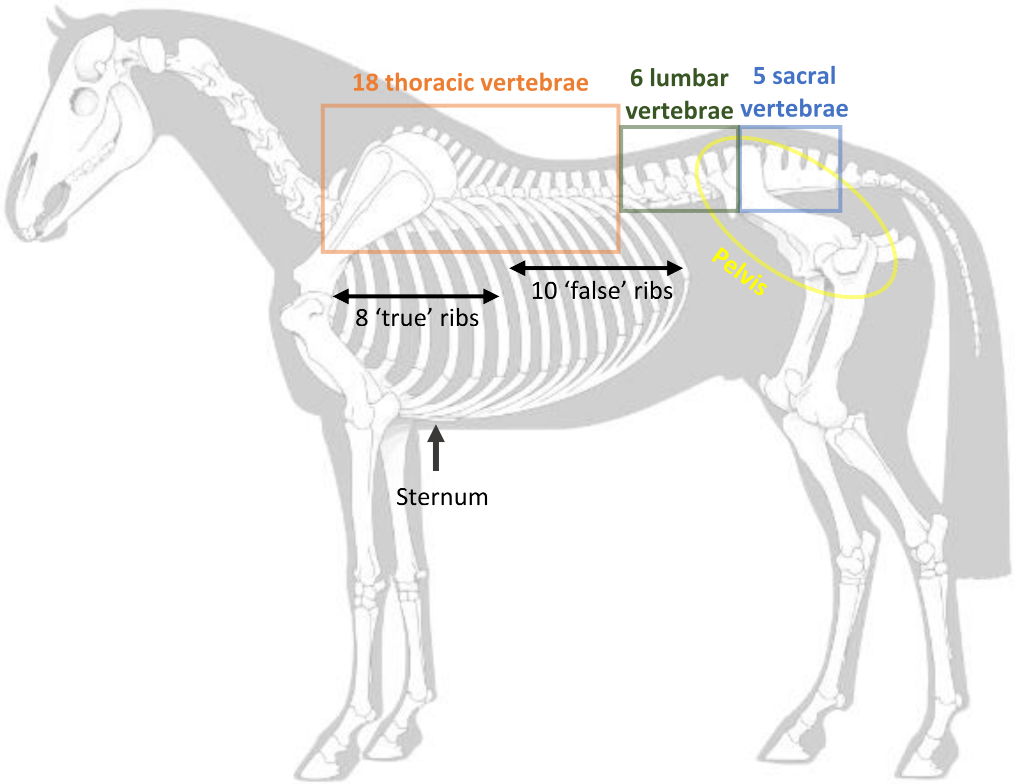


Figure 2.2 | The skeletal structures of the horse's trunk.

Table 2.1. Articulations of the horse's back, adapted from Jeffcott, Kidd and Bainbridge (2018).

Region	Articulation type	Articulations	N°
Thoracic			
	Synovial	Facet joints	1 cranial and caudal, bilaterally
	Synovial	Costovertebral joints	1 cranial and caudal, bilaterally
	Synovial	Costotransverse joints	1 bilaterally
	Fibro-cartilaginous	Articulation with the intervertebral discs	1 cranial and caudal
	Synsarcosis	Articulation with scapula	1 bilaterally
Lumbar			
	Synovial	Facet joints	1 cranial and caudal, bilaterally
	Synovial	Intertransverse joints	1 cranial and caudal, bilaterally*
	Fibro-cartilaginous	Articulation with the intervertebral discs	1 cranial and caudal
Sacral			
	Fusion	Facet/ intertransverse joints	None**
	Fibro-cartilaginous	Articulation with the intervertebral discs	1 cranial
	Synovial	Sacro-iliac joints	1 bilaterally

** Between the 2-3 most caudal lumbar vertebrae only, ** Only a synovial facet and intertransverse joint bilaterally with the most caudal lumbar vertebra.*

Defined by the length and direction of the vertebrae's dorsal spinous processes, the horse's back naturally follows a lordotic (hollow) curvature in the thoracic spine and a kyphotic (convex) curvature in the lumbosacral spine, as can be seen in Figure 2.2. The dorsal spinous processes angle dorsocaudally up to the anticlinal vertebra, the vertebra with an upwards-directed dorsal spinous process, which is typically located at thoracic level T15, ±1 spinal level (Jeffcott, Kidd and Bainbridge, 2018). Caudal from the anticlinal vertebra, the dorsal spinous processes angle dorsocranially up to sacral level, where the spinous processes' orientation changes to dorsocaudally again. The lowest point of the horse's back is located between thoracic levels T12-T14 which coincides with the lowest point of the saddle, generally placed between thoracic level T6 and lumbar level L1, and with the region where the rider is seated (Clayton, 2004).

Defined by the spinal morphological characteristics, the back segments allow movement in the three anatomical planes: flexion-extension in the median plane, lateral bending in the dorsal plane, and axial rotation in the transverse plane. As established in in-vitro studies, the ranges of motion (ROM) available between the back segments, the physiological ROM, differ between the different back segments and within the different planes (see Figure 2.3). The flexion-extension ROM is most prominent between thoracic segments T1-T2 and at the lumbosacral junction while the lateral bending and axial rotation ROM are most prominent between thoracic levels T10-T13, with the lateral bending ROM decreasing to minimal ranges in the caudal lumbar region (Townsend, Leach and Fretz, 1983). These physiological differences reflect the differentiated morphological characteristics of the facet joints, dorsal spinous processes, and intervertebral discs at the different spinal levels. At thoracic levels T1-T2, the facet surfaces are angled approximately 45 degrees and the spinous processes are short. Between thoracic levels T2-T16, the facet surfaces are orientated more horizontally whilst more vertically in the caudal thoracic and lumbar back regions, and the spinous processes elongate between thoracic levels T2–T8 after which they decrease until approximately the anticlinal vertebra, only slightly increasing again from there until the most caudal lumbar vertebra (Jeffcott, Kidd and Bainbridge, 2018). The intervertebral disc size is bigger at thoracic level T1-T2 compared to the other thoracolumbar levels and biggest at the lumbosacral junction (Townsend and Leach, 1984). Moreover, the transverse processes of the thoracic vertebrae are short in size and articulate with the ribs via the costotransverse joints, while they are notably larger and flattened horizontally in the lumbar region, articulating or fused via intertransverse joints in the caudal lumbar segments and with the sacrum, which limits the lateral bending ROM in this region (Jeffcott, Kidd and Bainbridge, 2018). While based on in-vitro experiments, these differentiations in the morphological and physiological characteristics between the spinal segments are key to understanding the biomechanics of a horse's back movement (Townsend and Leach, 1984), which is a central theme in this thesis.

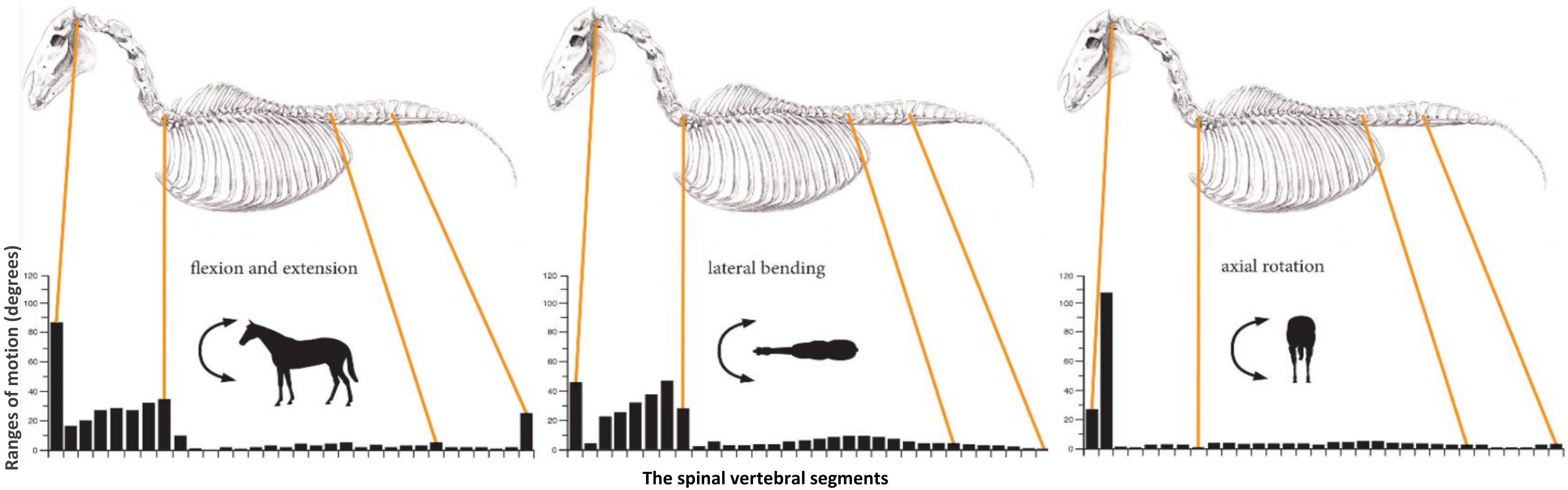


Figure 2.3 | The physiological ROM in the median (left), dorsal (middle) and transverse (right) plane of the spinal vertebral segments, as illustrated by Williams (2014). This figure is used with permission from the publisher.

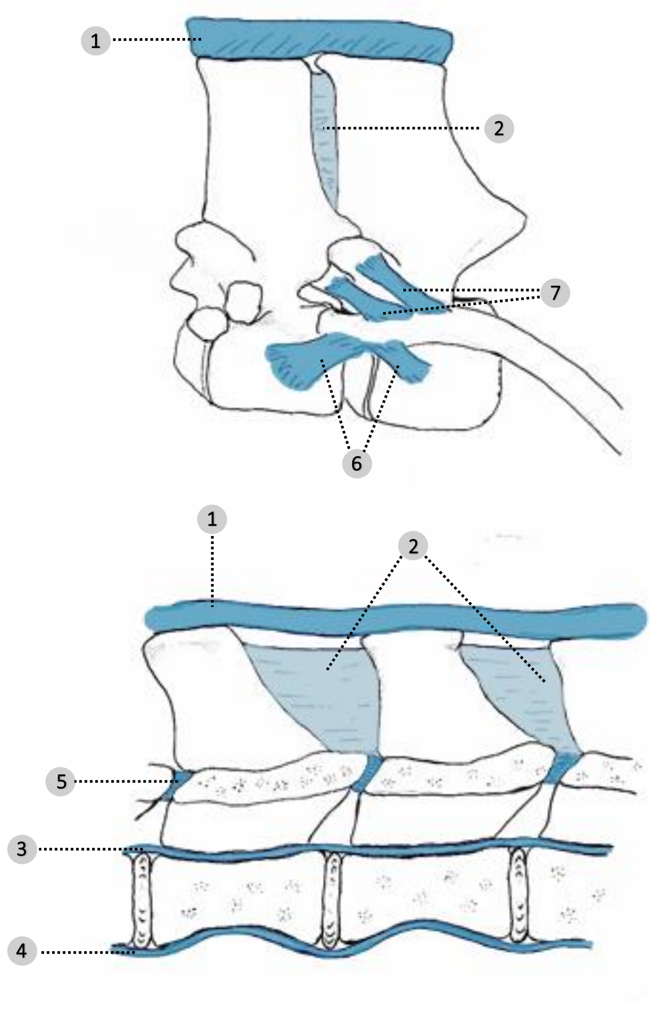
It must be considered that the joint movements in the different rotational directions are related. The laws by Fryette describe the coupling between lateral bending and axial rotation in the different spinal regions of the human body (Fryette, 1980). Several in-vitro (Townsend, Leach and Fretz, 1983; Denoix, 1999) and in-vivo (Faber *et al.*, 2000, 2001a) studies have investigated this coupling in the horse and reported a consistent heterolateral coupling between thoracic lateral bending and axial rotation; left lateral bending of the thoracic spine is coupled with an axial rotation towards the right (clockwise-rotation) and vice versa. The coupling between the thoracic lateral bending and axial rotation is most apparent between spinal segments T9 and T14, related to the morphology of the facet joints and ligamentous connections in this spinal region (Denoix, 1999). The same coupling of movements can be assumed in the lumbar spine, though the physiological ROM in these movement directions in this spinal region is very limited and therefore considered redundant (Denoix, 1999).

2.1.1.2 Ligamentous structures of the horse's back

The vertebral column is surrounded and connected by ligaments, built of fibrous connective tissue and providing passive support to the vertebrae while limiting excessive joint ROM. Ventrally, the horse's back segments are supported by the strong ventral longitudinal ligament *(lig. longitudinale ventrale)*, originating from the ventral side of the vertebral body at thoracic level T10 and inserted at the ventral side of the vertebral body at sacral level S1 (Jeffcott and Dalin, 1980). The ventral longitudinal ligament restricts extension and rotational movements in the horse's back, which is more pronounced in the lumbar region considering that the ligament starts narrow in the mid-thoracic region and increases in thickness in a cranio-caudal direction (Denoix, 1999). The cranial thoracic region lacks ventral ligamentous support, contributing to the prominent flexion-extension ROM in this region, and only limited ventral ligamentous support is present in the mid-caudal thoracic region, which is the spinal region that is directly loaded by a saddle and rider. This observation indicates that the ribcage as well as the active structures play an important role in withstanding extension forces in the thoracic region.

The longitudinal ligament can also be found dorsally, referred to as the *lig. longitudinale dorsale*, running across the dorsal side of the thoracolumbar vertebral bodies up to the sacrum and limiting their flexion movements (Denoix, 1999). Other ligaments stretching across the back segments dorsally are the flavum (*lig. flavum*)*,* interspinous *(lig. interspinalia*)*,* and supraspinous (*lig. supraspinale*) ligaments, which contribute to the role of the dorsal longitudinal ligament in controlling flexion movements and providing intervertebral stability to the horse's back (Jeffcott, Kidd and Bainbridge, 2018). The ligament flavum stretches between the thoracolumbar vertebral arches up to the sacrum, while the interspinous ligament runs between the dorsal spinous processes of all thoracolumbar segments, and the supraspinous ligament, a continuation of the funiculus part of the nuchal ligament in the neck region, runs between the tops of the dorsal spinous processes of all thoracolumbar segments (Jeffcott and Dalin, 1980). The interspinous and supraspinous ligaments are missing at the lumbosacral junction, contributing to the prominent physiological joint ROM at this level. The interspinous ligament demonstrates an oblique crossing arrangement of the fibres and is closely associated with the myofascial fibres of the *multifidus* and *longissimus* musculature, restricting distractive and rotational forces on the spine (Ehrle *et al.*, 2017). The supraspinous ligament is the strongest in the cranial thoracic region, which is related to its wider dimensions and more elastic properties in this region (Jeffcott, Kidd and Bainbridge, 2018). The ligament is closely associated with the thoracolumbar fascia and its fibres merge with those of the interspinous ligament, thereby also playing an important role in transmitting forces between the myofascial structures and the thoracolumbar vertebrae (Ehrle *et al.*, 2017). The interspinous and supraspinous ligaments have a dense sensory innervation, which explains the clinical pain symptoms seen in horses with impinging dorsal spinous processes (Ehrle *et al.*, 2017). The number of dorsal ligaments in contrast to the ventral ligaments in the back might relate to their collective function to control the dorsoventral gliding of the vertebrae, which has higher degrees of freedom into flexion than into extension (Denoix, 1999).

Laterally, the vertebral segments are supported by the costotransverse (*lig. costotransversarium*) and costovertebral (*lig. capitis costae radiatum* or *costovertebrale*) ligaments at thoracic level and by the *lig. intertransversaria* at lumbosacral level. The costotransverse ligament originates from the rib tubercle and inserts at the transverse process of its articulating thoracic vertebrae, whilst the costovertebral ligament runs between the rib head and the vertebral body of its articulating thoracic vertebrae, having a stabilising effect on the articulations between the thoracic vertebrae and the ribs (Jeffcott, Kidd and Bainbridge, 2018). The intertransverse ligament runs between the transverse processes of adjacent lumbar vertebrae up to the sacrum, limiting the amount of lateral bending ROM in the lumbosacral region, as well as the flexion-extension ROM at the lumbosacral junction (Denoix, 1999). An illustration of the ligamentous structures supporting the horse's back is shown in Figure 2.4.



1. Supraspinous ligament
2. Interspinous ligament
3. Dorsal longitudinal ligament
4. Ventral longitudinal ligament
5. Ligamentum flavum
6. Radiate ligament of head of rib
7. Costotransverse ligament

Figure 2.4 | The ligamentous structures of the vertebral column at thoracic levels T17-T18 from a side view (on top) and a cross-sectional side view (below).

2.1.2 The active system

The muscular anatomical structures form the active system of the horse's back, which can both facilitate and stabilise movement. The type of muscle contraction and the muscle's architecture influence the eventual movement outcome. A muscle contraction can either be concentric, isometric, or eccentric. The muscle fascicle length shortens during a concentric contraction, whilst it remains constant during an isometric contraction and lengthens during an eccentric contraction. Concentric contractions generate movement, whilst eccentric contractions counteract the movement (Radák, 2018). Muscle contractions are caused by the interaction between actin and myosin filaments, which are part of the muscle fibres. Three muscle fibre types exist: type I, IIA, and IIB. Muscles closer to the vertebral column have a higher concentration of type I fibres and fulfil a spinal stabilising role, whilst the more superficially located muscles are predominantly built of type II fibres, producing movement and locomotion (Hyytiäinen *et al.*, 2014) – as originally established in human medicine (Ng *et al.*, 1998). The characteristics of each muscle fibre type are shown in Table 2.2.

Table 2.2. The characteristics of the muscle fibres (Type I, IIA, and IIB), adapted from Karp (2004).

Characteristic	Type I	Type IIA	Type IIB
Contraction time	Slow	Fast	Fast
Resistance to fatigue	High	Intermediate	Low
Activity used for	Aerobic	Anaerobic (long-term)	Anaerobic (short-term)
Force production	Low	High	Very high
Capillary density	High	Intermediate	Low

The muscular structures of the horse's back can be defined as hypaxial or epaxial muscles based on their location relative to the vertebral column; hypaxial muscles lie ventrally to the vertebral column and epaxial muscles dorsally. The hypaxial muscle group include the abdominal, *iliopsoas*, *longus colli pars thoracis*, and diaphragm muscles. The epaxial muscle group include the *erector spinae*, *multifidus*, *sacrocaudalis dorsalis*, and *gluteus medius* muscles.

2.1.2.1 Hypaxial back musculature

The abdominal muscles refer to the *rectus abdominis, obliquus externus* and *internus abdominis,* and *transversus abdominis* muscles, which originate from the sternum and ribs and insert onto the lumbar spine and pelvic bones (Grönberg, 2002), as shown in Figure 2.5. The abdominal musculature can shorten the ventral line of the horse's trunk by concentric contraction, inducing flexion in the back segments when contracting bilaterally and lateral bend when contracting unilaterally. Working eccentrically and together with the epaxial musculature, the abdominal muscles control the inertially driven spinal movements during equine trot, and to a lesser extent walk, locomotion, as measured with surface electromyography (EMG) of the *rectus* and *obliquus internus abdominis* muscles (Zsoldos *et al.*, 2010; Kienapfel *et al.*, 2018). In the ridden horse, the abdominal musculature plays a vital role in controlling the effect of saddle and rider on the horse's back, inducing a more extended posture in the horse (Clayton, 2016a). Moreover, the abdominal muscles contribute to the efficiency of the mechanical coupling between the ventilatory and locomotory cycles in the horse, with flexion of the lumbosacral region induced by a contraction of the abdominal muscles during normal gait creating stiffness in the ribcage due to their anatomical attachments, supporting the expiration (Attenburrow and Goss, 1994).

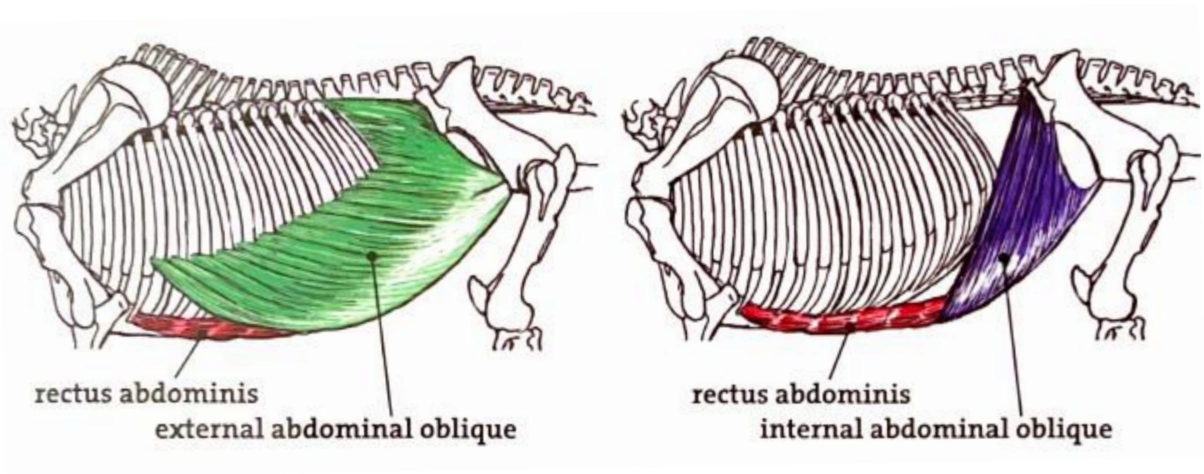


Figure 2.5 | The abdominal muscles, as illustrated by Stubbs and Clayton (2008). This figure is used with permission from the publisher.

The *iliopsoas* muscle group refers to the *psoas minor, psoas major*, and *iliacus* muscles. The *iliopsoas* muscles' skeletal attachments run from the sacrum, caudal thoracic (T16-18) and lumbar vertebrae, and ilium bone to the femur (Jeffcott, Kidd and Bainbridge, 2018). The *iliopsoas* muscles generate hip flexion, supported by the passive recoil of the pelvic limb tendons during locomotion (Payne *et al.*, 2005). Their muscular architecture demonstrate that the *psoas minor* has a primary postural stabilising role in the lumbopelvic region and the *psoas major* a locomotory role (Hyytiäinen *et al.*, 2014). Information on the ratio of muscle fibre type in the *iliacus* muscle inferring its role in spinal/ pelvic movement, is lacking from the equine literature. Due to the depth of the *iliopsoas* musculature, evaluation of the muscle's activity through means of EMG, using surface, fine-wire, or needle electrodes, is infeasible and only viable via rectal palpation, resulting in little evidence about the muscle group's role in the horse's locomotion.

The *longus colli pars thoracis* muscle is the only muscle directly supporting the cranial thoracic spine ventrally, which is the region of the back without ventral ligamentous structures. This muscle is a continuum of the *longus colli pars cervicis* muscles, supporting and flexing the cervical spine. The *longus colli pars thoracis* muscle spans over cervicothoracic segments C6-T6, attaching to the ventral surface of the vertebral segments and costovertebral joint capsules (Rombach, Stubbs and Clayton, 2014), although anatomical variations have been reported (May-Davis and Walker, 2015). According to the muscle architecture and rich proprioceptive innervation, the *longus colli pars thoracis* muscle is considered to be an important intersegmental vertebral stabilising muscle at the cervicothoracic junction while also producing flexion in this spinal region (May-Davis and Walker, 2015).

The horse's diaphragm has a sizeable tendinous centre and a muscular periphery, suspended from the sternum, rib 9 to 18 and the ventral vertebrae T15-L3 (Haussler, 1999a). The horse's diaphragm is the primary respiratory muscle, working mainly during inspiration and therefore being a crucial muscle when it comes to the exercise capacity of the horse (Fitzharris e*t al.,* 2020). This dome-shaped muscle predominantly consists of muscle fibres type I, elucidating the muscle's high resistance to fatigue and suggesting that the diaphragm could also be assigned a stabilising role in the horse's back mechanisms (Hyytiäinen *et al.*, 2014), as is supported by its tonic activity at halt (Hall *et al.*, 1991) and by human literature (Hodges *et al.*, 1997). The diaphragm is illustrated in Figure 2.6, together with the *iliopsoas*, *rectus abdominis, transversus abdominis*, and *longus colli pars thoracis* muscles.

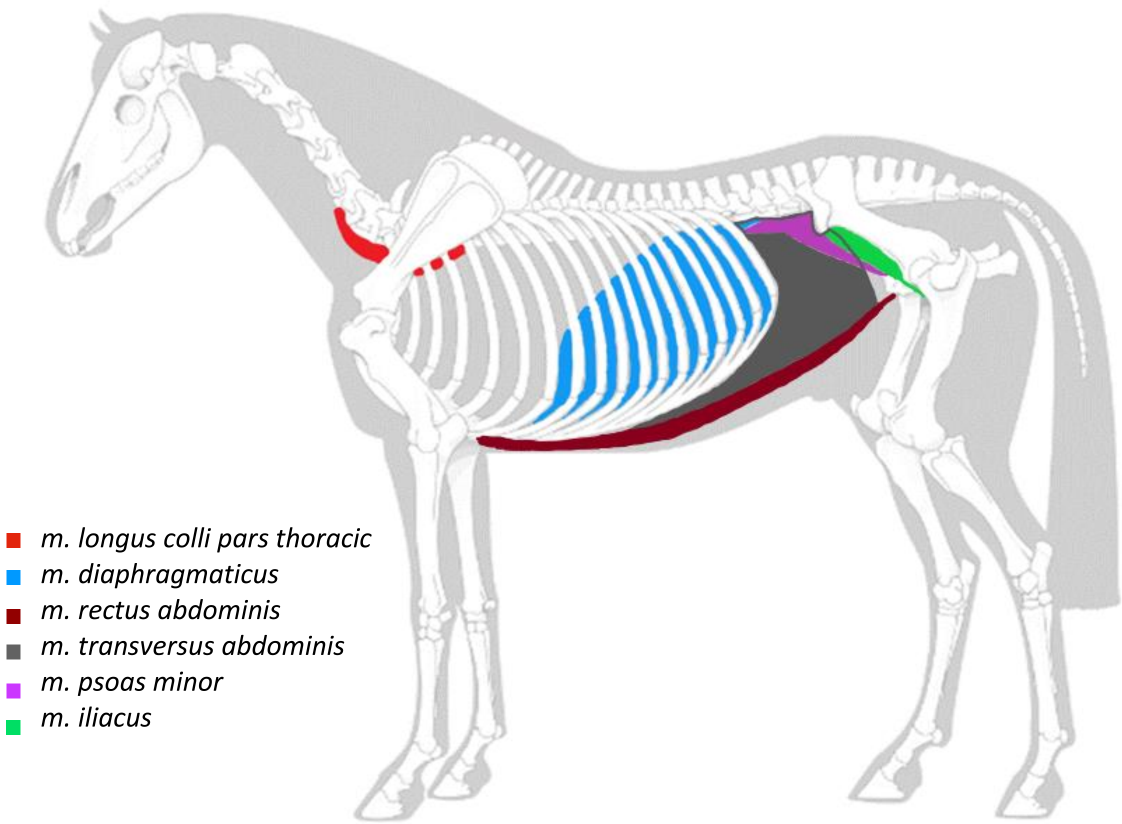


Figure 2.6 | The *iliopsoas, rectus and transversus abdominis*, *longus colli,* and diaphragm muscles.

2.1.2.2 Epaxial back musculature

The *erector spinae* musculature includes the *longissimus dorsi, spinalis,* and *iliocostalis* muscles (see Figure 2.7). Concentric contraction of the *erector spinae* musculature shortens the dorsal line of the horse's back, extending the spine, and laterally bends the back segments by unilateral contraction. The *longissimus dorsi* muscle is the largest muscle of the horse's back, originating from the cranial edge of the ilium wing, the sacrum and mammillary and spinous processes of the lumbar and thoracic vertebrae, and inserted at cranial thoracolumbar mammillary and spinous processes spanning over several vertebral segments, with its most cranial end inserting to the transverse processes of cervical vertebrae C4-C7 (Schultz and Elbrønd, 2018). The muscle architecture of the *longissimus dorsi* muscle varies between different spinal regions, with the thoracolumbar fascia splitting the muscle in a dorsomedial and ventrolateral portion from thoracic level T13 to the sacrum (Dietrich *et al.*, 2021). The differences in the muscle architecture, looking at the fascicle length, pennation angles, dimensions, and muscle fibre type composition, suggest a dominant role in generation locomotory forces, especially as a lateral flexor, of the *longissimus dorsi* in the cranial thoracic region while it plays an important role in both generating motion forces and stabilising the spine in the caudal thoracic and lumbosacral regions (Dietrich *et al.*, 2021). This differentiation was confirmed by in-vivo measurements, demonstrating a more dominant role in generating lateral bending in the mid-thoracic region (at T14) compared to the more caudal back segments, particularly at walk (Wakeling *et al.*, 2007), and eccentric, stabilising muscular activity during flexion and lateral bending of the spine in the caudal thoracic and lumbar regions (Robert, Valette and Denoix, 2001; Licka, Peham and Frey, 2004). The *spinalis* muscle sits on top of the *longissimus dorsi* muscle and its function is consequently closely associated with that of the *longissimus dorsi* muscle (Jeffcott, Kidd and Bainbridge, 2018). Given its location, the *spinalis* muscle is one of the muscles that is directly influenced by saddle fitting issues, transmitting saddle pressures to the underlying epaxial musculature. The *iliocostalis* muscle can be found laterally from the other *erector spinae* muscles, attaching to the posterior borders of the ribs and with the myofascial structures of the *longissimus dorsi* muscle in the mid-lumbar region (Schultz and Elbrønd, 2018), and has a predominant role in producing movement (Hyytiäinen *et al.*, 2014). Additionally, the *iliocostalis* muscle can also support expiration by retracting the ribs (Jeffcott, Kidd and Bainbridge, 2018).

The *multifidus* muscle originates from the vertebral spinous processes and vertebral laminae, crossing between one to five vertebral segments and inserts craniocaudally onto the mammillary processes and the lateral border of the sacrum (Schultz and Elbrønd, 2018). At the sacral level, the *multifidus* muscle continues as the *sacrocaudalis dorsalis* muscles (Stubbs *et al.*, 2006). The *sacrocaudalis dorsalis* muscle can be subdivided in two muscle portions; the *sacrocaudalis dorsalis lateralis* and the *sacrocaudalis dorsalis medialis* muscles. The *sacrocaudalis dorsalis lateralis* muscle attaches from the last two-to-three lumbar vertebrae, and the *sacrocaudalis dorsalis medialis* muscle from the third sacral vertebra, inserting at the cranial coccygeal vertebrae (Schultz and Elbrønd, 2018). The muscle's architecture indicates a primary stabilising role of the *multifidus* muscle in the horse's back (Stubbs, 2011). The muscle fibre types of the *sacrocaudalis dorsalis medialis* muscle are predominantly type I fibres, whilst the *sacrocaudalis dorsalis lateralis* muscle has an equivalent ratio of type I and type II fibres, indicating that these muscles also have a stabilising role (Hyytiäinen *et al.*, 2014).

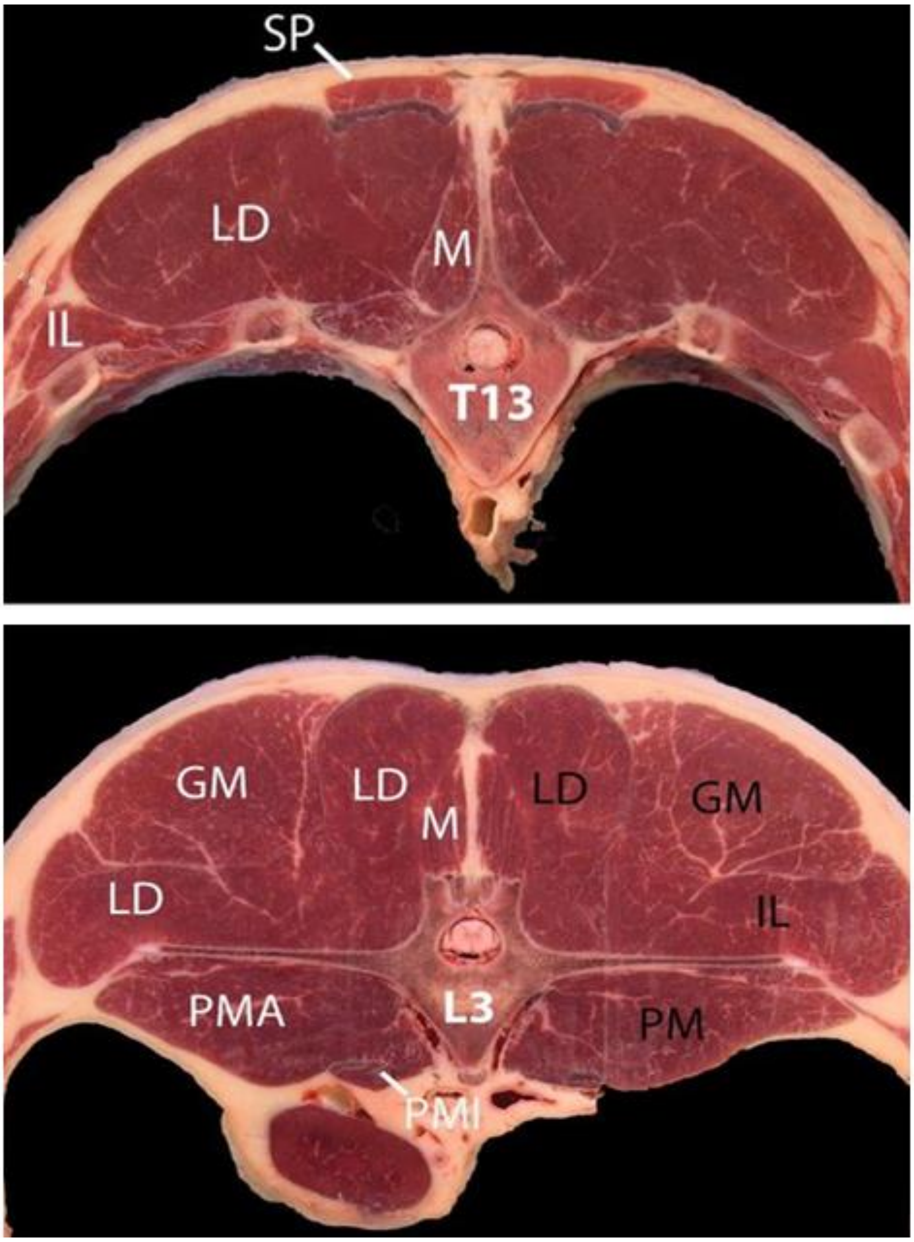


Figure 2.7 | A cross-sectional image of the epaxial musculature at thoracic (on top) and lumbar (below) level by Schultz and Elbrønd (2018). This figure is used with permission of the publisher. *Muscle abbreviations: IL = iliocostalis, LD = longissimus dorsi, SP = spinalis, M = multifidus, GM = gluteus medius, PMA = psoas major, PMI = psoas minor, PM = psoas*.

The *gluteus medius* muscle has a wide origin from the gluteal aponeurosis covering the *longissimus dorsi* muscle and reaching up to lumbar level L1 (better known as the gluteal tongue), and the ilium and inserts at the greater trochanter of the femur (Grönberg, 2002). Its locomotory function is to extend and abduct the hip (Payne e*t al.,* 2005). Given its muscle fibre type composition, the more superficial portion of the g*luteus medius* muscle is thought to play a prominent role in generating movement, whilst its deeper portion, which is closely connected to the l*ongissimus dorsi m*uscle via the gluteal tongue, can also have a stabilising influence on the lumbosacral spine (Hyytiäinen e*t al.,* 2014). Weakness of the g*luteus medius m*uscle can result in insufficient stabilisation of the pelvis during one-legged standing where the pelvis drops heterolateral, referred to as a positive Trendelenburg sign in the human literature (Hardcastle and Nade, 1985).

2.1.2.3 The myofascial system

While the insertions and origins of the back muscles are described above, more recent dissection studies have pointed out that part of those fibre attachments continue in the adjected myofascial structures, forming a continuum of myofascial tissue rather than a collection of isolated muscles (Elbrønd and Schultz, 2014, 2015, 2021). Myofascial structures refer to the fascia surrounding the muscles, whilst fascia is an umbrella term for the connective tissue with different interdependent layers throughout the body, from the epidermis to the bone (Bordoni and Myers, 2020). Appreciating the emerging nature of this research field, it is already acknowledged that the myofascial structures, together with the other musculoskeletal structures, play an important role in the way forces and tensions are distributed within the musculoskeletal system, referred to as the tensegrity of the body, via its elastic, proprioceptive, and even contractive properties (Elbrønd and Schultz, 2015).

2.1.3 The control system

The anatomical structures of the control system include the mechanoreceptors within the active and passive musculoskeletal structures, the vestibular system, the afferent and efferent neurons in the peripheral nervous system, and the movement-related structures in the central nervous system – being primarily the motor cortex and the cerebellum in the horse (Dyce, Sack and Wensing, 2002). The central nervous system receives sensory and proprioceptive feedback from the peripheral nervous system via the afferent neurons, whilst the central nervous system responds by activating efferent motoneurons innervating the muscles (McGowan and Hyytiäinen, 2017), the neural drive. The mechanoreceptors in the active musculoskeletal structures are also called proprioceptors, which include the muscle spindles and Golgi tendon apparatus, whilst these in the passive musculoskeletal structures include the Ruffini, Pacinian, Mazzoni, and Golgi joint and fascia receptors. The muscle spindles sense a muscle’s length, including the velocity of change in muscle length, whilst the Golgi tendon apparatus sense the active muscle tension (Roijezon, Clark and Treleaven, 2015). The mechanoreceptors in the passive musculoskeletal structures are stimulated by tension and compression loads during joint ROM (Roijezon, Clark and Treleaven, 2015). The control system's role in the functioning of the spine is thus to regulate muscular activity based on proprioceptive feedback, referred to as neuromotor control, securing optimal function and preventing injuries of the surrounding structures (McGowan and Hyytiäinen, 2017). For example, muscle activity will be stimulated when the muscle spindles sense increasing muscle length and muscle activity will be inhibited when the Golgi tendon apparatus senses high levels of muscle tension, preventing high levels of traction and tension in the involved structures (Roijezon, Clark and Treleaven, 2015).

Alongside the above-described neural circuit between the peripheral and central nervous system generating and controlling movement patterns, the output signals of the locomotory system are determined by intraspinal neural circuits called central pattern generators (CPGs). The CPGs can generate basic rhythmic motor patterns, such as cyclical walking patterns, even in the absence of peripheral afferent input (Brown, 1914). While empirical research studying CPGs in the horse is missing, the architecture of CPGs is thought to be the same for all quadrupeds and has already been established in other animals, such as cats and mice (Golubitsky *et al.*, 1999). The CPGs have been established to coordinate simple rhythmic patterns observed in quadrupedal locomotion, including walk, trot, and pace (Golubitsky *et al.*, 1999). Therefore, the CPGs are considered integral to the control system of the horse's locomotor apparatus, in particular to the generation of the rhythmic locomotory patterns of the limb movement (Clayton, 2016b).

2.1.4 So what is optimal spinal function?

Panjabi (1992a) described normal spinal function as the capacity to '*provide sufficient stability to match the instantaneously varying stability demands due to changes in spinal posture and static and dynamic loads'* (p. 384). Adhering to the definition by Panjabi (1992a), poor spinal function in the horse has been described as the loss of the capacity to control the ongoing movement patterns, resulting in micromotions exceeding the physiological ROM and predisposing the surrounding soft tissue structures to excessive strain and the development of injury (Clayton, 2012; McGowan and Hyytiäinen, 2017). The physiological joint ROM defines the movement available in the joint around the neutral joint position, where there is minimal resistance to movement (Haussler, 2016). Joint movement beyond the physiological zone, the paraphysiologic zone, requires more muscular engagement or force, crossing the so-called elastic barrier, whilst movement beyond this zone crosses the anatomical barrier of the joint movement, the pathologic zone, which is caused by excessive forces and can result in acute or chronic lesions of the surrounding musculoskeletal structures (Haussler, 2016). The different movement zones in a joint are shown in Figure 2.8.

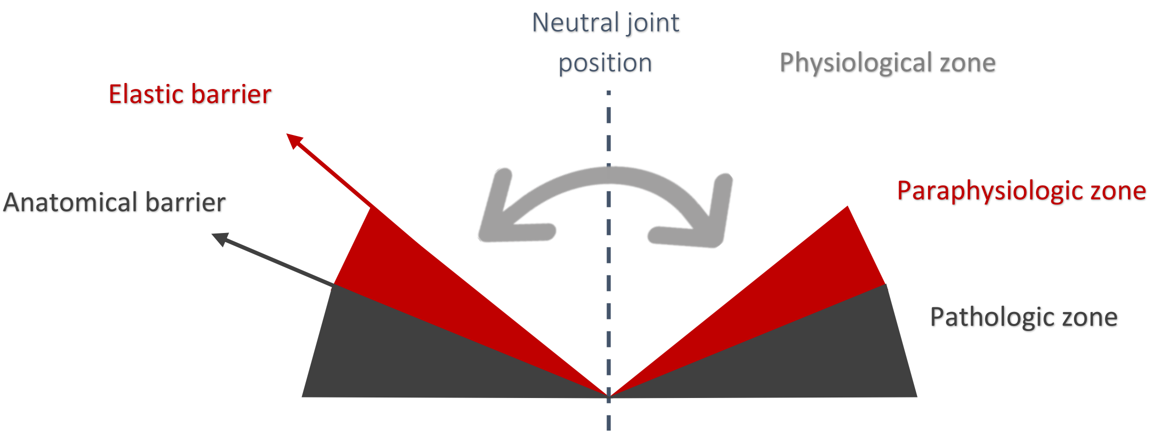


Figure 2.8 | A graphic representation of the joint mechanisms in relation to the zones of joint movement, adapted from Haussler (2016).

While the passive structures provide passive resistance to joint movement, defining the elastic barrier, it is the role of the active structures to control the joint movement within the physiological zone. In particular, this role is assigned to the stabilising musculature, the deep muscles predominantly built of type I muscle fibres (Hyytiäinen *et al.*, 2014). In human literature, clinical symptoms of back pain have been associated with poor neuromotor control in terms of delayed or decreased onset of muscular activity in the spinal stabilising musculature, in particular of the *transversus abdominis* (Hodges and Richardson, 1998, 1999) and *multifidus* muscle (MacDonald, Moseley and Hodges, 2009, 2010). When persistent, atrophy in the stabilising musculature will occur due to the neurogenic deactivation initiated by the presence of pain (Javanshir *et al.*, 2011), which will result in a decrease in the capacity to maintain the intervertebral neutral zones within the physiological zone and allow increased levels of strain on the surrounding structures and the risk of injury development, also referred to as spinal instability (Panjabi, 1992b). To compensate for the lack of stability, increased muscular activity of the superficial muscles is observed (Moseley and Hodges, 2005; MacDonald, Moseley and Hodges, 2010), referred to as muscular bracing (Van Dieën *et al.*, 2019). The more superficially located muscles are less efficient in stabilising movement and providing postural stability considering they are predominantly built of type II muscle fibres which rapidly fatigue, causing muscle soreness and pain, and the cocontraction of those muscles comes with the cost of spinal 'stiffness', causing higher tissue loading (Van Dieën *et al.*, 2019). Whilst stability is a primary component for optimal spinal function, the mobility component is thus of equivalent importance.

Disregarding the differences in the anatomy of quadrupeds versus bipeds, with the horse's back being orientated horizontally, the muscular architecture and neuroanatomy of the equine and human stabilising spinal musculature have been found comparative (Stubbs *et al.*, 2006; Stubbs, 2011), and it has been suggested that similar pathophysiological mechanisms occur in the development of back dysfunctions in the horse (Stubbs, 2011; Hyytiäinen *et al.*, 2014; McGowan and Hyytiäinen, 2017). Furthermore, associations have been found between the presentation of back pain (McGowan *et al.*, 2007) or spinal lesions (Stubbs *et al.*, 2010) and the cross-sectional area of the *multifidus* muscle, revealing asymmetries and reductions in the size of the muscle's cross-section area close to the pathological back region. As in human medicine, it is thought that the *transversus abdominis* (Clayton, 2012, 2016a) and diaphragm (Hyytiäinen *et al.*, 2014) muscles are of similar clinical importance as the *multifidus* muscle, which also demonstrate similarities in the muscles' architecture to the human's. Therefore, muscle function of the spinal stabilising musculature is considered to play a key role in promoting spinal functioning in the horse (Clayton, 2016a).

As aforementioned in the context of human medicine, mobility is of equivalent importance in optimal spinal function as stability, which is likewise in the equine spine. The equine back has long been considered a rather rigid and static structure (Van Weeren, 2006), which is true to some extent given the small amounts of movement available between back segments in the different planes, as described in Section 2.1.1. However, the small amounts of intersegmental motion are collectively capable of producing considerable amounts of regional vertebral motion (Haussler, 2018a) and are fundamental to allow efficient force transmission (Peham and Schobesberger, 2004). Using biomechanical simulations, it was found that local spinal stiffness, simulated as increased forces acting upon the thoracolumbar spine by the *longissimus dorsi* muscle representing increased muscle tone, results in higher internal forces and torques in the thoracolumbar spine in comparison to those induced by a rider's load at all gaits (Peham and Schobesberger, 2004). Clinically, spinal stiffness in the horse will progress in musculotendinous contractures and intra- and peri-articular adhesions and can advance into the development of osteoarthritis and even ankylosis of the concerning segments (Haussler, 1999b). Furthermore, reduced mobility in one vertebral segment triggers compensatory hypermobility, and eventually instability, in adjacent vertebral segments (Haussler, 1999b). Stiffness in the equine spine will thus alter the spinal tensegrity and increase the risk of injury development to a similar extent as instability would. Additionally, the ridden horse requires sufficient levels of spinal mobility to be able to perform sport-specific motor tasks while accommodating the rider's load (McGowan and Hyytiäinen, 2017) and suppleness of the back is a favoured performance characteristic (Hobbs *et al.*, 2020). It is also commonly believed that it is more difficult for a rider to absorb the movement of the horse when the horse is holding its back stiffly (Greve and Dyson, 2013a). It can be concluded that optimal spinal function in the ridden horse refers to the capacity to provide sufficient stability and mobility to match the biomechanical demands of the horse's spine when loaded with a saddle and rider while performing sport-specific motor tasks.

2.2 Functional assessments of the horse's back

Within equine medicine, a distinction is made between pathoanatomical and functional assessments (McGowan and Cottriall, 2016). Pathoanatomical assessments are more commonly used in veterinary practice to reach a clinical diagnosis, whilst functional assessments are used in physical and rehabilitation practice to reach a functional diagnosis (Haussler *et al.*, 2021a). A functional diagnosis refers to the evaluation of the functioning of the musculoskeletal structures during a provoking test or normal gait, including the evaluation of pain, mobility, and muscle function (Goff, 2016). Although these dysfunctions are often symptoms of a pathoanatomical diagnosis, they can also occur in subclinical conditions (Haussler, 1999b, 2000), implying that they can occur in horses considered injury-free and in active work, being the targeted population in this thesis.

While functional assessments are standard in equine clinical practice, the reported outcome measures of a horse's musculoskeletal functioning often lack objectivity (Tabor *et al.*, 2018), limiting the reliability of functional measures of the horse's back in the equine research field. In a Delphi study by Tabor *et al.* (2020), consensus on several outcome measures that are considered to be valid and reliable to evaluate musculoskeletal function in the horse was gained, advancing standardised equine practice. The outcome measures reported by Tabor *et al.* (2020) that relate to the horse's back in specific, are measures of the horse's posture, thoracolumbar epaxial muscle tone and reactivity, and thoracic epaxial muscle size and asymmetry. Additionally, the use of the croup or 'rounding' reflex has been considered useful and valid for the functional assessment of flexibility in the horse's back (Licka and Peham, 1998) and is recognised in equine practice as an appropriate assessment of coordination in the horse's back (Haussler *et al.*, 2021b). The use of the aforementioned functional measures of the horse's back is discussed below.

2.2.1 The assessment of posture in the horse's back

Posture refers to the configuration, or alignment, between body segments (Jull *et al.*, 2015). Tabor *et al.* (2019) evaluated the reliability of postural measurements, i.e. the thoracolumbosacral angle, using side-view photographs taken from a large sample of horses (n=190). Excellent intra-rater reliability was found when horses were photographed in a standardised posture, i.e. standing square with a neutral head-neck posture (Tabor *et al.*, 2019). Using this method, the thoracolumbosacral angle has been found to relate to the prevalence of back pain in horses with (n=38) and without (n=33) back pain, suggesting that a more extended posture is associated with spinal dysfunctions (Tabor, Mann and Williams, 2018). Jo Paul, a Chartered Human and Equine Physiotherapist, suggested that the horse's posture can be categorised according to three postural types based on their spinal alignment and overall muscle balance; the sway-backed or lordotic type, the straight-backed or herring gutted type, and the S-backed or lumbar roach type (Paul, 2016), which are shown in Figure 2.9.

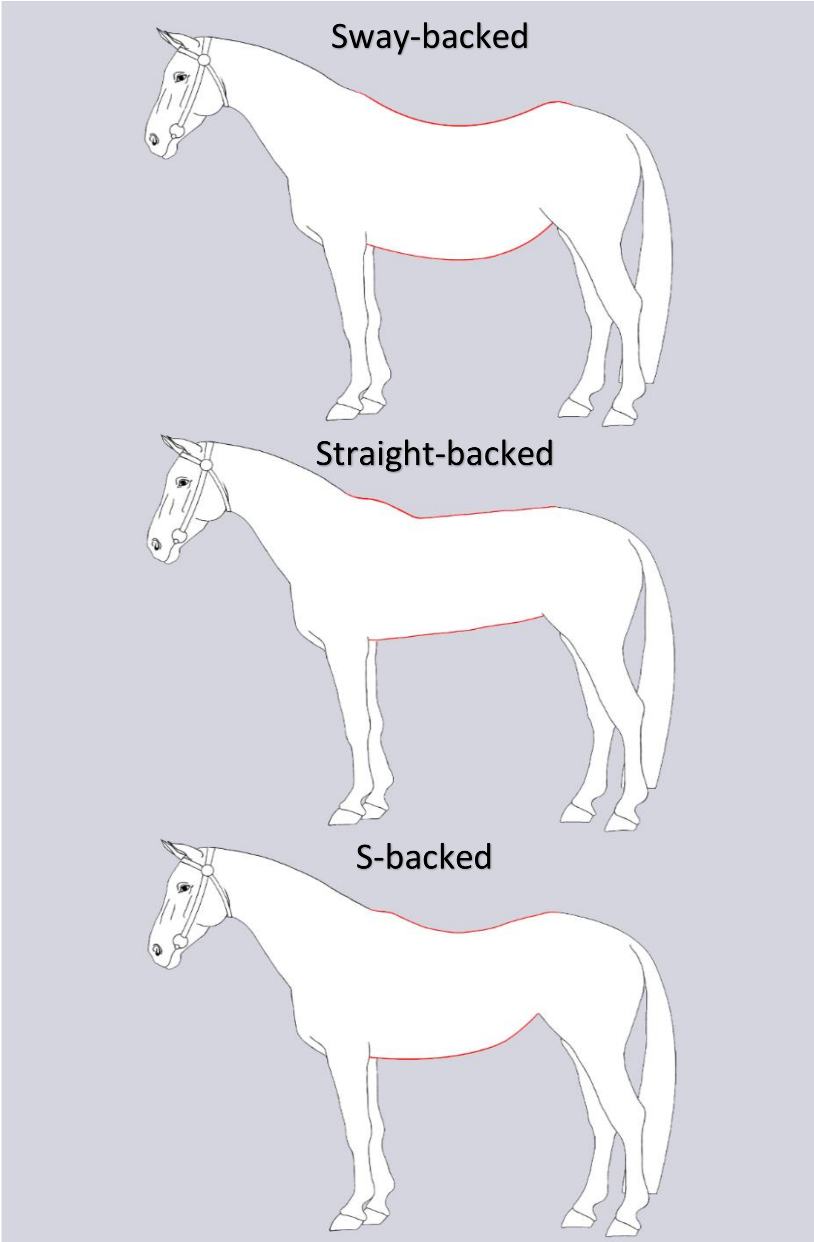


Figure 2.9 | An illustration of the three static postural types: the sway-backed (on top), straight-backed (in the middle), and S-backed (at the bottom) types, by Sci-llustrate.

Paul (2016) suggested that horses with a sway-backed postural type tend to have lengthened and hypotonic abdominal musculature, as is seen in human subjects (Kendall *et al.*, 2005, p. 67 and 72; Reeve and Dilley, 2009; Czaprowski *et al.*, 2018), and lack lateral bending and axial rotation ROM in the lumbar spine, as previously identified in horses with a greater ventral thoracic curvature (Johnston *et al.*, 2002). Horses with a straight-backed postural type typically show hypertonic abdominal and epaxial musculature, as is seen in human subjects (Kendall *et al.*, 2005, p. 68; Czaprowski *et al.*, 2018), whilst horses with an S-backed postural type are prone to restricted lumbosacral pitch ROM, as previously associated with a flatter lumbosacral angle (Johnston *et al.*, 2002). Trained to use Paul's classifications of postural type, excellent agreement (mean $\kappa=0.893$, $p<0.001$) was found between Equine Physiotherapists (n=3) evaluating the postural type of sport horses (n=21) based on a side-view photograph (Tabor *et al.*, 2023). These findings suggest that the evaluation of a horse's posture, i.e. thoracolumbosacral angle, and postural type using side-view photographs (see Appendix A.I) can be used as a valid and reliable functional assessment of the horse's back.

2.2.2 The assessment of muscle tone and reactivity in the horse's back

Muscle tone and reactivity, indicative of muscle-related pain, can be evaluated by a palpatory assessment or using pressure algometry (Tabor *et al.*, 2020). Palpation plays an essential role in the clinical assessment of musculoskeletal dysfunctions, but the interpretation of its outcome is highly subjective (De Heus *et al.*, 2010). Therefore, standardising the palpation technique and outcome scores is essential. Merrifield-Jones, Tabor and Williams (2019) constructed a scale to score the muscle tone and reactivity based on palpation (see Table 2.3), which has excellent interrater reliability (ICC=0.90) for the assessment of the horse's thoracolumbar epaxial musculature. The standardised protocol of the palpation is performed using the dominant hand's index finger (see Figure 2.10), with the horse standing square on a level surface. Pressure algometry provides an objective alternative to assess the mechanical nociceptive thresholds in the horse's thoracolumbar epaxial musculature (Haussler and Erb, 2006; Sullivan, Hill and Haussler, 2008; De Heus *et al.*, 2010), which is negatively correlated with the palpation scores of pain and muscle tone – higher pain and muscle tone scores relate with lower mechanical nociceptive values (Varcoe-Cocks *et al.*, 2006; De Heus *et al.*, 2010). However, pressure algometry measures are thought to lack reliability in comparison with manual palpation (Merrifield-Jones, Tabor and Williams, 2019) and can induce sensitivity or habituation to the pressure stimulation (De Heus *et al.*, 2010; Merrifield-Jones, Tabor and Williams, 2019). These considerations can aid decision-making when assessing muscle tone and reactivity in the horse's back.

Table 2.3. The scoring scale used for the evaluation of the muscular tone and reactivity, according to Merrifield-Jones, Tabor and Williams (2019).

Score	Description of score
0	Soft, low tone
1	Normal
2	Increased muscle tone but not painful
3	Increased muscle tone and/ or painful (slightly associated spasm on palpation, no associated movement)
4	Painful (associated spasm on palpation with associated local movement, i.e., pelvic tilt, extension)
5	Very painful (spasm plus behavioural response to palpation, i.e., ears flat back, kicking)

Figure 2.10 | A palpatory assessment of muscle tone and reactivity of the thoracic epaxial musculature, exerting pressure on the muscle using the dominant hand's index finger.

2.2.3 The assessment of muscle size and asymmetry in the horse's back

Muscle size and asymmetry of the horse's thoracic epaxial musculature has previously been measured in the horse using ultrasonography (Stubbs *et al.*, 2011; Tabor, 2015) and a FlexiCurve ruler (Greve, Murray and Dyson, 2015; Tabor, 2015). The use of ultrasonography to measure muscle size, in terms of the muscle's cross-sectional area, of the *multifidus* (McGowan *et al.*, 2007) and *longissimus* (Abe, Kearns and Rogers, 2012) muscles has good-to-excellent reliability (ICC = 0.83 and 0.95-0.98, respectively). However, ultrasonographic measurements require a trained ultrasonographer and the associated materials and software. The FlexiCurve ruler is a more accessible tool to measure epaxial musculature dimensions, though it can not specify the dimensions of the epaxial musculature isolated from each other nor from the underlying skeletal conformation. The FlexiCurve ruler is found to be a reliable tool to measure the horse's dimensions in the thoracic region with a measurement error of ±2 mm, but it is recognised that the measurements with the FlexiCurve ruler can be influenced by slight changes in the horse's posture at halt (Greve and Dyson, 2013b) and over an 8-hour time period due to postural changes (MacKechnie-Guire *et al.*, 2020a). The FlexiCurve ruler is to be placed on top of the spinal levels of interest (see Figure 2.17) in a horse standing squarely on a level surface. The practitioner then shapes the ruler around the horse's dorsum with moderate pressure and draws the ruler's outline onto an A2 graph paper. The horse's frontal thoracic width, quantified as the distance between the left and right extremes of the ruler's outline on the graph paper three and fifteen cm down the vertical, is used as an indication of the horse's back dimensions (Greve and Dyson, 2015).

The epaxial musculature dimensions have been associated with the presence of thoracolumbar osseous lesions, with a reduction in muscle size and more prominent muscular asymmetries observed in the region of the lesion (McGowan *et al.*, 2007; Stubbs *et al.*, 2010). On the other hand, an increase in the epaxial musculature dimensions has been associated with correct training methods and being ridden with correctly fitting saddles, and is thought to enable optimal spinal function (Greve and Dyson, 2015; Greve, Murray and Dyson, 2015). The assessment of a horse's epaxial musculature dimensions is thus recognised as another valid and reliable functional assessment of the horse's back, with the use of a FlexiCurve ruler being considered more accessible than the ultrasonography to quantify the horse's epaxial musculature dimensions.

Figure 2.11 | The use of a FlexiCurve ruler to measure the horse's thoracic epaxial musculature dimensions at thoracic level T8.

2.2.4 The assessment of flexibility and coordination in the horse's back

The horse's back flexibility can be assessed passively on a segmental level or actively on a regional level (Haussler *et al.*, 2021b). While the passive segmental flexibility evaluations are useful in equine clinical practice, they are mostly subjective and know a poor inter-rater reliability (De Heus *et al.*, 2010). Additionally, the validity of such evaluation in representing a horse's intersegmental flexibility is questioned considering the persisting postural muscular activity (Goff, 2016). The rounding reflex on the other hand, is considered a valid and reliable assessment to evaluate a horse's active regional dorsoventral flexibility (Licka and Peham, 1998). The practitioner performs the rounding reflex by applying firm digital pressure bilaterally along the intermuscular groove between the *biceps femoris* and *semitendinosus* muscles at a level lateral to the base of the tail (Haussler, 2018b), as depicted in Figure 2.12. For a valid test, the horse has to stand on a level surface and remain on four feet during the reflex. Normal thoracolumbosacral ROM allow a 2-4 cm elevation of the thoracolumbar junction (Haussler, 2018b), though the normal amount of spinal ROM differs between horses and the demonstrated ROM should be evaluated in the context of each horse's individual 'normal'. Haussler *et al.* (2020) developed a scale to standardise the subjective evaluation of the rounding reflex, scoring the horse's active spinal mobility, coordination, and core strength based on the movement quantity and quality (e.g. absent, controlled, jerky, or behavioural avoidance), and the horse's ability to hold the induced posture. The scale is provided in Table 2.4. While further research is still warranted to evaluate the reliability of this scale, it is considered a useful tool in the functional assessment of the horse's back flexibility and coordination.

Table 2.4. The scoring scale used for the evaluation of the rounding reflex, as described by Haussler *et al.* (2020).

Grade	Thoracolumbar functional response
0	No trunk elevation No reaction
1	≤ 1 cm trunk elevation Inconsistent response (uncoordinated, asymmetric) Not able to hold position
2	1-2 cm trunk elevation Coordinated spinal motion, epaxial muscle fasciculations Not able to hold position
3	2-3 cm trunk elevation Some epaxial muscle activation Able to hold position for 1-2 seconds
4	≥ 3 cm trunk elevation Complete rounding of trunk region, strong, bilateral epaxial muscle contraction Able to hold position indefinitely

Figure 2.12 | In comparison to a neutral posture at halt (on top), the rounding reflex stimulates the horse to elevate the trunk and flex the back (below).

2.3 Biomechanics of the horse's back

The horse's back is a complex biological spring and has to withstand the gravitational forces of its own mass alongside that of the saddle and rider while transmitting forces between the appendicular and axial skeleton. Several biomechanical models simplifying the complexity of the back biomechanics in the horse have been described. The Roman physician Galen (129-200 AD) compared the horse's back mechanics with the mechanics of a vaulted roof supported with limbs as four pillars. Zschokke's (1892) 'bridge' model replaced the vaulted roof concept, describing the horse's thoracolumbar vertebral bodies as a bridge's lower ledger, the *supraspinous* ligament as the bridge's upper ledger, the spinous processes and ligaments in between as smaller girders, and the limbs as two land abutments supporting the bridge. However, the models by Galen and Zschokke represent a static construction and did not consider the elastic properties of the spinal musculoskeletal structures. Today's most widely accepted model is Slijper's (1946) bow-and-string theory. The bow-and-string theory introduced the idea that the horse's vertebral column represents a bow and the abdominal musculature a string, with which it can operate the form of the bow. A tightened string will flex and 'round' the bow, whilst a slack string will extend and 'flatten' the bow.

While the bow-and-string model provides a valuable framework for conceptualizing the interplay between the vertebral column and the abdominal musculature (see Figure 2.13), it does not consider other 'strings' influencing the form of the vertebral column nor its form in the other anatomical planes. For instance, the shape of the vertebral column is influenced not only by the hypaxial abdominal musculature but also by the epaxial musculature. The bow-and-string model described by Slijper (1946) also does not include the couplings between the horse's thoracolumbar vertebral column and the cervical vertebral column nor with the appendicular skeleton, though these couplings are an integral component to the tensegrity of the horse's back. An in-vitro study previously demonstrated that flexing the neck provokes flexion in the thoracic spine by the tension it induces in the nuchal ligament (Denoix, 1999). The coupling between the movement of the appendicular and axial skeleton in a tetrapod implies that, without counteraction of the hypaxial and epaxial musculature, protraction of the thoracic limbs and retraction of the pelvic limbs induce extension in the thoracolumbar vertebral column, whilst flexion of the thoracolumbar vertebral column is induced by retracting the thoracic limbs and protracting the pelvic limbs (Gray, 1944). The interaction between the movement of the limbs and the shape of the thoracolumbar vertebral column, as presented in more recent models of the bow-and-string model (Van Weeren, 2004), is demonstrated in blue in Figure 2.13. However, the bow-and-string model with the interaction with the limbs integrated does not apply to the mechanics of the horse's back during normal locomotion, given that the movement of the limbs protract and retract successively rather than simultaneously (Faber *et al.*, 2000, 2001a).

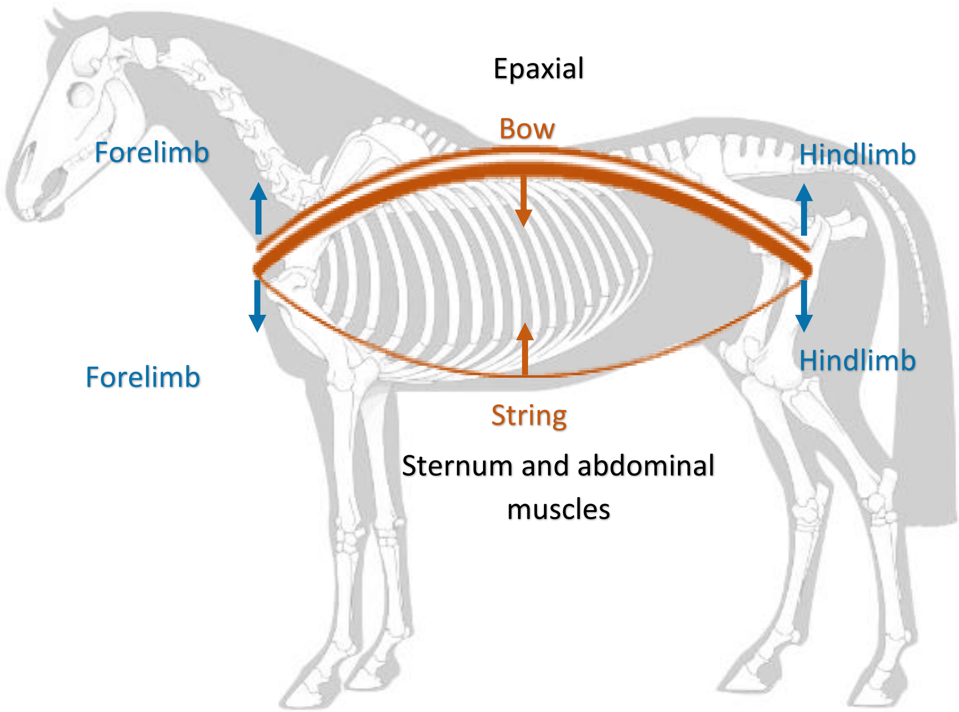


Figure 2.13 | The bow-and-string theory described by Slijper (1946), adapted according to Van Weeren (2004) to include the coupling with the limb movement in blue.

2.3.1 The horse's back biomechanics in locomotion

The horse's walk is a symmetrical four-beat gait without a suspension phase. During the walk, two cycles of flexion and extension occur in the horse's back and one cycle of lateral bending and axial rotation per stride. The peaks of the flexion movement at thoracic level T10 and sacral level S3 occur just before the mid-stance phases of the forelimbs and hindlimbs, respectively, coinciding with the peak and trough of the lateral bending and axial rotation cycles at these levels, with the latter two being heterolateral coupled (Faber *et al.*, 2000). The flexion-extension ROM are fairly constant going from the withers to the sacrum, while the lateral bending ROM are more prominent in the mid-thoracic region and the amount of axial rotation increases gradually towards the more caudal back segments, with the axial rotation overall being the most prominent back movement at the walk (Faber *et al.*, 2000). The walk represents an inverted pendulum mechanism, with the horse's centre of mass (CoM) reaching its highest point during the midstance phase of each limb, coinciding with the timepoint of the most potential and lowest kinetic energy (Clayton, 2016b). The inverted pendulum mechanism at the walk reduces the amount of muscular work required by exchanging potential and kinetic energy (Clayton and Hobbs, 2017).

The trot is a symmetrical two-beat gait with a suspension phase (Clayton and Hobbs, 2017). As in walk, two cycles of flexion and extension occur in the thoracolumbar spine and one cycle of lateral bending and axial rotation per stride at trot. The flexion peaks coincide with the mid-stand phases in the mid-thoracic region, which progressively lag towards the more caudal back regions. The lateral bending, coupled heterolateral with the axial rotation, peak and trough coincide with the mid-stance phases in the lumbar region, bending towards the ipsilateral hindlimb, which is anti-phased in the mid-thoracic region (Faber *et al.*, 2001a). Those spinal movements are driven inertially, and the epaxial and abdominal muscles control these movements eccentrically (Robert *et al.*, 2002; Wakeling *et al.*, 2007) while the diagonal pair of limbs limit twisting movements of the horse's back during the stance phases (Hobbs, Richards and Clayton, 2014). The trot gait represents a mass-spring-damper system in which the soft tissue structures of the limbs and trunk store elastic strain energy during the stance phases and release the elastic energy in the push-off phase, reducing the muscular work (Biewener, 2006).

Compared to the walk, the spinal ROM are more constant across the different back regions and movement directions and almost half the amplitudes for the flexion-extension and axial rotation ROM at trot (Faber *et al.*, 2001a). The dorsoventral and longitudinal acceleration amplitude of the trunk is, however, more prominent at trot (Barrey *et al.*, 1994). The epaxial and hypaxial musculature are more active at trot, stabilising the spine and thereby limiting the ROM between the back segments (Zsoldos *et al.*, 2010; Kienapfel *et al.*, 2018). The differentiation in the horse's back biomechanics between the gaits is reflected in the saddle movement, demonstrating more roll movement at the walk though more longitudinal and lateral movement at the trot (Galloux *et al.*, 1994).

2.3.2 The horse's back biomechanics in locomotion and the head-neck position

Previous literature revealed compensatory spinal movement patterns when the head-neck position is restricted in a higher or lower position compared to a free posture, which are more pronounced at walk than in trot (Rhodin, 2008). Examining high-level dressage horses on a treadmill (n=7), a higher head-neck position is seen to extend the cranial-mid thoracic region while flexing the caudal thoracic and lumbar region and reducing the flexion-extension ROM (Gómez Álvarez *et al.*, 2006). Lowering the head-neck position with the nose behind the vertical has an opposite effect on the back movement, which is associated with a stretch on the nuchal ligament (Gómez Álvarez *et al.*, 2006). In the same study horses, walking and trotting ridden in a working or 'competition' posture was seen to extend the horse's lumbosacral region less in comparison to a free head-neck position or a lower head-neck position (Rhodin *et al.*, 2009, 2018), which could be clarified by a more active engagement of the abdominal and *iliopsoas* musculature when ridden in the competition posture. These study findings confirm the coupling between the cervical and thoracolumbar spine and demonstrate the mechanisms of spinal tensegrity, where changes in one spinal region result in changes in the adjacent body regions through their elastic, proprioceptive, and contractive properties. The head and neck position of the horse should thus always be appreciated as a confounding factor in the horse's back biomechanics.

2.3.3 The horse's back biomechanics in locomotion and the speed and collection of gait

The horse's back biomechanics during walk and trot locomotion are also influenced by the speed and degree of collection of the horse's gait. At walk, increased speed accentuates the rocking motion of the horse's back, reflected in increased dorsoventral ROM of the back, which is more pronounced at sacrum compared to withers (Bogisch *et al.*, 2014). At trot, an increase in speed increases the muscular activity of the *longissimus dorsi*, *rectus abdominis*, and *gluteus medius* muscles (Robert *et al.*, 2002). The increased activity of those trunk muscles when speed increases has a stabilising role in the horse's back biomechanics, considering that the dorsoventral ROM and flexion-extension ROM of the horse's back decrease while the pro- and retraction angles of the limbs increase (Robert *et al.*, 2002; Bogisch *et al.*, 2014), thus counteracting the coupling between the appendicular and axial skeleton movement.

The degree of collection refers to the self-carriage of the horse, where a more collected gait is represented by a lower speed and shortened stride length (Clayton, 1994, 1995) in combination with a weight shift to the hindquarters, decreased fore- and hindlimb retraction, and increased flexion of the hindlimb and lumbosacral region (Weishaupt *et al.*, 2009). Those biomechanical responses are representative of a more engaged abdominal and *iliopsoas* musculature, implying the need of high levels of muscular strength and control to perform collective exercises. The biomechanics of the horse's back thus differ when ridden in a collected walk or trot in comparison to a medium or extended walk or trot, where the horse gradually increases its stride length and its overall body frame as described in the Fédération International Equestre (FEI) dressage guidelines (FEI, 2022).

2.3.4 The horse's back biomechanics in locomotion and lameness

Using a well-established sole pressure model to induce reversible lameness in one of the limbs of originally sound horses, researchers have been able to demonstrate compensatory movement patterns in both the appendicular and axial skeleton of the horse at walk and trot when a lameness is present. The horse's vertical displacement, velocity, and acceleration of the trunk will decrease during the stance phase of a lame limb at trot, though not at walk, with the difference in wither movement being more pronounced in the presence of a forelimb lameness and in sacrum movement in the presence of a hindlimb movement (Buchner *et al.*, 1996). Moreover, the mid-thoracic region flexes more during the sound-diagonal stance phase in the presence of a forelimb lameness and during the stance phase of the lame limb in the presence of a hindlimb lameness, while the caudal thoracic and lumbar regions extend more throughout the stride cycle and the mid-thoracic region bends more towards the lame side during the stance phase of the lame limb in both cases (Gómez Álvarez *et al.*, 2007, 2008). These findings illustrate analgesic movement patterns whereby less weight is put on the painful limb. One must therefore bear in mind that the presence of lameness can, as well, be a confounding factor in the horse's back biomechanics.

2.3.5 The horse's back biomechanics in locomotion and back dysfunctions

As outlined in Section 2.1.4, back dysfunctions in the horse can be presented as the incapacity to stabilise ongoing movements, referred to as instability, due to decreased and delayed activity of the deep, stabilising spinal musculature. Muscular bracing is an inefficient coping mechanism associated with back dysfunctions, with the more superficial musculature increasing in activity and tone in the attempt to take over the stabilising role of the deeper musculature, which leads to local rigidity. Reduced dorsoventral flexibility has been associated with clinical diagnoses, ranging from soft tissue injuries to spondylosis and impingement of the dorsal spinous processes (Jeffcott, 1980), presumably related to the muscular bracing mechanism. Another study inducing back pain in trotting horses (n=3) via an unilateral injection of lactic acid into the *longissimus dorsi* muscle in thoracolumbar region T10-L3 confirmed that horses with back pain will demonstrate apparent stiffness of the spine alongside compensatory lateral movement of the thoracolumbar region, though no major responses in the appendicular skeleton kinematics when trotting on a treadmill (Jeffcott *et al.*, 1982). However, Jeffcott *et al.* (1982) did not report which back regions in particular demonstrated those kinematic responses.

In agreement with Jeffcott (1980) and Jeffcott *et al.* (1982), Wennerstrand *et al.* (2004) found that horses with subjectively diagnosed back pain (n=12) demonstrate statistically less flexion-extension movements at walk and trot while demonstrating more prominent lateral bending ROM in comparison with sound horses without signs of back pain (n=33). Notably, the back pain in the horses examined by Wennerstrand *et al.* (2004) was located in the caudal thoracic and lumbar regions for all horses and the decreased dorsoventral movements occurred in the same region, while the increase in lateral bending ROM occurred in the mid-thoracic region. This increase in lateral movements might represent spinal instability in the region adjacent to the painful region, which is maintained rigid by the muscular bracing. The development of spinal instability as a consequence of an adjacent region being rigid has been described previously (Haussler, 1999b). Wennerstrand *et al.* (2009) examined sound riding horses without any signs of back pain (n=8) at walk and trot before and one hour and one, two, three, and seven days after inducing back pain by injecting lactic acid unilaterally into the *longissimus dorsi* muscle in thoracic region T13-T18. While Wennerstrand *et al.* (2009) reported inconsistent movement responses at the different time points after back pain was induced, they reported consistent muscle hypertonicity and hyperreactivity in the *longissimus dorsi* muscle and more extension in the caudal thoracic region and more lateral bending to the left side in the caudal thoracic and lumbar region during walk and trot locomotion up to three days after the injection.

The aforementioned empirical findings were collected in different equine populations and using different approaches or clinical diagnoses to distinguish between horses without and with back pain.

For example, Wennerstrand *et al.* (2004) identified horses with back pain based on a palpatory examination, while Jeffcott *et al.* (1982) and Wennerstrand *et al.* (2009) induced back pain via lactic acid injections. However, a trend was found for horses with back pain to demonstrate a more extended posture and decreased dorsoventral flexibility in the painful region in combination with compensatory lateral movements, which increase in the region adjacent to a painful region, during walk and trot locomotion compared to horses without signs of back pain. Those postural and movement responses are likely to represent muscular bracing in the painful region in combination with instability in the adjacent back regions. In conclusion, the presence of back dysfunctions will alter the horse's back movement significantly and forms another confounding factor in the horse's back biomechanics.

2.4 Movement analysis of the horse's back

A horse's back movement can be evaluated subjectively via visual observation or objectively using motion capture systems. Though protocols to standardise and individualise the evaluation of a horse's movement during gait analysis are being established (Bowen *et al.*, 2023), the visual observation of the horse's back movements remains subjective. The use of motion capture enables more standardised and objective practices to evaluate a horse's movement. Currently, the most popular motion capture tools in the equine industry are optical motion capture and inertial measurement units (IMUs) (Egan, Brama and McGrath, 2019).

2.4.1 Optical motion capture

Optical motion capture is considered the gold standard system in kinematic research settings due to its high accuracy and reliability to capture a subject's movement (Warner et al., 2010). An optical motion capture system consists of multiple cameras to capture a subject's movement in three dimensions (3D), often using skin-mounted reflective markers. While the optical motion cameras capture the movement of the markers in a 2D plane, the 2D data from a marker captured by two or more cameras is used to calculate the position of the markers in a 3D space by triangulation. To enable the computations involved in the triangulation, at least two optical motion cameras must see each marker for a successful data capture (Winter, 2009). Data capture with an optical motion capture system consequently relies on the line of sight of the markers, limiting the capture volume as well as its use in the field and implying that covered body areas of interest cannot be captured. The cameras are also high in cost and generally do not withstand unpredictable weather conditions (Chèze, 2014).

2.4.2 Inertial measurement units

The use of IMUs provides a convenient alternative solution to capture a subject's movement, which has grown in popularity in recent years due to their small size, low cost and practicability in in-field settings (Kok, Hol and Schön, 2017). IMUs contain a 3D accelerometer, gyroscope, and magnetometer, respectively measuring the sensor's acceleration, angular velocity, and absolute orientation in the IMU's local coordinate system (Pfau, Witte and Wilson, 2005; Kok, Hol and Schön, 2017). Integrating the gyroscope measurements provides an estimation of the IMU's orientation, whilst double integration of the accelerometer measurements, after subtraction of earth's gravity, of the IMU's position (Kok, Hol and Schön, 2017). Several signal processing steps have to be undertaken to enable integration of an IMU's motion signals. Firstly, the IMU's local coordinate system needs to be aligned with a global coordinate system. Aligning the IMU's coordinate system can be achieved through means of sensor fusion algorithms, combining the sensors' signals to sense gravity and magnetic North and thereby estimating the IMU's orientation, or by using the integrated angular velocity time series, though the latter option is deemed less accurate due to errors related to the gyroscope's bias (Bergamini *et al.*, 2014). The accelerometer and gyroscope biases form the second challenge in the processing of the IMU-derived signals. The accelerometer and gyroscope's biases are influenced by changes in the sensors' micro-electro-mechanical properties and lead to 'drift errors' that increase linearly with integration and quadratically with double integration (Camomilla *et al.*, 2018). The IMU's magnetometer is prone to a certain level of error too, influenced by ferromagnetic disturbances, which can alter the estimated heading orientation of the IMU (Bergamini *et al.*, 2014). The signal processing used to compensate for those sources of errors in an IMU's motion signal depends on the context in which the IMU is used and the movement outcomes of interest (Camomilla *et al.*, 2018).

In the context of equine movement analysis, compensation methods applied to obtain linear displacement outcomes are based on the assumption that the horse's locomotory movement patterns have a cyclical and steady-state nature and include mean-subtraction of the acceleration and velocity time series prior to integration and the application of a high-pass filter on the displacement time series (Pfau, Witte and Wilson, 2005; Bosch *et al.*, 2018). The mean-subtraction of the acceleration and velocity time series effectively means that the drift in the motion signals is removed by constraining the acceleration and velocity time series to return to its starting point over a defined cycle (Pfau, Witte and Wilson, 2005). The mean-subtraction applied in the equine gait analysis described by Pfau, Witte and Wilson (2005) and Bosch *et al.* (2018) uses a defined cycle, or moving window, of three strides. The high-pass filter applied on the displacement time series attenuates slow, non-cyclical components of the linear movements while maintaining the faster, within-stride cyclical components (Pfau, Witte and Wilson, 2005). The high-pass filter effectively removes the remaining drift in the displacement time series, while it also minimises the interstride differences. Martin (2015) evaluated the validity of differential rotational displacement outcomes of a horse's back movement, using the integrated time series of the IMU's gyroscope, also reporting the use of the high-pass filter on the obtained differential rotational timeseries. As a consequence of the applied compensation methods, IMUs are used to measure steady state locomotion only in the equine field.

2.4.3 The use of skin-mounted motion capture tools

The use of skin-mounted motion capture tools, i.e. optical motion capture using skin-mounted markers and the skin-mounted IMUs, enable non-invasive and objective measurements of a horse's back movement. While a non-invasive approach is preferred in practice, it must be acknowledged that measurements with skin-mounted motion capture tools do not essentially represent the movement of the vertebral segments of interest but rather that of the segment's anatomical landmark. The soft tissue artefact, or skin displacement, has to be considered as a certain source of error in the motion signal, including phenomena such as deformation and sliding of the skin over the underlying bone structures, effects of inertia, and muscular contractions (Chèze, 2014). The level of error caused by the soft tissue artefact can be controlled to some degree by placing the markers or IMUs on a short coat and having the same technician palpate the anatomical landmarks and fixate the markers or IMUs onto the anatomical landmarks (Serra Bragança *et al.*, 2018).

Faber *et al.* (2001b) validated the use of skin-mounted reflective markers against the use of bone-fixated markers in measuring back movement in horses (n=5) walking and trotting on a treadmill. For this validation study, Faber *et al.* (2001b) inserted Steinmann pins (3 mm) into the dorsal spinous processes of eight thoracolumbosacral vertebrae (T6, T10, T13, T17, L1, L3, L5, and S3) and left and right *tubera coxae* in sedated horses after administering local anaesthetics. Four spherical markers (9 mm) were affixed to each pin, allowing the definition of the vertebra's rigid body and 3D analysis of the spinal movement, for which the measurements were taken four hours after sedation. For the skin-mounted marker measurements, which were taken prior to sedation, only one marker was placed on top of the anatomical landmark of each vertebra, requiring a 2D projection approach. The movement outcomes measured were the flexion-extension and lateral bending angular displacements between the back segments, which were calculated as the angles between the horizontal and the vector between the marked spinal segments located cranially and caudally from the spinal segment of interest in the XZ and XY planes, respectively (see Figure 2.14). Faber *et al.* (2001b) reported root mean square differences between the two approaches of 10-20% of the ROM at walk and trot with an excellent correlation for most horses ($R \geq 0.9$), except for lateral bending in the lower thoracic and upper lumbar area at walk. The authors declare that the discrepancies seen between the two approaches relate to the skin displacement, restriction to 2D projection angles, and distance between the centre of rotation and the marker placement for the skin-mounted measures. However, the discrepancies between the two approaches were equivalent to the interstride variability in the movement outcomes. Therefore, the study by Faber *et al.* (2001b) provides evidence supporting the use of skin-mounted motion capture to measure a horse’s back movement, though caution has to be taken when interpreting lateral bending movement in the thoracolumbar junction at walk.

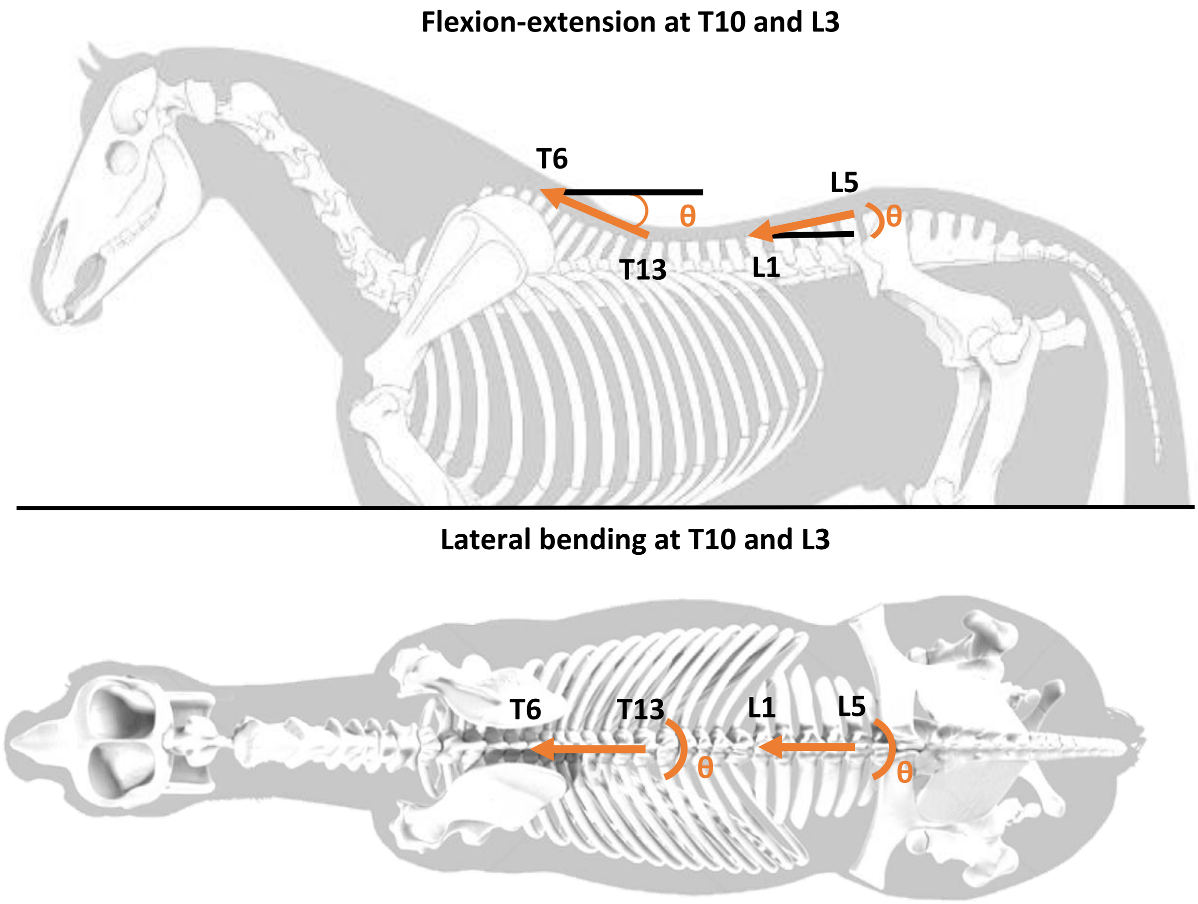


Figure 2.14 | An illustration of the flexion-extension (on top) and lateral bending (below) angular displacements at T10 and L3, as defined by Faber *et al.* (2001b).

The use of skin-mounted IMUs (Inertia Cube 3, Intersense, Bedford, USA) to measure pelvic rotational movement at the level of the *tubera sacrale* has also been validated against the use of bone-fixated IMUs in horses walking and trotting on a treadmill (Goff *et al.*, 2010). A poor correlation between the two methods was reported, indicating inaccuracies when measuring sacral and iliac rotational movement with skin-mounted IMUs. It should be noted that there have been significant advances in IMU accuracy and data processing methods since and that the results reported by Goff *et al.* (2010) may not apply to the current technology using IMUs. No study was found to report the evaluation between skin-mounted and bone-fixated IMUs in measuring the kinematics of the horse’s thoracolumbar back segments. However, the outcomes of skin-mounted IMUs, processed using the methods referred to in Section 2.4.2, have been evaluated against optical motion capture using skin-mounted markers.

Pfau, Witte and Wilson (2005) established a system using IMUs (MT9, Xsens, Enschede, The Netherlands), known as the EquiGait© system, to quantify a horse's back ROM and validated the system's outcomes against optical motion capture at all gaits on a treadmill, demonstrating acceptable levels of error (≤6% of the horse's back movement at walk and ≤12% at trot). Using the same inertial measurement system, Warner, Koch and Pfau (2010) validated the use of the IMUs against optical motion capture to quantify the linear displacements in horses (n=6) trotting overground and reported a ratio between the limits of agreement and the ROM within 28% and 21% at back segments T6, T10, T13, L1, and S3 for the laterolateral and dorsoventral displacement, respectively. Similar results were found for the differences in dorsoventral displacement at the withers and sacrum in horses (n=7) trotting overground measured using optical motion capture and the inertial measurement system outlined by Bosch *et al.* (2018), known as the EquiMoves© system. This system collects the motion signals at a higher sampling frequency (200 versus 100 Hz) and applies a slightly different method to filter the IMUs' motion signals, adhering to the Butterworth filter described by Serra Bragança *et al.* (2020), compared to the system described by Pfau, Witte and Wilson (2005).

A final study validating movement outcomes of the horse's back collected with IMUs against optical motion capture was conducted by Martin (2015), who evaluated the use of the IMUs to quantify flexion-extension or 'differential pitch' amplitudes, calculated as the integrated subtraction of adjacent IMUs' angular velocities (see Figure 2.15). Mean (±standard deviation) differences in the thoracolumbar differential pitch values were within 0.1±0.4° (*R*≥0.97) in a horse trotting on a treadmill (Martin, 2015). Considering that the use of skin-mounted markers is validated against bone-fixated markers using optical motion capture by Faber *et al.* (2001b), it can be concluded that a horse's back movement can reliably be measured using skin-mounted IMUs as well, reporting the above described outcome measures.

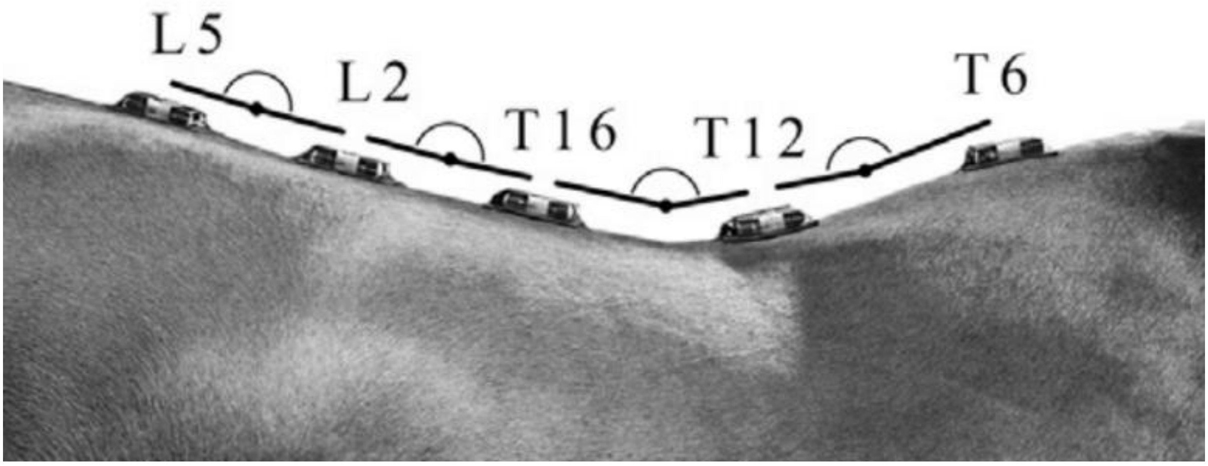


Figure 2.15 | The differential pitch angles at T6-T12, T12-T16, T16-L2, and L2-L5, as illustrated by Martin (2015). This figure is used with permission from the publisher.

2.5 Summary

This literature review provides a platform about how the horse's back functions and how this can be evaluated. Current knowledge of the functional anatomy and biomechanics of the horse's back was reviewed, and functional assessments to evaluate the functioning of the back as well as research methods to measure the movement of the back were discussed. This literature review established that optimal spinal function in the ridden horse can be defined as the capacity to provide sufficient stability and mobility to match the biomechanical demands of the horse's back when loaded with a saddle and rider while performing sport-specific motor tasks. Functional assessments can be used to evaluate a horse's back functioning, which is common practice in the clinical field and include the evaluation of musculoskeletal pain, mobility, and muscle function. Studying how the horse's back moves and what causes it to move, i.e. the biomechanics of the horse's back, it is evident that the horse's back movement is coupled with that of the cervical and appendicular skeleton. Spinal dysfunctions also influence the horse's back movement, inducing a more extended posture as well as decreased dorsoventral flexibility in the painful region in combination with compensatory lateral movements which increase in the region adjacent to a painful region. This literature review concludes with an overview of the research methods used for the movement analysis of the horse's back, confirming that skin-mounted motion capture tools can validly and reliably be used for this purpose.

While the study of the horse's back biomechanics when loaded with a saddle and rider is central to this thesis, this review concentrated on unloaded spinal functioning and biomechanics, though specified to the profile of the ridden horse. Appreciating the complexity of the horse-saddle-rider interaction as well as the growing evidence related to this research field, a second review study concentrating on the literature related to the biomechanical interaction between saddle, rider, and the horse's back was merited, being presented in the following Chapter.

CHAPTER THREE

3 The horse-saddle-rider interaction: a systematic review of the effect of a saddle and rider on the horse's back biomechanics

3.1 Introduction

Understanding the horse-saddle-rider interaction is vital to promoting equine health, welfare, and athletic performance. The advent of motion capture and pressure sensing technologies has enabled a vast growth in research investigating the horse-saddle-rider interaction, supporting equine practice in both clinical and performance settings (van Weeren and Back, 2014). Optical motion capture collecting the movement of skin-mounted markers and skin-mounted inertial measurement units (IMUs) are the main motion capture tools used for equine movement analysis (Egan, Brama and McGrath, 2019), which have been discussed in Chapter 2 of this thesis (Section 2.4). Pressure sensing technology in the form of a saddle pressure mat has been established to quantify the pressures and forces exerted upon the contact area between the saddle and horse, referred to as the saddle pressure measurements (Jeffcott, Holmes and Townsend, 1999; de Cocq, van Weeren and Back, 2006). The saddle pressure measurements related to the magnitude of the pressures are used as surrogate measure of the impact of load on the horse's back (Janura *et al.*, 2012). The growth in research investigating the horse-saddle-rider interaction using motion capture and pressure sensing technologies warrants review studies, which provide a transparent way of gathering, synthesising, and appraising the findings of studies on a particular topic and supporting related research projects and industry practices in keeping up with the current literature (Bahadoran *et al.*, 2020).

A topic of particular interest in the equine industry is the management of back functioning in the ridden horse, both for welfare and performance-related motivations (van Weeren and Back, 2014). As discussed in Chapter 2, optimal spinal function in the horse can be defined as the capacity to provide sufficient stability and mobility to match the biomechanical demands of the horse's back when being ridden. Conceivably related to its biomechanical demands, back dysfunctions are common in ridden horses (Jeffcott, 1979; Wennerstrand, 2008; De Cocq, 2012) and appropriate monitoring of the demands according to the functioning of the concerning musculoskeletal structures forms the basis of efficient prevention or rehabilitation management of the musculoskeletal dysfunctions (Haussler *et al.*, 2021a). Therefore, the evaluation of the biomechanical demands of the horse's back alongside the evaluation of the horse's back functioning, is of interest in the management of back health in the ridden horse. The evaluation of the biomechanical demands of the ridden horse's back entails measurements of the effect of saddle and rider, including the effect of the girth, on the horse's back biomechanics, i.e. measurements of the horse's back movement and the forces acting upon the back using the aforementioned motion capture tools and saddle pressure mats (de Cocq and van Weeren, 2014). To facilitate the development of valid and relevant research methods and methodologies in succeeding studies investigating the effect saddle and rider have on the horse's back biomechanics, a review study evaluating what is known already and, perhaps more importantly, what is not known yet about this research topic is merited.

Additional to informing succeeding research, systematically reviewing the literature related to a particular topic can provide an effective way of raising awareness in the industry and impacting industry practice (Bahadoran *et al.*, 2020). Greve and Dyson (2013a) previously reviewed the evidence about the interaction between horse, saddle, and rider, revealing a list of features related to each that might contribute to poor performance and informs equine practice about the factors to consider when poor performance is observed. Similar to the list defined by Greve and Dyson (2013a), a list of the factors related to the saddle and rider that might alter the horse's back biomechanics when ridden could inform equine practice about the factors to consider when back dysfunctions are observed. Clayton and Hobbs (2017) addressed the state of knowledge at that time about the biomechanics of the horse-rider interaction, raising awareness of horse behaviour and movement, as well as the impact of the rider on the horse. Whilst Clayton and Hobbs (2017) outlined how a horse's locomotory biomechanics affect the rider's posture, movements, and forces across the different gaits, how a saddle and rider affect the posture, movements, and forces of the horse's back has not yet been addressed in a systematic review study. However, a study of such kind could advance our understanding about the biomechanical demands of the back in the ridden horse and, thereby, support clinical practice in managing back health in the ridden horse.

The aim of this study was to identify, evaluate, and summarise the current evidence on the effect of a saddle and rider on the horse's back biomechanics and relate the reported biomechanical outcomes of the horse's back to the horse's back functioning. Studies detailing alterations in saddle pressure measurements and kinematic measurements of the horse's back when loaded with a saddle and rider during straight-line walk and trot locomotion were of interest. Therefore, a systematic review was conducted, which (1) identifies and (2) evaluates the methodological quality of the literature investigating the effect of a saddle and rider on the saddle pressure measurements and kinematic measurements of the horse's back during straight-line walk and trot locomotion, (3) summarises the extracted evidence through a narrative synthesis, stratified based on saddle- and rider-related characteristics interacting with the horse's back biomechanics, and (4) discusses how the reported biomechanical outcomes relate to the horse's back functioning.

3.2 Methods

This systematic review was conducted according to recommendations outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklist for reporting systematic reviews (Page *et al.*, 2021).

3.2.1 Literature search

Inclusion and exclusion criteria for the studies' population, intervention, control or comparison, and outcomes (PICO) were defined to include studies relevant to this systematic review's research aim and objectives (Table 3.1), according to Santos *et al.* (2007). It was chosen to exclude studies reporting measurements from riding disciplines other than those overlapping with the Olympic equestrian disciplines (i.e. dressage, showjumping, and eventing). Those disciplines were opted for in order to represent comparative data from the horse's back biomechanics when ridden during straight-line walk and trot locomotion, considering straight-line walk and trot exercises form a standard component within the warm-up/ training of horses ridden according to those disciplines, including riding school and general purpose horses. These criteria were obtained via discussion with a research panel, including the PhD student and supervisors and a research technician at Hartpury University who was previously involved in the screening process of the review studies by Perrett *et al.* (2021) and Harris *et al.* (2023).

Table 3.1. The eligibility criteria defined for each PICO component.

PICO components	Eligibility criteria	
	Inclusion	Exclusion
Population	• Ridden horses (riding school horses, dressage, showjumping, eventing, and general purpose) • In-vivo subjects	• Unbacked/ retired horses • Other riding disciplines • Other animals or humans • In-vitro or simulated
Intervention	• Related to the saddle • Related to the rider	• Unrelated to the saddle • Unrelated to the rider
Control	• The study horses act as their own control	
Outcome	• Measurements of the horse's back kinematics and saddle pressures during straight-line walk and trot locomotion	• Not related to the horse's back kinematics or saddle pressures during straight-line walk and trot locomotion
Design	• Randomised controlled trial • Observational study • Pilot study	• Meta-analysis or review • Conference/ Congress abstracts • Grey literature
Language	• English • Dutch • French	Other languages

PICO = population, intervention, control, and outcome.

Based on the eligibility criteria, search strategies were defined and four academic research databases were searched: PubMed, Wageningen Academic Publishers, ScienceDirect, and Wiley Online Library. The search strategies for each database were defined using medical subject headings (MeSH) and free terms with Boolean operators "AND" or "OR", as shown in Table 3.2. The search strategy for the Pubmed database included wildcard characters, indicated with an asterisk and used to include different suffixes of the search terms. For example, biomechanic* was used to include the terms biomechanic, biomechanics and biomechanical. In ScienceDirect, the filter 'Article type' was applied to automatically search for research articles and case studies and exclude review articles, book chapters, conference abstracts and short communications. All databases were first searched on the 13th of May, 2022, by the PhD student. The database search was repeated on the 20th of January, 2023, to include contemporary literature throughout the timeline of this thesis. Applying the defined search strategies, 115 studies were identified in Pubmed, 249 in Wageningen Academic Publishers, 120 in ScienceDirect, and 126 in Wiley Online Library. In addition, hand searches were conducted to identify studies that were not indexed in the databases or targeted by the search strategies. The hand-searching was performed by the PhD student by reviewing the reference lists of included studies and related review studies (Greve and Dyson, 2013a; Clayton and Hobbs, 2017). The hand-searching resulted in the inclusion of another six full-texts, bringing the total number of studies reviewed to 616.

Table 3.2. The search strategies used for the literature search and the number of studies identified in each database on the 20th of January, 2023.

Database	Search strategy	Number of studies
Pubmed	horse AND (saddle OR rider) AND (biomechanic* OR kinematic* OR movement OR motion OR kinetic* OR force OR pressure) AND (back OR withers OR thoracic OR lumbar OR sacrum OR thoracolumbar OR thoracolumbosacral OR spine)	115
Wageningen Academic Publishers	horse AND (saddle OR rider) AND (biomechanic OR kinematic OR movement OR motion OR kinetic OR force OR pressure) AND (back OR withers OR thoracic OR lumbar OR sacrum OR thoracolumbar OR thoracolumbosacral OR spine)	249
ScienceDirect	horse AND (saddle OR rider) AND (biomechanic OR kinematic OR movement OR motion OR kinetic OR force OR pressure) AND (back OR withers OR thoracic OR lumbar OR sacrum OR thoracolumbar OR thoracolumbosacral OR spine)(*) (*) *The filter 'Article type' was applied to include only research articles and case reports*	120
Wiley Online Library	"horse" in Abstract and "saddle OR rider" in Abstract and "biomechanic OR kinematic OR motion OR kinetic OR force OR pressure" in Abstract and "back OR withers OR thoracic OR lumbar OR sacrum OR thoracolumbar OR thoracolumbosacral OR spine" anywhere	126

3.2.2 Screening of records

Study eligibility was determined through a two-tiered process, including (1) screening of the study's title and abstract by the PhD student and (2) independent screening of the study's full text by the PhD student and research technician. Any discrepancies between the two researchers in the second stage of the screening process were resolved through discussion until consensus was reached.

3.2.3 Scoring of the methodological quality

The quality of each study included after the screening process was assessed independently by the PhD student and research technician using the quantitative 'QualSyst' risk of bias assessment tool and guidelines. The QualSyst tool allows evaluation of the methodological quality and risk of bias of quantitative studies with varying study designs (Kmet, Lee and Cook, 2004), in contrast to the abundant quality checklists used in systematic reviews which only allow evaluation of randomized controlled trials. Thereby, the QualSyst tool supported critical appraisal of the evidence collected within this systematic review regardless of its diversity.

The QualSyst tool evaluates 14 items (see Appendix A.II and A.III), scored from 0 to 2 (0 = item criteria are not met, 1 = criteria are partially met, 2 = criteria are met) or with 'NA' (not applicable) if the criteria were believed not to be applicable for the study. For example, all studies in this systematic review were assigned an 'NA' score on QualSyst item seven, as blinding of the study participants – being horses – was deemed not applicable. In the context of this systematic review, QualSyst item 4, evaluating if the study subject features were sufficiently described, was given a score of 2 if the study included information about the horses' age, breed, discipline, training level, and clinical condition and the riders' body mass and riding level, whilst a score 1 was given when one or more of those demographic parameters of the studied subjects were missing. For QualSyst item 9, evaluating if the study sample size was appropriate, a score of 2 was given if the study sample size was equal to or greater than 30, and studies including three horses or less scored 0. This interpretation of sample sizes was based on the central limit theorem; sample sizes equal to or greater than 30 are considered sufficient for the central theorem to hold, meaning that the distribution of sample means will approximate a normal distribution (Kwak and Kim, 2017). The other QualSyst items were considered self-explanatory in the context of this research.

The interrater agreement on the total scores of the QualSyst tool between the two researchers was excellent (weighted kappa=0.889, $p<0.001$). Where discrepancies were found in the QualSyst scores of the individual studies between the two researchers, an agreement was found through discussion in light of the scoring consistency. The final quality score of each study is presented as a percentage, which is calculated by dividing the sum of the scores on the 14 QualSyst items by the number of applicable QualSyst criteria, multiplied by 100. A score of ≥75% indicates a high methodological quality, and 55-75% and ≤55% indicate a moderate and low methodological quality, respectively (Kmet, Lee and Cook, 2004).

3.2.4 Narrative synthesis

Study findings were collated into a textual narrative, suiting the heterogenous nature of the identified literature (Campbell *et al.*, 2018). The synthesis without meta-analysis (SWiM) guidelines for systematic review studies were adhered to (Campbell *et al.*, 2020). Firstly, the study findings were grouped according to two study areas, investigating the effect of (1) the saddle or (2) the rider on the horse's back biomechanics. For each study area, a descriptive summary table was produced detailing the study aims, samples, outcome measures, and measurement tools relevant to this systematic review (see template in Appendix A.IV). Within each study area, study findings associated with the same saddle- or rider-related characteristics were collated and summarised in an effect direction plot. Where available, effect measures were reported in the narrative synthesis. Finally, the narrative synthesis evaluated how the reported study findings relate to the horse's back functioning, which is outlined in the discussion. The data extraction and narrative synthesis were performed by the PhD student.

3.3 Results

3.3.1 Literature search

The literature search resulted in 616 research studies. Fifty-seven duplicate studies were removed, and 486 studies were excluded after the title and abstract screening using the defined inclusion and exclusion criteria. Another 35 studies, including three of the six manually selected studies, were excluded after the full-text screening. Ultimately, 38 studies complied with all study criteria and were included in this systematic review. The study selection procedure is presented in Figure 3.1.

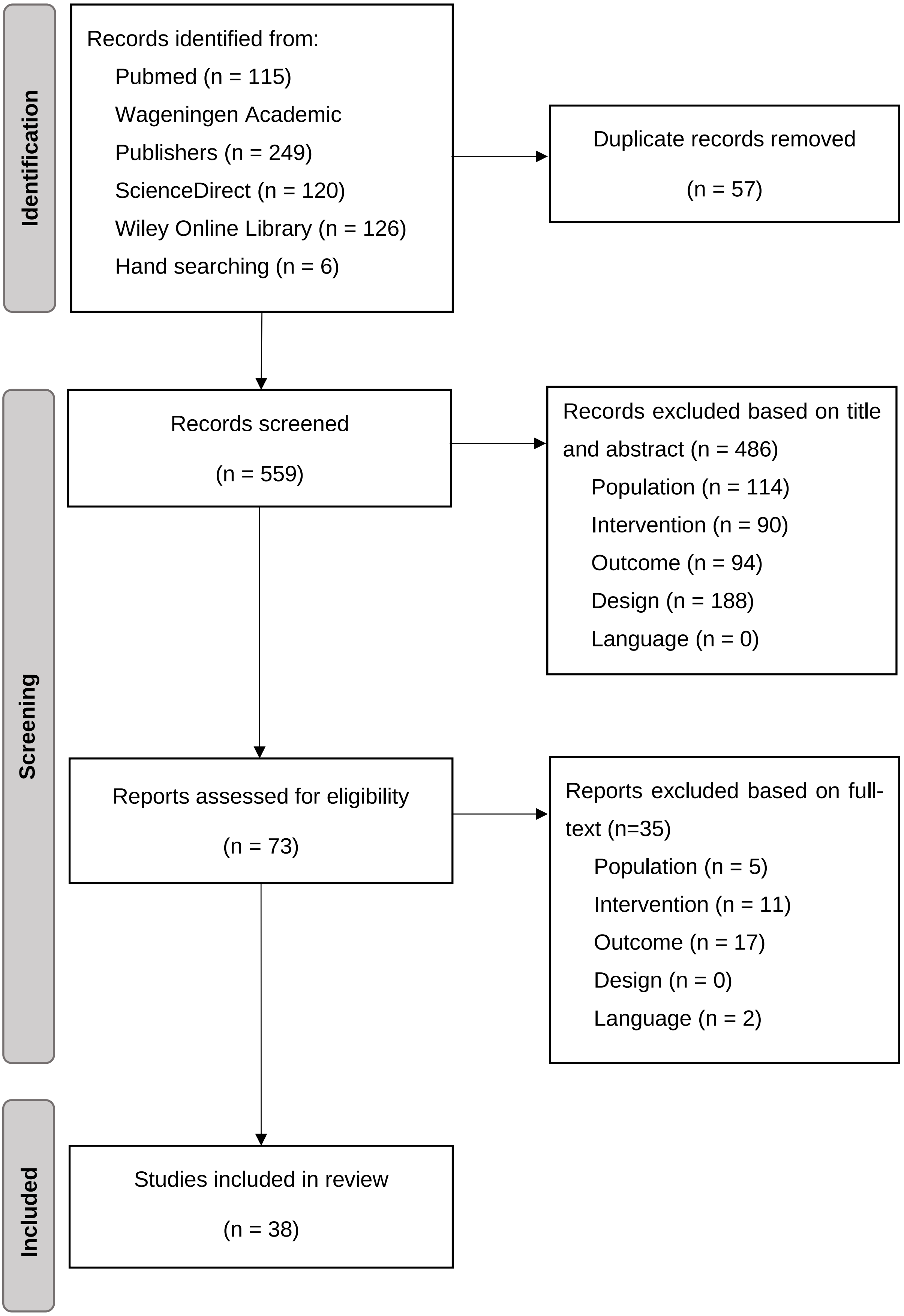


Figure 3.1 | Flowchart of the screening of records according to the PRISMA guidelines.

3.3.2 Methodological study scores

The methodological quality evaluation using the QualSyst tool demonstrated that, out of the 38 studies, 16 had a high methodological score, 16 had a moderate score, and 6 had a low score. The two highest-scoring studies (88%) are the studies by MacKechnie-Guire *et al.* (2019) and Gunst *et al.* (2019), while the two lowest-scoring studies (38%) are the studies by Harman (1994) and Lagarde *et al.* (2005). The methodological score for each study is shown in Table 3.3.

Table 3.3. Methodological score per study based on the quantitative 'QualSyst' risk of bias assessment tool.

Author(s)	Question described	Appropriate study design	Appropriate subject selection	Features described	Random allocation	Researchers blinded	Subjects blinded	Outcome measures defined and bias robust	Appropriate sample size	Analytic methods well described	Estimate of variance reported	Controlled for confounding	Results reported in detail	Conclusion supported by results	Rating
Belock et al (2012)	2	2	1	2	2	0	NA	2	1	2	1	2	2	2	high
Bogisch et al (2014)	2	2	1	2	NA	0	NA	2	1	2	2	1	2	2	high
Byström et al (2010)	2	2	1	1	2	0	NA	2	1	2	2	2	2	2	high
Byström et al (2020a)	2	2	1	2	0	0	NA	2	1	2	2	1	2	1	moderate
Clayton et al (2013)	2	2	1	1	2	0	NA	2	1	2	1	2	2	2	high
Clayton, O'Connor and Kaiser (2014)	1	2	1	2	2	0	NA	2	1	2	2	2	2	2	high
De Cocq, van Weeren and Back (2004)	1	1	1	2	2	0	NA	2	1	2	2	1	2	1	moderate
De Cocq et al (2009a)	1	2	1	2	2	0	NA	2	1	2	2	1	2	1	moderate
Dittmann et al (2021)	2	2	2	2	0	0	NA	1	2	2	2	1	2	2	high
Dyson et al (2019)	2	2	2	2	2	0	NA	1	1	2	2	1	2	2	high
Egenvall et al (2019)	2	2	1	1	0	0	NA	2	1	2	2	1	2	2	moderate
Fruehwirth et al (2004)	1	2	1	1	NA	0	NA	1	1	1	1	1	1	1	low
Gunst et al (2019)	2	2	2	2	NA	0	NA	2	2	2	2	1	2	2	high
Harman (1994)	1	2	1	1	0	0	NA	1	1	0	0	1	1	1	low
Heim et al (2016)	1	2	1	1	0	0	NA	2	1	2	1	1	1	1	low
Kotschwar, Baltacis and Peham (2010a)	1	2	1	1	0	0	NA	2	1	2	2	2	2	2	moderate

Kotschwar, Baltacis and Peham (2010b)	1	2	1	1	0	0	NA	2	1	2	2	2	1	2	moderate
Lagarde et al (2005)	1	2	0	0	0	0	NA	2	0	1	0	0	2	2	low
Licka, Kapaun and Peham (2004)	2	2	1	1	0	0	NA	1	1	2	1	1	2	2	moderate
MacKechni-Guire et al (2018)	2	2	2	2	1	0	NA	2	1	2	2	1	2	2	high
MacKechnie-Guire et al (2019)	2	2	1	2	2	2	NA	2	1	2	2	1	2	2	high
MacKechnie-Guire et al (2020b)	2	2	2	2	0	0	NA	2	1	2	2	1	2	2	high
MacKechnie-Guire, Fisher and Pfau (2020)	2	2	2	2	2	0	NA	2	1	2	2	1	2	2	high
MacKechnie-Guire and Pfau (2021a)	2	2	2	2	0	0	NA	2	1	2	2	1	2	2	high
MacKechnie-Guire and Pfau (2021b)	2	2	2	2	0	0	NA	2	1	2	2	1	2	2	high
MacKechnie-Guire et al (2021)	2	2	2	2	1	0	NA	2	1	2	2	2	2	2	high
Martin et al (2015)	2	2	1	1	0	0	NA	1	0	1	0	1	2	1	low
Martin et al (2016)	2	2	1	1	NA	0	NA	2	0	2	1	2	2	1	moderate
Martin et al (2017a)	1	1	1	1	0	0	NA	2	0	2	2	2	2	1	moderate
Martin et al (2017b)	2	2	1	1	0	0	NA	2	0	2	2	2	2	2	moderate
Meschan et al (2007)	2	2	1	1	0	0	NA	1	1	1	2	2	2	1	moderate
Murray et al (2017)	2	2	1	1	1	0	NA	2	1	2	1	1	2	2	moderate
Peham et al (2004)	1	2	1	1	0	0	NA	2	1	2	2	2	2	1	moderate
Peham et al (2009)	2	2	1	1	2	0	NA	2	1	2	2	2	2	2	high
Persson-Sjodin et al (2018)	2	2	2	2	2	0	NA	2	1	2	2	1	2	2	high
Roepstorff et al (2009)	2	2	1	1	0	0	NA	2	1	2	0	1	2	2	moderate
Roost et al (2019)	2	2	2	1	2	0	NA	1	1	2	2	1	2	1	moderate
Von Peinen et al (2010)	2	1	1	1	1	0	NA	1	1	1	1	1	1	1	low

NA = not applicable.

3.3.3 Narrative synthesis: how a saddle alters the horse's back biomechanics

A total of 21 studies were found to report how a saddle alters the horse's back biomechanics, including a total of 453 horses used for ridden work at varying training levels. A descriptive summary table detailing the study aims, population, outcome measures, and measurement tools of each of those studies can be found in Table 3.4. This narrative synthesis collates the results of those studies, revealing how a saddle and saddle-related characteristics alter a horse's back biomechanics. The identified saddle-related characteristics that alter a horse's back biomechanics include saddle fit, design, and type, and the use of saddle pads.

Table 3.4. A descriptive summary table of the studies investigating the effect of a saddle on the horse's back biomechanics (n=21).

Study	Study aim(s)	Study sample	Outcome measure(s)	Measurement tool(s)
Belock et al (2012)	To compare P distribution under a conventional saddle and a treeless saddle at sitting trot	Horses: n=8, Arabian riding school horses, 15±5 years, riders: n=1, 57 kg, saddle fit: acceptable	Mean total F and F of saddle mat halves and thirds and mean and max P when ridden overground in sitting trot with a conventional and treeless saddle	Saddle pressure mat
Byström et al (2010)	To assess the influence of girth strap placement and panel flocking material on saddle P during riding	Horses: n=6, Warmblood riding school horses, riders: n=3, 53-66 kg, saddle fit: sufficient	Max total F and peak P in saddle mat quadrants when ridden overground in sitting and rising trot with different saddle flocking materials and girth strap placements	Saddle pressure mat
Clayton et al (2013)	To measure F and P on the horse's back when riding with a conventional saddle compared to bareback riding	Horses: n=7, Arabian horses, 16±5 years, riders: n=1, 57 kg, saddle fit: acceptable	Mean total F, F of saddle mat halves, and mean and max P when ridden overground in sitting trot with and without saddle (bareback)	Saddle pressure mat
Clayton, O'Connor and Kaiser (2014)	To compare F and P distribution beneath a conventional and treeless saddle with panels	Horses: n=6, Arabian riding school horses, 16±1 years, riders: n=1, 66 kg, saddle fit: acceptable	Mean and max total F and P and mean F of saddle mat halves and thirds when ridden overground in sitting trot with a conventional and treeless saddle	Saddle pressure mat
De Cocq, van Weeren, and Back (2004)	To determine the effects of a saddle and weight on the back-movements of the horse	Horses: n=9, 9 years on average, Warmblood riding school horses, saddle fit: NC	Lumbar flexion-extension movement when walking and trotting unloaded, with a saddle, and with a loaded saddle (75 kg) on a treadmill	Optical motion capture
Dittmann et al (2021)	To investigate how well the subjective assessment of saddle fit correlates with saddle P measurements during riding	HRP: n=196, horses: 10±3 years, various disciplines and breeds, riders: 67±11 kg, saddle fit: assessed by a veterinarian	Highest mean P (four adjacent sensors with the highest mean P) when ridden overground at walk and sitting and rising trot with varying saddle fit issues	Saddle pressure mat
Fruehwirth et al (2004)	To evaluate P distribution under an English saddle at walk and trot	HRP: n=12, horses: 7-25 years, various breeds and training levels, riders: 68±10 kg, saddle fit: well-fitting	Max overall F, max F in the saddle mat quarters, and withers ROM when walking and trotting overground with a saddle	Saddle pressure mat & Optical motion capture
Harman (1994)	To examine the effects of saddle pads on the fit of saddles and evaluate saddle fitting cases	HRP: n=10, riders: light-to-heavy weight, saddle fit: assessed by a veterinarian	Saddle peak P and total saddle F when ridden overground at walk and trot with different saddle pads and saddle fit issues	Saddle pressure mat
Heim et al (2016)	To establish normal back ROM in an uniform horse population at trot under different conditions	Horses: n=27, riding/ driving Franches-Montagnes stallions, riders: n=1, saddle fit: NC	LL and DV ROM at L3 and sacrum when trotting overground without and with a saddle	IMUs

Kotschwar, Baltacis and Peham (2010a)	To evaluate the F acting on the horse's back using saddle pads underneath a fitting saddle	Horses: n=18, 12±6 years, competition horses, riders: n=1, 80 kg, saddle fit: good	Max overall F when ridden in walk and sitting trot on a treadmill with a saddle pad compared to without	Saddle pressure mat
Kotschwar, Baltacis and Peham (2010b)	To test whether saddle pads improve the fitting of an excessively wide saddle	Horses: n=16, 11±5 years, riders: n=1, 80 kg, saddle fit: tree one size too wide	Max overall F when ridden in walk and sitting trot on a treadmill with different saddle pads	Saddle pressure mat
MacKechnie-Guire et al (2018)	To determine the effect of an asymmetrically positioned saddle on P distribution under the saddle and back movement	Horses: n=7, 9±3 years, various disciplines, competition horses, riders: n=6, 67±11 kg, saddle fit: asymmetric saddle position	Sacrum 3D translational ROM, MinD, and MaxD, and max P and F beneath the inside and outside saddle panels when ridden overground in rising trot with an (a)symmetric saddle position	Saddle pressure mat & IMUs
MacKechnie-Guire et al (2019)	To quantify the effect of a wide and a narrow saddle on saddle P distribution and thoracolumbar kinematics	Horses: n=14, 9±1 years, Warmblood dressage or jumping competition horses, riders: n=2, 70±1 kg, saddle fit: correct and incorrect (too wide/ narrow)	Mean and peak P beneath cranial and caudal aspect of the saddle, max overall F, and 3D translational and rotational ROM of the horse's back when ridden overground with an (in)correctly fitting saddle in sitting trot	Saddle pressure mat & IMUs
MacKechnie-Guire, Fisher, Pfau (2020)	To quantify the effect of saddle half pads on P distribution beneath a fitting saddle	HRP: n=12, horses: 11±3 years, high-level dressage horses, riders: 69±6 kg, saddle fit: correct	Mean and peak P beneath cranial and caudal aspect of the saddle when ridden overground in sitting trot with different saddle pads	Saddle pressure mat
MacKechnie-Guire et al (2021)	To quantify saddle P distribution in relation to saddle fit	Horses: n=8, 10±2 years, elite jumping horses, riders: n=1, 69 kg, saddle fit: correct and too wide/ narrow	Mean and peak P beneath cranial and caudal aspect of the saddle when ridden overground with an (in)correctly fitting saddle in sitting trot	Saddle pressure mat
Martin et al (2015)	To evaluate the effect of a prototype saddle with short panels on the biomechanics of the horse's back during rising trot	Horses: n=2, 7-12 years, riding school horses, riders: n=1, 70 kg, saddle fit: NC	Mean P of transversal thirds of the P mat and flexion-extension ROM of the back when ridden overground in rising trot with a standard/ prototype saddle	Saddle pressure mat & IMUs
Martin et al (2017a)	To evaluate the effect of a prototype saddle with large panels on the biomechanics of the horse's back during rising trot	Horses: n=3, 7-12 years, riding school horses, riders: n=1, 72.1 kg, saddle fit: assessed	Mean P of transversal thirds of the P mat and flexion-extension ROM of the back when ridden overground in rising trot with a standard/ prototype saddle	Saddle pressure mat & IMUs
Meschan et al (2007)	To assess if the width of the tree alters the P distribution on the equine back	Horses: n=19, 10±5 years, riders: n=1, 80 kg, saddle fit: correct and too wide/ narrow	Mean P of transversal and longitudinal thirds of the P mat when ridden in walk and trot on a treadmill with a correctly/ wide/ narrow fitting saddle	Saddle pressure mat
Murray et al (2017)	To compare peak P between fitting saddles and a saddle designed to reduce P at T10–T13	Horses: n=13, 8-16 years, elite dressage horses, riders: n=7, saddle fit: correct	Mean peak P in the T10-T13 region when ridden overground in sitting trot with a standard and modified saddle	Saddle pressure mat
Peham et al (2004)	To show that a non-fitting saddle disturbs the rider–horse interaction	Horses: n=21, 4-22 years, various levels and breeds, riders: n=1, 75 kg, saddle fit: one correct and one with incorrect tree width	Inter-stride coefficient of variance of the 3D displacement, velocity and acceleration at L4 when ridden in sitting trot on a treadmill with a correctly and incorrectly fitting saddle	Optical motion capture
Von Peinen et al (2010)	To relate the saddle P with clinical manifestations of ill-fitting saddles	HRP: n=39, horses: 5-18 years, various breeds, without and with clinical signs of saddle fit problems, saddle fit: varied	Mean and max P of 4 sensors bilateral in withers area with saddle sores/ dry spots when ridden overground at walk and rising trot	Saddle pressure mat

P = pressure, F = force, NC = saddle fit was not clarified, HRP = horse-rider pairs, Max = maximum, ROM = range of motion, LL = laterolateral, DV = dorsoventral, 3D = three-dimensional, MinD and MaxD = difference in the vertical movement trough and peak between step cycles, IMUs = inertial measurement units.

3.3.3.1 The saddle

The evidence extracted about the effect of a saddle on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.2). The evidence demonstrated that a well-fitting dressage saddle, without a rider, induces forces equivalent to almost two-and-a-half times the saddle's weight at walk and three-to-four times at trot (Fruehwirth *et al.*, 2004). When riding with a saddle compared to without, the saddle reduces mean and peak pressures though increases the total forces on the horse's back considering the pressures are distributed over a larger area (all $p<0.05$) (Clayton *et al.*, 2013). The evidence further demonstrated that a saddle, without a rider, does not alter a horse's lumbosacral movements in comparison to no saddle, measured by means of the lumbosacral flexion-extension angles or ROM at walk and trot (all $p>0.05$) (de Cocq, van Weeren and Back, 2004) and the lumbosacral laterolateral and dorsoventral ROM at trot (all $p>0.05$) (Heim *et al.*, 2016).

Study	Outcome measures	Saddle conditions	Walk	Trot
Fruehwirth et al (2004)	Max overall saddle force	With vs. without saddle	2-2.5 times the saddle's weight	3-4 times the saddle's weight
Clayton et al (2013)	Mean total force, mean and peak saddle pressures	Ridden with vs. without saddle		Pressures ↓ Force ↑
De Cocq, van Weeren and Back (2004)	Lumbosacral flexion-extension angles and ROM	Without vs. with saddle*	↔	↔
Heim et al. (2016)	LL and DV ROM at L3 and sacrum	With vs. without saddle		↔

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there is no statistical difference = ↔. Colour coding: the study has a low, moderate, or high methodological quality. Sample size coding: ≤3 study horses, 4-29 study horses,* ***≥30 study horses****. * = on a treadmill. Max = maximum, ROM = ranges of motion, LL = laterolateral, DV = dorsoventral.*

Figure 3.2 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by a saddle.

3.3.3.2 Saddle fit

The evidence extracted about the effect of saddle fit on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.3). The evidence demonstrated that saddle fit issues subjectively assessed by a veterinarian correlate with saddle pressure measurements (Harman, 1994; Dittmann *et al.*, 2021). An inadequate saddle panel quality, less dynamic saddle stability, asymmetric panels, and incorrect panel angles and widths are each associated with higher saddle pressures when the horse is ridden at walk, sitting trot or rising trot (all $p<0.05$) (Dittmann *et al.*, 2021). An asymmetric position of the saddle, or saddle slip, is associated with higher peak pressure under the inside panel portion ($p\leq0.05$) and decreased laterolateral sacrum ROM ($p=0.03$) when ridden in rising trot, compared to after saddle slip correction (MacKechnie-Guire *et al.*, 2018). Mean and peak pressures are also higher in horses with clinical signs of an incorrectly fitting saddle, i.e. dry spots in the saddle area after ridden exercise and back soreness, compared to horses without those signs ($p<0.05$) (Von Peinen *et al.*, 2010).

The evidence further demonstrated that riding the horse with an incorrect tree width increased the saddle pressures and alters the horse's back kinematics. Riding the horse with a too narrow saddle increases saddle pressures in the caudal third of the pressure mat at walk and in sitting trot (both $p<0.01$) (Meschan *et al.*, 2007) and with 14% in the caudal half of the saddle in sitting trot ($p=0.01$) (MacKechnie-Guire *et al.*, 2019), while too wide saddles increase saddle pressures in the middle third of the pressure mat at walk and in sitting trot (all $p<0.01$) (Meschan *et al.*, 2007) and with 8.5% in the cranial half of the saddle in sitting trot ($p=0.003$) (MacKechnie-Guire *et al.*, 2019). In rising trot as well, riding the horse with a correctly fitting saddle tree induces lower peak pressures, in the cranial saddle region half in particular, than saddles with a too narrow or too wide saddle tree ($p=0.04$) (MacKechnie-Guire *et al.*, 2021). Comparing the horse's back kinematics when ridden in sitting trot with different tree widths, a too narrow or wide saddle decreases laterolateral ROM at T13 with 8% ($p=0.004$) and 6% ($p=0.02$), while the too narrow saddle also decreases the dorsoventral ROM at this level with 6% ($p=0.004$) (MacKechnie-Guire *et al.*, 2019). An incorrect saddle tree width can also increase the variability of the horse's back movement, quantified as an increase in the craniocaudal velocity ($p<0.05$) and laterolateral acceleration ($p<0.01$) coefficient of variance at L4 when ridden in sitting trot in a saddle with an incorrectly versus a correctly fitting tree width (Peham *et al.*, 2004).

<table>
<tr><th>Study</th><th>Outcome measures</th><th>Saddle conditions</th><th>Walk</th><th>Trot</th></tr>
<tr><td>Harman (1994)</td><td>Peak saddle pressures and total saddle force</td><td>Saddle fit issues</td><td colspan="2">↓↑↔</td></tr>
<tr><td>Dittmann et al (2021)</td><td>Highest mean saddle pressures</td><td>Saddle fit issues vs. correctly fitting saddles</td><td colspan="2">↑</td></tr>
<tr><td>Von Peinen et al (2010)</td><td>Mean and peak saddle pressures</td><td>saddle fitting problems vs. fitting saddles</td><td colspan="2">↑</td></tr>
<tr><td rowspan="2">MacKechnie-Guire et al (2018)</td><td>Peak saddle pressures</td><td rowspan="2">Before vs. after correction asymmetric saddle position</td><td rowspan="2"></td><td>Contralateral ↑</td></tr>
<tr><td>CC, LL, DV ROM, and MinD, MaxD at sacrum</td><td>LL sacrum ↑</td></tr>
<tr><td>Meschan et al (2007)</td><td>Mean saddle pressures</td><td>Too narrow/ widely fitting vs. correctly fitting saddle*</td><td colspan="2">Caudal ↑ (narrow)
Middle ↑ (wide)</td></tr>
<tr><td rowspan="2">MacKechnie-Guire et al (2019)</td><td>Peak saddle pressures</td><td rowspan="3">Too narrow/ widely vs. correctly fitting saddle</td><td rowspan="2"></td><td>Caudal ↑ (narrow)
Cranial ↑ (wide)</td></tr>
<tr><td>CC, LL, DV and roll, pitch, yaw ROM at T5, T13, T18, L3 and sacrum</td><td>LL & DV T13 ↓ (narrow)
CC T5 ↓ (wide)
LL T13 ↓ (wide)</td></tr>
<tr><td>Mackechnie-Guire et al (2021)</td><td>Mean and peak saddle pressures</td><td></td><td>Cranial ↑</td></tr>
<tr><td>Peham et al (2004)</td><td>3D displacement, velocity, acceleration CoV at L4</td><td>Correctly vs. incorrectly fitting saddle tree*</td><td></td><td>CC velocity ↓
LL acceleration ↓</td></tr>
</table>

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there is no statistical difference = ↔. ↓↑↔ when different alterations were described for individual horses. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤ 3 study horses, 4-29 study horses,* ***≥30 study horses****. * = on a treadmill.*

CC = craniocaudal, LL = laterolateral, DV = dorsoventral, ROM = ranges of motion, CoV = coefficient of variance, MinD and MaxD = difference in the vertical movement trough and peak between step cycles, 3D = three-dimensional.

Figure 3.3 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by saddle fitting issues.

3.3.3.3 Saddle design

The evidence extracted about the effect of saddle design on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.4). The evidence demonstrated that alterations to the saddle design can alter the saddle pressures and that an increase in saddle pressures seems to coincide with reduced ROM in the corresponding back region and vice versa. Shortening the panels of a saddle by 10 cm decreases the mean pressures in the cranial third of the pressure mat (-3.9%, p=0.006, and -7.3%, p<0.0001, respectively), while increasing saddle pressures in the middle (+12.0% and +26.1%, both p<0.0001) and caudal (+77.6% and 83.5%, both p<0.0001) thirds of the pressure mat during the rising and sitting phase of the rising trot (Martin *et al.*, 2015). These alterations coincide with increased flexion-extension ROM in the thoracolumbar regions T6-T12 during the rising and sitting phase of the rising trot (+267.5%, p=0.05, and +58.9%, p<0.0001, respectively), T12-T16 during the sitting phase (+59.3%, p<0.0001), and T16-L2 during the rising phase (+68.3%, p<0.0001) and reduced flexion-extension ROM in the thoracolumbar regions T16-L2 during the sitting phase (-26.2%, p=0.05) and L2-L5 during the rising and sitting phase (-25.4%, p<0.01, and -40.6%, p<0.0001, respectively) (Martin *et al.*, 2015). Widening the panels of a saddle by 5 cm each side increases mean pressure in the cranial (+0.3 kPa during the rising phase and +0.9 kPa during the sitting phase, both p<0.05) and middle (+1.0 kPa during the sitting phase, p<0.05) thirds of the pressure mat when the horse is ridden in rising trot, while decreasing peak pressures in the caudal third of the pressure mat (-0.7 kPa during the rising phase and -1.8 kPa during the sitting phase, both p<0.05) (Martin *et al.*, 2017a). These alterations coincide with increased flexion-extension ROM in the thoracolumbar regions T12-T16, T16-L2 during the sitting phase of the rising trot (+1.8° and +2.3° respectively, both p<0.05) and L2-L5 during the rising phase (+0.8°, p<0.05) and decreased flexion-extension ROM in the thoracolumbar regions T12-T16 and T16-L2 during the rising phase (-1.3° and -0.8° respectively, p<0.05) (Martin *et al.*, 2017a). The protocol saddle described by Murray *et al.* (2017), with a modified shape of the saddle tree, panel length and attachment point of the stirrup bars and girth billets, reduces saddle pressures in the T10-T13 region by 55-68% in comparison to a correctly fitting dressage saddle when the horse is ridden in sitting trot (p<0.01). Comparing the saddle pressures when ridden in a foam-filled versus a woollen flocked saddle in sitting trot, higher peak pressures are found in the caudal saddle region for the foam-filled saddle (p<0.05) (Byström *et al.*, 2010), though it must be noted that the collected evidence only evaluated one type of foam. Comparing the saddle pressures when ridden in a saddle with a V-girth system (where the cranial strap attaches to the cranial point of the tree and the caudal strap with a sliding attachment to the middle and rear parts of the tree) versus with a traditional girthing system in sitting trot, the V-girth system exerts higher peak pressures in the cranial saddle region (p<0.05) (Byström *et al.*, 2010).

Study	Outcome measures	Saddle conditions	Walk	Trot
Martin et al (2015)	Mean pressures in longitudinal thirds of the pressure mat	Saddle with shortened panels vs. standard saddle		Cranial region ↓ , mid-caudal regions↑
	Differential pitch ROM at T6-T12, T12-T16, T16-L2, L2-L5			Sitting phase: T6-T12 ↑, T12-T16 ↑, T16-L2 ↓, L2-L5↓ Rising phase: T6-T12 ↑, T16-L2 ↑, L2-L5↓
Martin et al (2017a)	Mean pressures in longitudinal thirds of the pressure mat	Saddle with widened panels vs. standard saddle		Cranial region ↑, caudal region↓
	Differential pitch ROM at T6-T12, T12-T16, T16-L2, L2-L5			Sitting phase: T12-T16 ↑, T16-L2 ↑ Rising phase: L2-L5 ↑, T12-T16 ↓, T16-L2↓
Murray et al (2017)	Peak pressures in the T10-T13 region	Experimental vs. standard saddle		↓
Byström et al (2010)	Peak saddle pressures	Foam-filled vs. woollen flocked saddle		Caudal ↑
		V-girth system vs. traditional girthing		Cranial ↑

*Legend. Outcome measure increases = ↑, decreases = ↓, or where there is no statistical difference = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤ 3 study horses, 4-29 study horses, ≥30 study horses. * = on a treadmill. ROM = ranges of motion.*

Figure 3.4 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by different saddle designs.

3.3.3.4 Saddle type

The evidence extracted about the effect of saddle type on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.5). The evidence demonstrated that a standard treeless saddle (Belock *et al.*, 2012) or one with an incorporated large panel and full-length gullet (Clayton, O'Connor and Kaiser, 2014) induces higher mean and peak pressures in comparison to a correctly fitting treed saddle when the horse is ridden sitting trot (all $p<0.05$). Additionally, evidence was found that showjumping saddles induce higher saddle pressures in comparison to dressage saddles when the horse is ridden at walk and trot ($p<0.05$) (Dittmann *et al.*, 2021). It must be noted that Dittmann *et al.* (2021) did not control for saddle fit in this comparison while they reported more saddle fitting issues in the showjumping saddles compared to the dressage saddles ($p<0.05$).

Study	Outcome measures	Saddle conditions	Walk	Trot
Belock et al (2012)	Mean and peak saddle pressures, saddle forces	Treeless vs. treed saddle		Pressures ↑
Clayton, O'Connor and Kaiser (2014)				
Dittmann et al (2021)	Highest mean saddle pressures	Showjumping vs. dressage saddles	↑	↑

*Legend. Outcome measure increases = ↑, decreases = ↓, or where there are no statistical differences = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤ 3 study horses, 4-29 study horses, ≥30 study horses. * = on a treadmill.*

Figure 3.5 | An effect direction plot of the statistically significant alterations in saddle pressure measurements, induced by different saddle types.

3.3.3.5 The use of saddle pads

The evidence extracted about the effect of the use of saddle pads on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.6). The evidence demonstrated that saddle pads of woollen material might be most effective to decrease saddle pressures. Compared to using no saddle pad, a woollen saddle pad, but not a gel, leather, or foam saddle pad, decreases the maximum overall forces at walk (p=0.009) and in sitting trot (p=0.038) when the horse is ridden in a correctly fitting saddle (Kotschwar, Baltacis and Peham, 2010a). Also compared to using no saddle pads, a woollen half-pad decreased the mean pressures in the caudal saddle region (p≤0.0001) while a gel half-pad increases the mean pressures in the cranial saddle region (p=0.03) when the horse is ridden in a correctly fitting saddle in sitting trot (MacKechnie-Guire, Fisher and Pfau, 2020). Dittmann *et al.* (2021) reported lower saddle pressure values in the horse-rider combinations using a woollen saddle pad as well (p<0.003), but not for any other type of saddle pads, compared to when ridden with non-padded saddle blankets in all gaits, though saddle fit was not controlled for in this comparison. When ridden in saddles with fitting issues, the use of a saddle pad is highly subject-dependent (Harman, 1994; Kotschwar, Baltacis and Peham, 2010b) and does not alter the maximum overall saddle force when the horse is ridden in a saddle with a too-widely fitted tree at walk and in sitting trot in comparison to using no saddle pad (p>0.05) (Kotschwar, Baltacis and Peham, 2010b).

Study	Outcome measures	Saddle conditions	Walk	Trot
Kotschwar, Baltacis and Peham (2010a)	Maximum total saddle forces	With saddle pad vs. without*	↓ (woollen pads)	
Kotschwar, Baltacis and Peham (2010b)		With saddle pad vs. without in a too wide saddle*	↓↑↔	
Mackechnie-Guire, Fisher and Pfau (2020)	Mean and peak saddle pressures	With saddle pad vs. without		Cranial ↑ (gel pad)
				Caudal ↓ (woollen pad)
Dittmann et al (2021)	Highest mean saddle pressures	With saddle pads vs. without	**↓ (sheepskin)**	
Harman (1994)	Saddle pressures	With saddle pad vs. without	↓↑↔	

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there are no statistical differences = ↔. ↓↑↔ when different alterations were described for individual horses. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤ 3 study horses, 4-29 study horses,* ***≥30 study horses****. * = on a treadmill.*

Figure 3.6 | An effect direction plot of the statistically significant alterations in saddle pressure measurements, induced by the use of saddle pads.

3.3.4 Narrative synthesis: how a rider alters a horse's back biomechanics

A total of 22 studies were found to report how a rider alters the horse's back biomechanics, including a total of 487 horses used for ridden work at varying training levels. A descriptive summary table detailing the study aims, population, outcome measures, and measurement tools of each of those studies can be found in Table 3.5. This narrative synthesis collates the results of those studies, revealing how a rider and rider-related characteristics alter a horse's back biomechanics. The identified rider-related characteristics that alter a horse's back biomechanics include the rider's body mass, seating style, riding skills, and asymmetries.

Table 3.5. The descriptive summary table of the studies investigating the effect of a rider on the horse's back biomechanics (n=22).

Study	Study aim(s)	Study sample	Outcome measure(s)	Measurement tool(s)
Bogisch et al (2014)	To describe the effect of increasing velocities within one gait on resulting saddle F	HRP: n=7, horses: 14±4 years, high-level dressage horses, riders: 78±17 kg, saddle: fitted	Min and max of total saddle F when ridden at walk and in sitting trot on the treadmill	Saddle pressure mat
Byström et al (2010)	To assess the influence of saddle-related alterations on saddle P during riding	Horses: n=6, Warmblood riding school horses, riders: n=3, 53-66 kg, saddle fit: sufficient	Max total F and peak P in saddle mat quadrants when ridden overground in sitting and rising trot	Saddle pressure mat
Byström et al (2020a)	To compare movement symmetry in horses walking and trotting on a treadmill unridden in a free posture and ridden in a dressage frame	HRP: n=7, horses: 14±4 years, high-level dressage horses, riders: 78±17 kg, saddle fit: NC	MinD and MaxD of withers and sacrum movement unloaded in a free posture and ridden in a dressage frame at walk and sitting trot on the treadmill	Optical motion capture
De Cocq et al (2009a)	To determine the effects of rising and sitting trot on the movements of the horse's back	Horses: n=12, 11±4 years, Warmblood riding school horses, riders: n=1, 84kg, saddle fit: NC	Lumbar flexion-extension movement at trot unridden and ridden overground in sitting and rising trot	Optical motion capture
Dittmann et al (2021)	To investigate how well the subjective assessment of saddle fit correlates with saddle P measurements during riding	HRP: n=196, horses: 10±3 years, various disciplines and breeds, riders: 67±11 kg, saddle fit: assessed by a veterinarian	Highest mean P (four adjacent sensors with the highest mean P) when ridden overground in walk and sitting and rising trot	Saddle pressure mat
Dyson et al (2019)	To assess the gait responses of horses to riders of similar ability, but different body mass	Horses: n=6, various breeds, riders: n=4 (60.8, 77.8, 91.0, 142.1 kg), saddle fit: assessed and adjusted if required	MinD and MaxD of withers and sacrum when ridden overground by a light, moderate, heavy, and very heavy rider in rising trot	IMUs
Egenvall et al (2019)	To investigate the effects of HNPs and rider on movement symmetry of the withers at walk	HRP: n=7, horses: advanced-level dressage horses, riders: 78±17 kg, saddle fit: well-fitted	MinD of withers unridden and ridden in walk on a treadmill in 6 different HNP	Optical motion capture
Fruehwirth et al (2004)	To evaluate P distribution under an English saddle at walk and trot	HRP: n=12, horses: 7-25 years, various breeds and training levels, riders: 68±10 kg, saddle fit: well-fitting	Max overall F, max F in the saddle mat quarters, and withers ROM when ridden overground at walk and sitting trot	Saddle pressure mat & Optical motion capture
Gunst et al (2019)	To investigate the effects of rider asymmetries in sitting trot on the F distribution on the horse's back	HRP: n=80, horses: 8±3 years, various breeds and disciplines, riders: 68.5±11.6 kg, saddle fit: NC	F difference between left and right halves of P mat when ridden overground in sitting trot in relation to the rider's handedness, footedness, hip collapse and upper body tilt indexes	Saddle pressure mat & IMUs for measurements of the rider's asymmetries
Heim et al (2016)	To establish normal back ROM in a uniform population of horses trotting under different conditions	Horses: n=27, riding/ driving Franches-Montagnes stallions, riders: n=1, saddle fit: NC	LL and DV ROM at L3 and sacrum when trotting overground unridden and ridden in sitting and rising trot	IMUs

Lagarde et al (2005)	To compare the horse-rider interaction with an expert and a novice rider via coordination dynamics	Horses: n=1, riders: n=2 (1 professional, 1 recreational), 65 kg, saddle fit: NC	Temporal regularity of the vertical peaks and troughs of the sacrum when ridden overground in sitting trot by a professional and recreational rider	Optical motion capture
Licka, Kapaun and Peham (2004)	To document the effect of an experienced and novice rider on the vertical movement of the horse's croup	Horses: n=20, 4-22 years, various breeds and training levels, riders: n=1 experienced, 1 novice, 65 kg, saddle fit: NC	Symmetry % of the vertical sacrum movement at trot unridden and when ridden overground by an experienced and a novice rider	Optical motion capture
MacKechnie -Guire et al (2020b)	To evaluate the effect of rider asymmetry on equine locomotion	HRP: n=10, horses: 12±1 years, Warmblood dressage and eventing horses, riders: 71±11 kg, saddle fit: correct	3D translational and rotational ROM of the horse's back and MinD and MaxD of withers and sacrum when ridden overground in rising trot without and with induced rider-asymmetry	IMUs
MacKechnie -Guire and Pfau (2021a)	To compare the back kinematics in dressage horses when ridden in sitting trot and trotting in-hand	Horses: n=10, 11±1 years, high-level dressage horses, riders: n=4, 74±1 kg, saddle fit: correct	Differential rotational ROM and MinD and MaxD of the horse's back unridden and ridden overground in (sitting) trot	IMUs
MacKechnie -Guire and Pfau (2021b)	To compare the back kinematics in dressage horses when ridden in sitting trot and trotting in-hand	Horses: n=10, 11±1 years, high-level dressage horses, riders: n=4, 74±1 kg, saddle fit: correct	Differential rotational ROM of the horse's back unridden and ridden overground in (sitting) trot	IMUs
Martin et al (2016)	To evaluate the effect of the rider's position at rising trot on the P distribution and the horse's back movements	Horses: n=3, 7-12 years, riding school horses, riders: n=1, 72.1 kg, saddle fit: well-fitted	Mean P of transversal thirds of the P mat and flexion-extension ROM of the back during the sitting vs. rising phase of the trot when ridden overground	Saddle pressure mat & IMUs
Martin et al (2017b)	To evaluate the effects of the rider on the horse's back kinematics under the saddle during the trot	Horses: n=3, 7-12 years, riding school horses, riders: n=1, 70 kg, saddle fit: well-fitted	Flexion-extension ROM of the horse's back when trotting overground with a saddle and ridden in rising trot	IMUs
Peham et al (2004)	To show the influence of the rider on the variability of the horse's gait	Horses: n=21, 4-22 years, various levels and breeds, riders: n=1, 75 kg, saddle fit: correct	Inter-stride coefficient of variance of the 3D displacement, velocity and acceleration at L4 when trotting unridden and ridden in sitting trot on a treadmill	Optical motion capture
Peham et al (2009)	To compare the stability of the rider's seat in different positions at the trot	Horses: n=10, 13±6 years, various breeds, riders: n=1, 80 kg, saddle fit: fitted	Min, max and mean overall F when ridden in rising, sitting, and two-point seated trot on the treadmill	Saddle pressure mat
Persson-Sjodin et al (2018)	To assess how different seating styles influence the horse's movement symmetry at trot	Horses: n=26, 8-18 years, Warmblood dressage and jumping horses, riders: n=1, 60 kg, saddle fit: NC	MinD and MaxD of the sacrum when trotting overground unridden and ridden in a rising, sitting and two-point seat	IMUs
Roepstorff et al (2009)	To demonstrate whether rising trot causes asymmetrical effects on the horse's locomotion patterns	HRP: n=7, horses: 14±4 years, high-level dressage horses, saddle fit: NC	Vertical movement at T6, L5, and S3 when ridden at left and right rising trot on a treadmill	Optical motion capture
Roost et al (2019)	To assess pressure distribution and magnitude in horses ridden by riders of similar ability but different body mass	Horses: n=6, various breeds, riders: n=4 (60.8, 77.8, 91.0, 142.1 kg), saddle fit: assessed and adjusted if required	Mean P of the saddle mat quadrants and mean and max P over the total saddle mat area when ridden by a light, moderate, heavy, and very heavy rider overground at walk and rising trot	Saddle pressure mat

P = pressure, F = force, NC = saddle fit was not clarified, HRP = horse-rider pairs, Min = minimum, Max = maximum, MinD and MaxD = difference in the vertical movement trough and peak between step cycles, HNP = head-neck positions, ROM = range of motion, LL = laterolateral, DV = dorsoventral, 3D = three-dimensional, IMUs = inertial measurement units.

3.3.4.1 The rider

The evidence extracted about the effect of a rider on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.7). The evidence demonstrated that forces beneath the saddle are equivalent to the rider's weight when riding the horse at walk and twice the rider's weight in sitting trot (Fruehwirth *et al.*, 2004), with saddle force maxima and minima respectively increasing and decreasing with the horse's speed at walk (+34.1% and -26.0% of the rider's weight (N)/(m/s), $p<0.01$) and trot (+44.9% and -12.2% of the rider's weight (N)/(m/s), $p<0.01$) (Bogisch *et al.*, 2014).

The evidence further demonstrated that a rider alters the horse's back movement by extending the back, decreasing roll and yaw ROM in the cranial back region underneath the saddle while increasing ROM between the more caudal back segments. Compared to walking with a saddle, the rider decreases the ROM at the withers ($p<0.05$) (Fruehwirth *et al.*, 2004), though ROM direction was not clarified in this study. Compared to trotting with a saddle, the rider increases the degree of extension ($p<0.001$) while increasing the flexion-extension ROM ($p<0.001$) in the lumbosacral region in both the sitting and rising trot, and decreases the degree of flexion in the sitting trot only ($p<0.001$) while increasing lateral bending ROM in the rising trot only ($p\leq0.005$) (de Cocq *et al.*, 2009a). The rider in the sitting trot also decreases the ROM of the withers ($p<0.05$) (Fruehwirth *et al.*, 2004), while the rider in the rising trot also increases the flexion-extension ROM at T6-T12 during the rising (+1.7(0.8)°, $p<0.05$) and the sitting (+3.4(0.3)°, $p<0.05$) phases of the rising trot and at T12-T16 during the rising phase (+1.2(0.4)°, $p<0.05$), while decreasing the flexion-extension ROM at T12-T16 (-1.3(0.4)°, $p<0.05$) and T16-L2 (-0.6(0.2)°, $p<0.05$) during the sitting phase (Martin *et al.*, 2017b), compared to trotting with a saddle. Compared to trotting without a saddle or rider, the rider in the sitting trot decreases the differential roll and yaw ROM at T5-T13 ($p\leq$0.0001-0.04), while increasing the differential roll, pitch, and yaw ROM at T18-L3 ($p<$0.0001-0.003) (MacKechnie-Guire and Pfau, 2021a, 2021b). Compared to trotting without and with a saddle, the rider decreases the dorsoventral ROM at L3 and the sacrum (all $p<0.001$) and the laterolateral ROM at the sacrum ($p<0.04$) in the sitting and rising trot, while decreasing the laterolateral ROM at L3 only in the rising trot ($p<0.001$) (Heim *et al.*, 2016).

Inconsistent evidence was found for the effect of a rider on the asymmetry of the horse's back movement. A rider decreases the asymmetry at wither level when walking in a more restricted, high head-neck position ($t(118)$=2.68-4.03, $p\leq$0.001-0.01) but not in more freely head-neck positions or a competition position ($p>0.05$) (Egenvall *et al.*, 2019) nor when comparing walking ridden in a dressage frame compared to walking unridden in an unrestricted head-neck position ($p>0.05$) (Byström *et al.*, 2020a). When ridden 'on the bit' by an experienced dressage rider in sitting trot compared to trotting in-hand/ unrestrained, a rider decreases the asymmetry at the withers ($p=0.02$), T18 ($p=0.04$), L3 ($p=0.04$) and sacrum ($p=0.01$) according to MacKechnie-Guire and Pfau (2021a), does not alter sacrum movement symmetry (p>0.05) according to Persson-Sjodin *et al.* (2018), and increases the sacrum movement asymmetry (1.4%, p=0.016) according to Licka, Kapaun and Peham (2004) and the withers (p=0.01) and sacrum (p<0.001) movement asymmetry according to Byström *et al.* (2020a). When ridden in rising trot, the rider increases the asymmetry at the sacrum in comparison to when trotting unridden (p<0.05) (Persson-Sjodin *et al.*, 2018).

Evidence also demonstrated that the rider has a stabilising effect on the horse's back movement, quantified as a decrease in the craniocaudal velocity (p<0.05) and acceleration (p<0.01) coefficient of variance at L4 when ridden in sitting trot compared to when trotting unridden (Peham *et al.*, 2004).

<table>
<tr><th>Study</th><th>Outcome measures</th><th>Ridden conditions</th><th>Walk</th><th>Trot</th></tr>
<tr><td rowspan="2">Fruehwirth et al (2004)</td><td>Max overall saddle force</td><td rowspan="2">Ridden vs. with saddle</td><td>~ the rider's weight</td><td>2 times the rider's weight</td></tr>
<tr><td>ROM at withers</td><td colspan="2">↓</td></tr>
<tr><td>Bogisch et al (2014)</td><td>Min and max saddle forces</td><td>At higher vs. lower speeds*</td><td>Min ↓
Max ↑</td><td>Min ↓
Max ↑</td></tr>
<tr><td rowspan="2">De Cocq et al (2009a)</td><td>Lumbosacral flexion and extension angles</td><td>Sitting and rising trot vs. unridden</td><td rowspan="2"></td><td>Sitting trot: Flexion ↓
Sitting and rising trot: Extension ↑</td></tr>
<tr><td>Lumbosacral FE and LB ROM</td><td>Sitting and rising trot vs. unridden</td><td>Sitting and rising trot: FE ↑
Rising trot: LB ↑</td></tr>
<tr><td>Martin et al (2017b)</td><td>Differential pitch ROM at T6-T12, T12-T16, T16-L2, L2-L5</td><td>Ridden in rising trot vs. unridden</td><td></td><td>Sitting phase: T6-T12 ↑
T12-T16 ↓, T16-L2 ↓
Rising phase: T6-T12 ↑, T12-T16 ↑</td></tr>
<tr><td>Mackechnie-Guire and Pfau (2021a)</td><td>MinD and MaxD at T5, T13, T18, L3, TS</td><td rowspan="2">Ridden in sitting trot vs. unridden</td><td></td><td>MinD L3 ↓
MaxD T5, T18, TS ↓</td></tr>
<tr><td>Mackechnie-Guire and Pfau (2021b)</td><td>Differential roll, pitch, yaw ROM at T5-T13, T13-T18, T18-L3, L3-TS</td><td></td><td>Roll, yaw T5-T13 ↓
Roll, pitch, yaw T18-L3 ↑</td></tr>
<tr><td>Heim et al (2016)</td><td>LL and DV ROM at L3 and sacrum</td><td>Ridden vs. with or without a saddle</td><td></td><td>↓</td></tr>
<tr><td rowspan="2">Egenvall et al (2019)</td><td rowspan="2">Withers MinD</td><td>Ridden vs. unridden in restricted, high HNP*</td><td>↓</td><td rowspan="2"></td></tr>
<tr><td>Ridden vs. unridden in free/ competition HNP*</td><td>↔</td></tr>
<tr><td>Byström et al (2020a)</td><td>Withers and sacrum MinD and MaxD</td><td>In competition HNP vs. unridden in free HNP*</td><td>↔</td><td>MinD and MaxD withers ↑
sacrum MaxD ↑</td></tr>
<tr><td>Persson-Sjodin et al (2018)</td><td>Sacrum MinD and MaxD</td><td>Sitting, rising, and 2-point seated trot vs. unridden</td><td></td><td>↑ (rising trot)
↔ (sitting or 2-point seated trot)</td></tr>
<tr><td>Licka, Kapaun and Peham (2004)</td><td>Sacrum movement asymmetry %</td><td>Ridden by an experienced rider vs. unridden</td><td></td><td>↑</td></tr>
<tr><td>Peham et al (2004)</td><td>3D linear displacement, velocity, and acceleration inter-stride CoV at L4</td><td>Ridden vs. unridden*</td><td></td><td>CC velocity ↓
CC acceleration ↓</td></tr>
</table>

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there are no statistical differences = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤3 study horses, 4-29 study horses,* ***≥30 study horses****. * = on a treadmill.*

ROM = ranges of motion, min= minimum, max = maximum, FE = flexion-extension, LB = lateral bending, LL = laterolateral, DV = dorsoventral, MinD and MaxD = difference in the vertical movement trough and peak between step cycles, CoV = coefficient of variance, CC = craniocaudal, 3D = three-dimensional.

Figure 3.7 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by a rider.

3.3.4.2 The rider's body mass

The extracted evidence of the effect of the rider's body mass on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.8). The evidence demonstrated that attaching a mass, equivalent to that of a rider (75 kg), to the saddle induces more extension and less flexion in the lumbosacral region at both gaits (all $p<0.05$) (de Cocq, van Weeren and Back, 2004). The evidence further demonstrated that a rider's body mass correlates with the saddle pressures and can cause signs of lameness, i.e. increased movement asymmetries. At walk and trot, the rider's body mass is positively correlated with the highest mean saddle pressures (R^2=0.5-0.9, $p<0.0015$) (Dittmann *et al.*, 2021) and the mean and peak total saddle pressures are significantly lower for a rider with a light body mass (10-12% of the horse's body mass) in comparison to riders with a moderate, heavy, or very heavy body mass ($p<0.001$) (12-15%, 15-18%, and >18% of the horse's body mass, respectively) and for riders with a moderate or heavy body mass in comparison to a rider with a very heavy body mass ($p<0.001$) (Roost *et al.*, 2020). In rising trot, the rider's body mass is also positively correlated with the movement asymmetry at the sacrum (R^2=0.4, $p<0.05$) (Dyson *et al.*, 2019).

Study	Outcome measures	Ridden conditions	Walk	Trot
De Cocq, van Weeren and Back (2004)	Lumbosacral flexion-extension angles and ROM	Without vs. with loaded saddle*	Extension ↑, Flexion ↓ ROM ↔	
Dittmann et al (2021)	Highest mean saddle pressure	Ridden by riders with higher vs. lower body mass	↑	
Roost et al (2020)	Mean and peak saddle pressures	Ridden by riders with higher vs. lower body mass	↑	
Dyson et al (2019)	Withers and sacrum MinD and MaxD	Ridden by riders with higher vs. lower body mass		Sacrum MaxD ↑

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there is no statistical difference = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤ 3 study horses, 4-29 study horses,* ***≥30 study horses****. * = on a treadmill.*

Figure 3.8 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by the rider's body mass.

3.3.4.3 The rider's seating style

The extracted evidence of the effect of the rider's seating style on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.9). The evidence demonstrated that being seated induces higher saddle pressures compared to rising in the saddle. In the sitting trot compared to the rising trot, the rider induces lower minimum saddle forces ($p<0.05$) (Peham *et al.*, 2009) but higher maximum saddle forces ($p<0.001$-0.05) (Peham *et al.*, 2009; Byström *et al.*, 2010) and mean ($p<0.001$) and peak ($p<0.05$) pressures on the horse's back, though lower peak pressures in the cranial outer saddle quadrant ($p<0.05$) (Byström *et al.*, 2010). In the two-point seated trot compared to the sitting and rising trot, the rider induces lower maximum forces ($p<0.05$) (Peham *et al.*, 2009). In the sitting phase compared to the rising phase of the rising trot, the rider induces higher mean saddle pressures (+3.1 kPa, $p<0.05$), in particular in the mid and caudal thirds of the pressure mat (+1.9 kPa and +8.5 kPa, respectively, both $p<0.05$) (Martin *et al.*, 2016).

The alterations associated with the rider's seating style in the saddle pressure measurements coincide with alterations in the horse's back movement. In the sitting compared to the rising trot, the rider induces less lumbosacral flexion ($p\leq0.001$), flexion-extension ROM ($p<0.001$), lateral bending ROM ($p\leq0.005$) (de Cocq *et al.*, 2009a), and dorsoventral ROM at L3 ($p<0.001$), but increases laterolateral ROM at L3 ($p<0.001$) according to Heim *et al.* (2016). In the sitting phase compared to the rising phase of the rising trot, the rider decreases the flexion-extension ROM at T12-T16 and T16-L2 (-3.2° and -1.2°, $p<0.05$) and increases the flexion-extension ROM at T6-T12 and L2-L5 (+1.7° and +0.7°, $p<0.05$) (Martin *et al.*, 2016) and lowers the horse's lumbar (L5) back ($p<0.05$) (Roepstorff *et al.*, 2009). Riding the horse in rising trot on the left diagonal slightly lowers the withers during the left forelimb/ right hindlimb push-off compared to when on the right diagonal ($p<0.05$) (Roepstorff *et al.*, 2009).

Study	Outcome measures	Ridden conditions	Walk	Trot
Peham et al (2009)	Mean, min, and max saddle forces	Ridden in sitting vs. rising*		Min ↓, max ↑
		Ridden in 2-point seated vs. sitting*		Min ↑, max ↓
		Ridden in 2-point seated vs. rising*		Max ↓
Byström et al. (2010)	Mean saddle pressures, Max saddle forces	Ridden in sitting vs. rising trot		↑
	Peak saddle pressures			↑, cranial outer quadrant ↓
Martin et al (2016)	Mean saddle pressures	Sitting vs. rising phase of the rising trot		↑ in middle & caudal thirds
	Differential pitch ROM at T6-T12, T12-T16, T16-L2, L2-L5			T6-T12 ↑, T12-T16 ↓, T16-L2 ↓, L2-L5 ↑
De Cocq et al (2009a)	Lumbosacral flexion and extension angles	Ridden in sitting vs. rising trot		Flexion ↓
	Lumbosacral FE and LB ROM			FE ↓, LB ↓
Heim et al (2016)	LL and DV ROM at L3 and sacrum	Ridden in sitting vs. rising trot		LL at L3 ↑, DV ↓
Roepstorff et al (2009)	Vertical position and ROM at T6, L5, and sacrum	Sitting vs. rising phase of the rising trot*		Position L5 ↓
		On the left vs. right diagonal in rising trot*		Position T6 ↓

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there are no statistical differences = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤3 study horses, 4-29 study horses, **≥30 study horses**. * = on a treadmill.*

Min = minimum, Max = maximum, FE = flexion-extension, LB = lateral bending, ROM = ranges of motion, LB = lateral bending, LL = laterolateral, DV = dorsoventral.

Figure 3.9 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by the rider's seating style.

3.3.4.4 The rider's riding skills

The extracted evidence of the effect of the rider's riding skills on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.10). The evidence demonstrated that the horse's back movement is more regular, though not more symmetric when ridden by a less skilled rider compared to a more skilled rider. The time interval between the troughs, but not the peaks ($p>0.05$), of the horse's sacrum vertical movement is less variable ($t(14)=2.85$, $p<0.05$) when ridden by a professional rider compared to when ridden by a recreational rider in sitting trot (Lagarde *et al.*, 2005). Conversely, the movement symmetry of the horse's sacrum does not differ when ridden by a novice and an experienced dressage rider in sitting trot ($p>0.05$), though this difference is highly subject-dependent (Licka, Kapaun and Peham, 2004).

Study	Outcome measures	Ridden conditions	Walk	Trot
Licka, Kapaun and Peham (2004)	Symmetry % of sacrum movement	Ridden by an experienced vs. novice rider		↔
Lagarde et al (2005)	Regularity of trunk oscillations	Ridden by an expert vs. hobby rider		↑

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there are no statistical differences = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: ≤3 study horses, 4-29 study horses,* ***≥30 study horses****. * = on a treadmill.*

Figure 3.10 | An effect direction plot of the statistically significant alterations in kinematic measures of the horse's back, induced by the rider's riding skills.

3.3.4.5 The rider's asymmetries

The extracted evidence of the effect of the rider's asymmetries on the horse's back biomechanics is summarised in an effect direction plot (Figure 3.11). The evidence demonstrated that a rider's asymmetries, albeit physical or (induced) postural, relate to the symmetry of the pressure distribution on the horse's back and the horse's back movement. In sitting trot, riders collapsing in one hip induce higher forces in the pressure mat half contralateral to the side of the hip collapse (+1.5 N/hip collapse°, $p<0.001$) and riders tilting their upper body to one side induce higher forces in the pressure mat half ipsilateral to the side of the tilt (+1.4 N/hip collapse°, $p<0.001$) (Gunst *et al.*, 2019). Comparing a horse's back movement in rising trot when ridden by a rider without and with an asymmetric posture induced via means of shortening one stirrup by 5 cm, the rider with the asymmetric stirrup lengths increases the yaw ROM at T5 ($p=0.003$), L3 ($p=0.04$), and sacrum ($p=0.02$) on both reins, while increasing laterolateral ROM at T5 ($p=0.04$), T18 ($p=0.04$), and L3 ($p=0.03$) only on the rein with the shortened stirrup on the outside and decreasing pitch ROM at T5 ($p=0.03$) and L3 ($p=0.04$) and roll ROM at T5 ($p=0.05$) only on the rein with the shortened stirrup on the inside (MacKechnie-Guire *et al.*, 2020b). The horse's back movement asymmetry does not differ when ridden in rising trot by a rider with symmetric and asymmetric stirrup lengths ($p>0.05$) (MacKechnie-Guire *et al.*, 2020b).

Study	Outcome measures	Ridden conditions	Walk	Trot
Gunst et al (2019)	Saddle forces	Ridden by riders with left vs. right upper or lower body laterality		↔
		Ridden by riders with vs. without a hip collapse		**Contralateral ↑**
		Ridden by riders with vs. without upper body tilt		**Ipsilateral ↑**
Mackechnie-Guire et al (2020b)	CC, LL, DV and roll, pitch, yaw ROM at T5, T13, T18, L3, and sacrum	Ridden by a rider with vs. without induced asymmetry		Shortened stirrup on outside: Yaw T5, L3, TS ↑, LL T5, T18, L3 ↑ Shortened stirrup on inside: Yaw T5, L3, TS ↑, pitch T5, L3 ↓, roll T5 ↓
	MinD and MaxD at T5, sacrum			↔

Legend. *Outcome measure increases = ↑, decreases = ↓, or where there is no statistical difference = ↔. Colour coding: study has a low, moderate, or high methodological quality. Sample size coding: <u>≤ 3 study horses</u>, 4-29 study horses, **≥30 study horses**. * = on a treadmill.*

CC = craniocaudal, LL = laterolateral, DV = dorsoventral, ROM = ranges of motion, TS = in between tubera sacrale.

Figure 3.11 | An effect direction plot of the statistically significant alterations in saddle pressure measurements and kinematic measures of the horse's back, induced by the rider's asymmetries.

3.4 Discussion

This study aimed to identify, evaluate, and summarise the current evidence on the effect of a saddle and rider on the horse's back biomechanics during straight-line walk and trot locomotion. The methodological quality of the collected evidence varied from low to high, with the majority of the evidence having a moderate-to-high methodological quality. Collectively, the evidence demonstrates that saddle and rider (1) increase saddle pressure measurements with forces equivalent to the rider's weight at walk and twice the rider's weight at trot, which increase when going up in speed, (2) more extension in the lumbosacral region at walk and trot, (3) decrease roll and yaw ROM in the cranial back region underneath the saddle, while increasing ROM in the different directions between the more caudal back segments at trot, with preliminary evidence indicating similar responses at walk, (4) higher saddle pressures are associated with decreased ROM in that area, and vice versa, (5) induce inconsistent alterations in the asymmetry of the horse's back movement when ridden at walk, which are associated with the horse's head-neck position, and in sitting trot, but increase asymmetry at the sacrum in rising trot, and (6) have a stabilising effect on the horse's back movement. These biomechanical responses are influenced by the fitting, design, and type of the saddle, the use of saddle pads, and the rider's body mass, seating style, riding skills, and asymmetries. A second aim of this study was to relate the reported biomechanical outcomes of the horse's back to the horse's back functioning, which is discussed below.

3.4.1 How saddle pressure measurements relate to a horse's back functioning

Excessive pressures on soft tissue structures can cause pressure-induced injuries, including inflammation and focal oedema, muscle soreness, and epaxial muscle atrophy (Von Peinen *et al.*, 2010). Understanding how to minimise peak pressures exerted on the horse's back when ridden is thus in the interest of managing back health in the ridden horse. This systematic review demonstrated consistency in the evidence that correctly fitting saddles reduce peak pressures on the horse's back, with conventional saddles doing so more effectively than treeless saddles. The review also demonstrated that alterations in saddle design and the use of saddle pads considered in function of saddle fit, as well as managing the rider's body mass and asymmetries in function of the individual horse, might aid further reduction of peak pressures and optimisation of pressure distribution.

Clinical thresholds of 11 kPa for mean pressures and 30 kPa for maximum pressures measured with a saddle pressure mat have also previously been used as outcome measure of the saddle pressure measurements (Byström *et al.*, 2010), with pressures exceeding these thresholds increasing the risk of back pain in the horse (Werner *et al.*, 2002; Nyikos *et al.*, 2005). In the study by Von Peinen *et al.* (2010), pressure measurements in horses with clinical signs of saddle/ back soreness exceeded the mean and maximum pressure thresholds at all gaits (with 39-178% and 2-87% respectively) in contrast to clinically sound horses with correctly fitting saddles, for which the mean and maximum pressures remained below the thresholds at all gaits. Although the findings from Von Peinen *et al.* (2010) support the use of the thresholds suggested by Byström *et al.* (2010), values exceeding these thresholds in 'healthy' horses with no signs of back problems, saddle soreness, or lameness and with a correctly fitting saddle were seen in other studies, such as these by Murray *et al.* (2017) and Mackechnie-Guire *et al.* (2018). Therefore, alterations in saddle pressures should be evaluated in the context of the individual horse-saddle-rider combination and the clinical saddle pressure thresholds should be interpreted with caution and were, therefore, not reported in this systematic review.

3.4.2 How the horse's back posture relates to a horse's back functioning

As defined in Chapter 2, posture can be defined and measured as the alignment between body segments. The alignment of the horse's back is measured as the flexion-extension angle between the lumbosacral segments by de Cocq, van Weeren and Back (2004) and de Cocq *et al.* (2009a). De Cocq, van Weeren and Back (2004) suggested that the increase in the degree of extension in the horse's back when loaded with a saddle and rider could contribute to the development of back problems. When the spine is extended, the interspinous processes spaces narrow, which can induce compression on the interspinous ligament and friction between the spinal processes (Denoix, 1999) and may lead to spinal osseous lesions if occurring repetitively (Jeffcott, 1980; Zimmerman, Dyson and Murray, 2012). Therefore, the degree of extension of the ridden horse's back is of particular interest in advancing our understanding of the loading mechanisms of the back and the association with spinal pathomechanisms in the ridden horse. This systematic review demonstrated consistency in the evidence for the horse's lumbosacral region to extend more when loaded with a rider, or an equivalent weight, at walk and trot. However, no studies were found to report the degree of extension in the thoracic region when ridden, although the mid-caudal thoracic region has the highest prevalence of pathological changes in the equine spine (Townsend *et al.*, 1986; Zimmerman, Dyson and Murray, 2011; Clayton and Stubbs, 2016). Considering the association between rider-induced extension in the horse's back and the prevalence of back problems in the ridden horse (Jeffcott, 1980; de Cocq, van Weeren and Back, 2004), quantitative measurements of the degree of extension in the horse's mid-caudal thoracic region when loaded with a saddle and rider could provide new insights about the pathomechanisms of back problems in the ridden horse. Furthermore, more evidence is warranted to evaluate the extrapolation of the study findings from de Cocq, van Weeren and Back (2004) and de Cocq *et al.* (2009a) to the general equine population when ridden and in the field. Chapter 4 expands on this research field of interest, investigating novel research methods to quantify the horse's back posture, including the mid-caudal thoracic region, when loaded with saddle and rider and in the field. Regardless of the need for more quantitative evidence to continuate these study findings, it is suggested that improving core strength and postural control in the horse can support the horse in accommodating the extending effect of a rider's load on the horse's back, in favour of the horse's back functioning (Clayton, 2012, 2016a). How the horse's back functioning relates to the degree of extension in the horse's back when loaded with a saddle and rider is investigated in Chapter 5B.

3.4.3 How ROM of the horse's back relate to a horse's back functioning

The majority of the studies included in this systematic review that investigated the horse's back kinematics reported ROM values. Associations between back kinematics when ridden and saddle pressures were identified. An increase in saddle pressures seems to coincide with reduced ROM in the corresponding back region and vice versa. The area between the withers and the mid-thoracic region (T13) is considered to be exposed to the highest pressures (Von Peinen *et al.*, 2010; Murray *et al.*, 2017) and represents the region where ROM decreases (Fruehwirth *et al.*, 2004; MacKechnie-Guire and Pfau, 2021a, 2021b) when ridden. Being ridden was also found to increase the ROM between the more caudal back segments (de Cocq *et al.*, 2009a; MacKechnie-Guire and Pfau, 2021a, 2021b). Furthermore, alterations in saddle design (Martin *et al.*, 2015, 2017a) and the rider's seating style (Martin *et al.*, 2016) that increased saddle pressures in a particular saddle region coincided with reduced flexion-extension ROM in this saddle region, with compensatory increased ROM in adjacent back regions where pressures reduced.

The decrease in ROM at the withers when ridden was suggested to represent a stabilising effect of the rider (Fruehwirth *et al.*, 2004). However, from the available evidence, it is not yet clear if this locomotory adaptation is effectively induced by the rider, who engages the horse to stabilise its spinal movement, or by the saddle, which may constrain the skin and/ or back movement by its placement on the mid-caudal thoracic region. This area will be further investigated in Chapter 5A of this thesis. The increased ROM observed in the more caudal segments of the horse's back (from T13 onwards) might represent a compensatory movement pattern from the decreased ROM in the more cranial back segments, resulting from a mechanical transmission between the spinal segments. However, as acknowledged by de Cocq *et al.* (2009a), increased ROM in the horse's back kinematics can indicate both a mobilising and a destabilising effect on the horse's back. How the increased ROM observed when ridden links to the horse's back functioning will also be studied further in Chapter 5 of this thesis.

3.4.4 How asymmetry of the horse's back movement relates to a horse's back functioning

Movement asymmetries are associated with asymmetric loading of the musculoskeletal system and abnormal levels of upper body movement asymmetry are considered an indication of lameness in the horse (van Weeren *et al.*, 2017, 2018). Lameness induces movement adaptations in the horse's back in terms of posture and ROM (Gómez Álvarez *et al.*, 2007, 2008). However, some degree of asymmetry is common in healthy and functional sports horses (Rhodin *et al.*, 2017; van Weeren *et al.*, 2017) and, as demonstrated by this systematic review, can originate from rider- and horse-related factors (Byström *et al.*, 2020b). The findings from this study demonstrated that the horse's movement asymmetries are closely associated with the head-neck position the horse is ridden in as well as with the rider's seating style and body mass. When ridden with an asymmetric seating style, such as the rising trot (Persson-Sjodin *et al.*, 2018), or by a rider with a higher body mass (Dyson *et al.*, 2019), hindlimb push-off asymmetry increases, which is measured as the difference between the peak vertical positions of the sacrum during the two step cycles. The interpretation of the horse's movement asymmetries should thus be made in the context of the individual horse, where abnormal levels of asymmetry are considered unfavourable for overall musculoskeletal function.

3.4.5 How variability of the horse's back movement relates to a horse's back functioning

Movement variability, the variation in a specified movement pattern, is recognised to play an important role in the optimal functioning of healthy and adaptable systems in human sports medicine (Van Emmerik and Van Wegen, 2000). Whilst high levels of movement variability can be associated with a lack of balance and motor control (Newell and Corcos, 1993), too low levels of movement variability can be an indicator of musculoskeletal pathologies, such as back pain (Seay, Van Emmerik and Hamill, 2011) or lameness in the horse (Peham *et al.*, 2001). In the equine literature, movement variability has also been associated with movement 'stability' (Peham *et al.*, 1998a) and the harmony of the horse-rider interaction (Peham *et al.*, 1998b), with more consistent movement patterns indicating more stabilised movement and a more harmonic interaction between horse and rider. This systematic review demonstrated that a rider, particularly a more skilled rider riding in a correctly fitting saddle, can decrease the variability of the horse's back movement, thereby having a stabilising effect on the horse's back movement. However, it could be speculated that in the horse as well, lower levels of movement variability indicate better back functioning to a certain extent, with variability below those levels potentially indicating back pain and problems. As suggested by Egan, Brama and McGrath (2019), knowing the individual horse's optimal level of variability could enable early detection of problems if the horse deviates from its own optimal window.

3.4.6 Limitations of the evidence included in this systematic review

The main limitation of the evidence included in this systematic review is that most experimental findings were based on a small sample size. This limitation questions the validity of the evidence for the general equine population, warranting future research to recruit bigger study samples. Secondly, whilst this systematic review provided an overview of the saddle- and rider-related characteristics that can be considered as confounding factors in research studying the horse-saddle-rider interaction, a considerable proportion of studies identified in this systematic review did not control for these confounding factors in their research methodologies. For example, this systematic review found consistent evidence for saddle fit to influence a horse's back biomechanics, though 34% of the studies did not mention if saddle fit was verified in their study horses. In the studies reporting saddle fit, saddle fit was evaluated by a veterinarian, qualified/ trained saddle fitter, or saddle maker, though some studies did not clarify by who and how saddle fit was evaluated, indicating inconsistent saddle fitting practice within the literature. Along the same lines, previous literature has demonstrated that the head-neck position (Rhodin, 2008) and degree of collection (Byström, 2019) a horse is ridden in influences the horse's back kinematics, while the majority of studies did not report the head-neck position and degree of collection the horses were ridden in. The speed of the horse's gait is another confounding factor in the study of the horse's back biomechanics (see Section 2.3.3), which was not controlled for, or the control of speed was not clarified, in 13% of the identified studies. Additionally, the clinical condition of the study horses is missing detail in a majority of the studies (see Appendix A.V), though associations between the horse's back biomechanics and the presence of lameness (Gómez Álvarez, 2007) or back dysfunctions (Wennerstrand, 2008) have previously been established. These observations might thus indicate a certain level of confounding bias in the identified experimental findings. Future research reporting measures of the ridden horse's back biomechanics is recommended to report how characteristics related to the horse, saddle, and rider have been controlled for to optimise its methodological quality.

3.4.7 Limitations of the systematic review study

The main limitation of this study is the large heterogeneity observed in the outcome parameters, study conditions, and study populations of the identified studies. As a result, a meta-analysis or overall effect size calculations were precluded and a narrative synthesis was performed. A common criticism of a narrative synthesis is that it is subject to poor transparency (Campbell *et al.*, 2018), though attempts were made to address this by adhering to the SWiM guidelines defined by Campbell *et al.* (2020). Another limitation of this systematic review is that three studies were excluded due to a language barrier; studies in German were not included for analysis. Additionally, grey literature and conference abstracts were not considered for inclusion as the design of such would not suit the study synthesis protocol involved in a systematic review, which might have induced a certain level of publication bias within this study. The risk of researcher bias was mitigated by involving a research technician experienced in conducting systematic review studies, who evaluated the studies' eligibility for inclusion and methodological quality independently from the PhD student. Only minimal discrepancies between the two researchers were found, which were resolved by a verbal agreement, implying a minimal level of research bias.

3.5 Conclusion

This systematic review has revealed that a saddle and rider increase the biomechanical demands of the horse's back during straight-line walk and trot locomotion by increasing the pressures/ forces acting upon the horse's back and altering its movement patterns. The forces exerted on the horse's back when ridden are equivalent to the rider's weight at walk and twice the rider's weight at trot, which increase when going up in speed. The movement responses in the horse's back include an increase in the degree of extension in the lumbosacral region, decreased roll and yaw ROM in the more cranial back region underneath the saddle while the ROM between the more caudal back segments increase in the different directions, inconsistent alterations in the asymmetry of the horse's back movement, and more stabilised movement patterns. Associations between the horse's back movement and the saddle pressures were identified as well, with an increase in saddle pressures coinciding with reduced ROM in the corresponding back region and vice versa. The identified biomechanical responses induced by saddle and rider were further influenced by the fitting, design, and type of the saddle, the use of saddle pads, and the rider's body mass, seating style, riding skills, and asymmetries. Understanding how to minimise peak pressures exerted on the horse's back when ridden is considered favourable in the interest of back functioning in the ridden horse, as well is controlling the extending effect of a rider's load on the horse's back and riding-related factors inducing abnormal levels of asymmetry or movement variability in the horse. How the ROM relate to the horse's back functioning is not fully understood yet, which will be further investigated in Chapter 5B of this thesis. The findings from this systematic review can support equine practitioners in evidence-based decision-making when managing back health in the ridden horse and inform future researchers studying the biomechanical interaction between horse, saddle, and rider about the challenges and opportunities in current equine literature.

CHAPTER FOUR

4 Exploring novel research methods to measure a horse's back movement and posture when saddled and in field conditions

4.0 Background

Studying a horse's back movement when ridden advances our understanding of the biomechanical demands of the horse's back when loaded with a saddle and rider. As described in Chapter 2, optical motion capture is considered the gold standard to measure the horse's back movement (Warner, Koch and Pfau, 2010). However, optical motion capture cannot be used for measurements of the horse's back region covered by the saddle, being the mid-caudal thoracic region, given that optical motion capture relies on a line of sight of the optical motion cameras on markers affixed to the body region of interest (Chèze, 2014). Also consequent to the optical motion capture's dependency on a line of sight, the capture volume depends on the number of optical motion cameras, which are high in cost and generally do not withstand unpredictable weather conditions, limiting its use in field conditions (Chèze, 2014). Inertial measurement units (IMUs) overcome the limitations of optical motion capture in quantifying the movement of the horse's back region covered by the saddle (Martin *et al.*, 2017b) and in field conditions (Warner, Koch and Pfau, 2010; Bosch *et al.*, 2018). Inertial measurement systems using skin-mounted IMUs have already been developed and validated for measurements of the linear, rotational (Pfau, Witte and Wilson, 2005), and differential rotational (Martin, 2015) movement amplitudes of the horse's back, but not yet for measuring the alignment between IMUs placed on the horse's back, defining the horse's 'posture'. As aforementioned, the horse's posture when ridden can be associated with the development of back problems. Therefore, research methods enabling measurements of the movement and posture of the horse's back, including the mid-caudal thoracic region, when loaded with a saddle and rider are of interest in pursuing advances in our understanding of the biomechanical demands of the ridden horse's back.

This Chapter outlines two novel research methods to measure a horse's back movement and posture when loaded with a saddle and rider. The development of a (loaded) experimental saddle without a seat and a pilot study evaluating the capture rate of the mid-caudal thoracic region using optical motion capture in a horse at halt, walk, and trot on a treadmill with the (loaded) experimental saddle are described in part A of this Chapter. Part B describes the signal processing protocol of a preliminary hybrid optical-inertial motion capture approach overcoming the limitations of the individual motion capture tools in measuring a horse's back movement, as well as a pilot study evaluating its level of error against optical motion capture in measuring a horse's back movement and posture while on a treadmill, and identifying its sources of error prior to its use in field.

CHAPTER FOUR – PART A

4A The development of an experimental saddle allowing optical motion capture of a horse's mid-caudal thoracic back movement

4.1 Introduction

Optimal functioning of the back plays a fundamental role in the welfare and performance of the ridden horse, and research is warranted to advance our understanding of the pathomechanisms of back problems in this population (Greve and Dyson, 2013a). The back region that is most prone to the development of back problems in the horse is the mid-caudal thoracic region (Townsend et al., 1986; Zimmerman, Dyson and Murray, 2011; Clayton and Stubbs, 2016). When ridden, the horse's mid-caudal thoracic region is directly loaded with the weight of the saddle and rider, which increases the gravitational forces acting upon the horse's back and causes the back to extend in all gaits (de Cocq and van Weeren, 2014). However, the effect of a saddle and rider's weight on the horse's posture in the mid-caudal thoracic region has not yet been studied, whilst this has previously been associated with the development of back problems in the horse (de Cocq, van Weeren and Back, 2004). De Cocq, van Weeren and Back (2004) measured the flexion-extension displacements in the lumbosacral region in riding school horses when loaded with a saddle and a mass equivalent to that of a rider (70 kg). Considering that de Cocq, van Weeren and Back (2004) used optical motion capture for their kinematic measurements and the saddle occluded the mid-caudal thoracic region to the optical motion cameras, they were limited to measuring the lumbosacral region. To advance our understanding of the development of back problems in ridden horses, the horse's posture in the mid-caudal thoracic region when loaded with a saddle and rider is of particular interest. Therefore, a loading mechanism representing that of an ordinary saddle and rider that does not cover the horse's mid-caudal thoracic midline is merited, facilitating optical motion capture and, thereby, postural measures of this region in loading conditions equivalent to those when ridden.

In the study by de Cocq, van Weeren and Back (2004), a rider's load was represented by a lead mass of 75 kg attached on top of the saddle and alongside the saddle flaps. Naturally, the effect of a rider on the horse's back cannot be simplified to a mere physical load, as already suggested by Byström *et al.* (2020a). However, using a passive weight has the advantage of providing a more standardisable approach to studying the effect of a saddle and rider's weight on the horse's back movements, eliminating the confounding rider-related features revealed in the systematic review (Chapter 3), such as the rider's body mass, riding skills and asymmetries. Additionally, it facilitates study conditions where mounting the rider on the saddle is not feasible, as would be the case for a saddle without a seat.

Using a saddle loaded with additional weights to study how a rider's load influences the horse's movement patterns has been practised by multiple researchers already (Schamhardt, Merkens and Van Osch, 1991; Van Oldruitenborgh-Oosterbaan, Barneveld and Schamhardt, 1995; de Cocq, van Weeren and Back, 2004; Valentin *et al.*, 2010). Van Oldruitenborgh-Oosterbaan, Barneveld and Schamhardt (1995) reported no statistical differences in the workload (heart rate and plasma lactate concentration), temporal stride kinematics (stride and stance duration), or limb kinematics (maximal fetlock extension and the total fetlock ROM) of well-trained horses (n=9) when walking, trotting, and cantering on a treadmill loaded with a saddle and additional lead weights (90 kg) or ridden by a male rider (90 kg) who '*tried to influence the horse minimally*'. Similar to de Cocq, van Weeren and Back (2004), Van Oldruitenborgh-Oosterbaan, Barneveld and Schamhardt (1995) attached the lead weights on top of the saddle and alongside the saddle flaps. While taking into consideration that Van Oldruitenborgh-Oosterbaan, Barneveld and Schamhardt (1995) only recruited one rider of moderate/ heavy body mass, these study findings suggest that lead weights can adequately represent a rider's weight when studying how a rider's load influences a horse's movement patterns. Thereby, the use of a saddle without a seat and with lead weights attached on top and alongside the saddle flaps was considered a potential approach to facilitate optical motion capture measurements of how a saddle and, theoretically, a rider's mass influences the movement and posture of a horse's mid-caudal thoracic back region.

The research question addressed in this study was if a horse's mid-caudal thoracic region could be captured with optical motion cameras while loaded with a saddle with a mass equivalent to that of a rider. Establishing research methods that positively meet this research question will enable future research to follow up on the studies by de Cocq, van Weeren and Back (2004), who reported that weight has an extending effect on the horse's back based on increased extension degrees in the lumbosacral region in riding school horses (n=9) walking, trotting, and cantering with a loaded saddle (75 kg) on a treadmill. It is thought that such research will advance our understanding of the biomechanical demands and pathomechanisms in the mid-caudal thoracic region of the ridden horse, which can eventually support equine practice in managing back health in this population.

To answer this research question, an experimental saddle without a seat to which weights can be attached was designed and a pilot study was conducted. The aim of the pilot study was to evaluate the suitability of the experimental saddle, without and with weights attached, for investigating the effect of a load representative of a saddle and rider on the horse's movement and posture in the mid-caudal thoracic region. Therefore, the study objective was to evaluate the capture rate of reflective markers affixed to the skin overlying anatomical landmarks of the mid-caudal thoracic spinous processes in a horse at halt, walk, and trot on a treadmill with the experimental saddle, without and with weights attached, using optical motion cameras. It was hypothesised that the experimental saddle, without and with additional weights, would allow reliable optical motion capture of the horse's mid-caudal thoracic region, implying that markers could be traced throughout an entire 10-second standing and 40-second walking and trotting trial.

4.2 Methods

This study was approved by the Ethical Committee at Hartpury University (ETHICS2020-46). Informed consent from the owners of the horses participating in this study was obtained before their horses participated in the data collection, and they were able to withdraw their horses from the study up until the point of data collection.

4.2.1 Study horses

Two horses that were in active ridden work and considered sound by their owners were recruited from the Hartpury livery population. Both horses undertook regular treadmill exercise at the Hartpury Equine Therapy Centre prior to the data collection. The demographic details of the study horses are outlined in Table 4.1.

Table 4.1. The demographic characteristics of the study horses.

	Age (years)	Weight (kg)	Breed	Sex	Discipline
Horse 1	17	556	Irish sport horse	Mare	All-rounder
Horse 2	14	552	Irish sport horse	Mare	All-rounder

4.2.2 The experimental saddle

The design of the experimental saddle was discussed and constructed in cooperation with the Worshipful Company of Saddlers (London, UK). The experimental saddle was built from a layered wooden tree (17.5 inches, or 44.5 cm, with a medium width size). The experimental saddle was designed without a seat and with a 7 cm distance at the narrowest point between the left and right tree bars, enabling optical motion capture of the horse's mid-caudal thoracic back region using skin-mounted reflective markers affixed to anatomical landmarks of spinous processes. The saddle was designed without knee rolls or stirrup bars since the saddle was not designed for ridden purposes. The saddle was designed with six girth straps, including a v-strap at the caudal part of the saddle to provide different girthing options in the function of saddle fit. While Byström *et al.* (2010) reported higher peak pressures in the outer cranial saddle quadrant for a v-strap girthing system in comparison to a traditional girthing strap system, this system is applied in saddle fitting practices when more stability of the saddle's movement on the horse's back is favoured. The saddle panels were woollen flocked, and the final design of the experimental saddle, depicted in Figure 4.1, weighed 8.0 kg.

Figure 4.1 | The final design of the experimental saddle. The saddle was designed without a seat to allow optical motion capture of the midline of the horse's mid-caudal thoracic region. Metal pins were screwed into the saddle tree to allow additional weights to be attached to it.

4.2.3 The loaded experimental saddle

Weights were constructed to allow gradual loading of the saddle once placed on the horse's back. The weights were attached to the saddle in four loading increments by sliding the individual weights over the pins screwed onto the experimental saddle and securing their position on the saddle tree with fixation screws. The first loading increment included placing a 4.8 kg mass of lead on the left and right cranial and mid-section of the saddle tree (sliding the weights over the first five pins on the left and right side of the saddle tree). For the second loading increment, an additional 11.1 kg mass of lead was placed on the left and right cranial and mid-section of the saddle tree – which hangs along the saddle flaps. The third loading increment included placing an additional 6.3 kg mass of lead on top of the other weights on the left and right cranial and mid-section of the saddle tree. For the fourth loading increment, an additional 4.4 kg mass of lead was placed on the left and right caudal section of the saddle tree (sliding the weights over the last two pins on the left and right side of the saddle tree). In total, these weights resulted in a load of 53.2 kg, or 61.2 kg with the saddle included. The mass of the fully loaded saddle represented the mass of a light-weighted rider for the study horses, which is described as 10-12% of the horse's body mass by Dyson *et al.* (2019) and Roost *et al.* (2020). The fully loaded saddle and the individual loading increments are depicted in Figure 4.2.

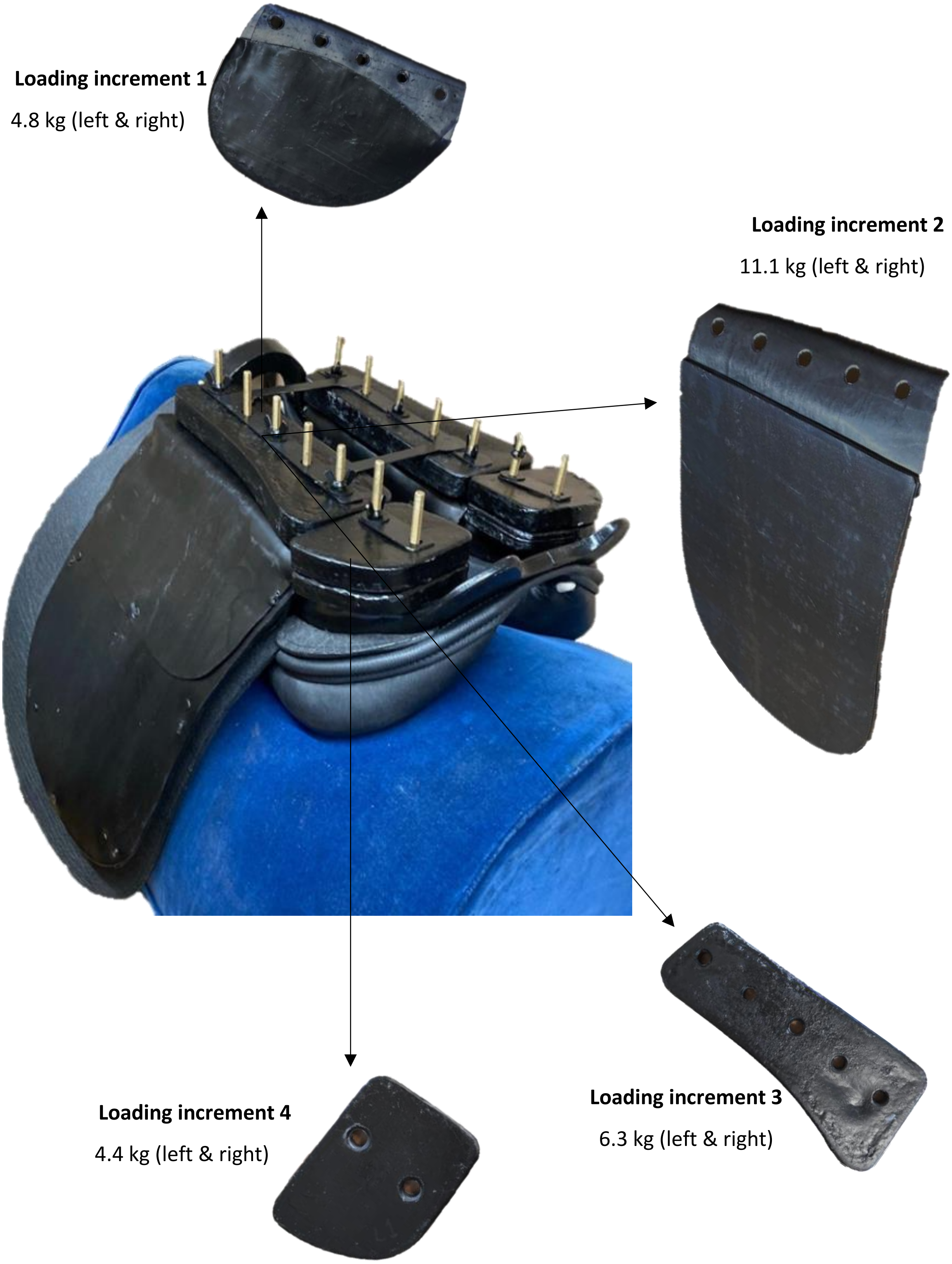


Figure 4.2 | The experimental saddle with the additional weights on top, secured with screws. The four loading increments are depicted individually and weigh 53.2 kg in total.

4.2.4 Saddle fit

The saddle fit of the experimental saddle to both horses was evaluated and adjusted where needed by two Society of Master Saddlers Qualified Saddle Fitters (SMS QSF) in cooperation with the Master Saddle Maker. In function of the saddle fit, a saddle pad was used for Horse 2, and the girthing differed between the two study horses. For Horse 1, the most cranial and caudal girth straps were used, whilst the second most cranial and caudal girth straps were used for Horse 2. A leather, non-elastic girth was used for both horses. The experimental saddle fitted both horses correctly, adhering to the SMS guidelines. Previous research demonstrated a fair agreement between SMS QSF for evaluating the overall saddle fit using the SMS guidelines (Guire *et al.*, 2017).

4.2.5 Kinematic measurements

Kinematic measurements were captured for Horse 1 only. Ten hemispherical reflective markers (33 mm in diameter) were attached to the horse, on the skin overlying the anatomical landmarks of the spinous processes of the 6th, 10th, 13th, and 18th thoracic vertebrae (T6, T10, T13, and T18), the 3rd lumbar vertebra (L3), and the 3rd sacral vertebra (S3), the left and right *tubera coxae* (LTC and RTC) and the left fore and hindlimb hoofs, using double-sided tape. The movement of the markers was captured by five motion capture cameras (Miqus M3, Qualisys AB, Gothenburg, Sweden) suspended from the rafters above the treadmill within a 5 m range, as shown in Figure 4.3. One video camera (Miqus Video, Qualisys AB, Gothenburg, Sweden) was placed perpendicular to the treadmill and used to enable retrospective visual observation of the trial. The cameras were daisy-chained and connected to a laptop running Qualisys Track Manager (version 2020.1, Qualisys AB, Gothenburg, Sweden). The optical motion capture system collected the data sampling at 100 Hz. This sampling frequency coheres to the Nyquist sampling theorem, according to which the minimal sampling frequency must be at least twice that of the highest-frequency component in the captured signal (Robertson et al., 2014). Considering the stride frequency of a trotting horse is typically between 1.3 and 1.8 Hz(Clayton, 1994; Hoyt *et al.*, 2006) and the body moves up and down twice, the sampling frequency would have to be 7.2 Hz or higher for data capture of the horse's upper body movement at walk and trot. The optical motion capture system was calibrated at the beginning of the data collection using a static L-shaped calibration frame and a calibration wand (601.8 mm), moving the calibration wand through the capture volume throughout the calibration capture. The long arm of the calibration frame was positioned close to the right-side border, positive in the direction of travel, whilst the short arm was parallel to the short side of the treadmill and positive to the left (see Figure 4.3). The defined coordinate system followed the right-hand rule, with its X and Y-axes aligning with the long and short arm of the calibration frame, respectively. The average residual of the cameras obtained by calibration ranged from 0.31 to 0.86 mm, and the standard deviation of the wand length was 0.65 mm.

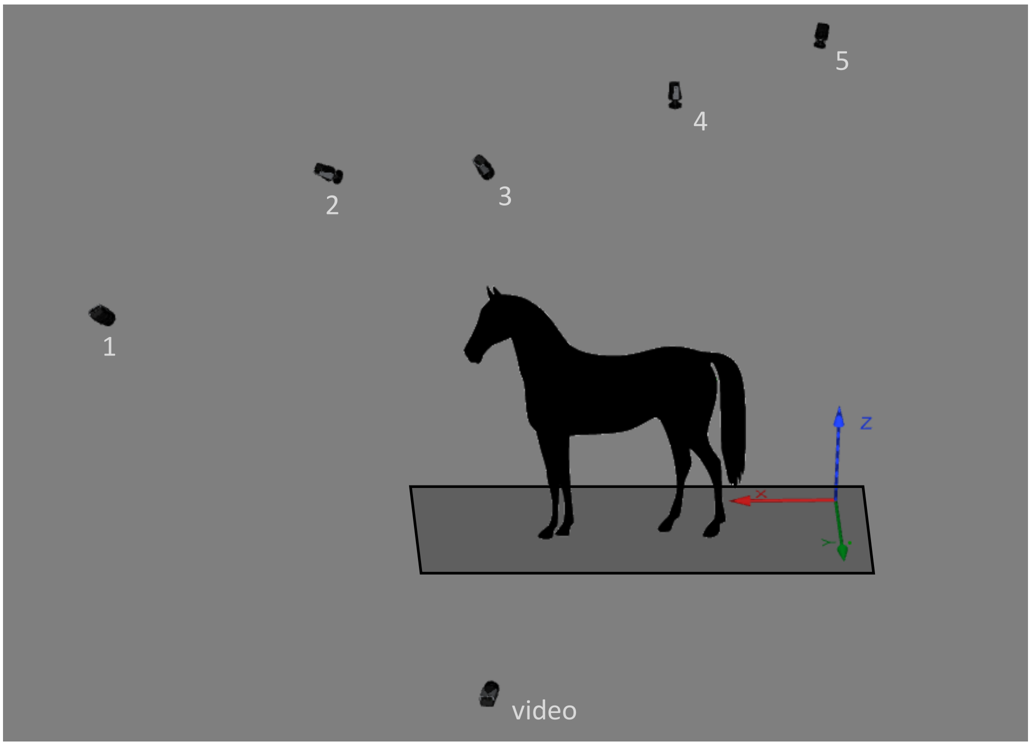


Figure 4.3 | Five motion capture cameras and one video camera were organised around the treadmill. The coordinate system was located behind and on the right side of the horse's position.

4.2.6 Study protocol

Once tacked up with the experimental saddle, Horse 1 completed a study protocol on the treadmill. The horse was first acclimatised to the walking treadmill speed (1.4 m/s) for 30 seconds, after which a 40-second walking capture was performed. The horse was then acclimatised to the trotting treadmill speed (3.0 m/s) for 30 seconds, after which a 40-second trotting capture was performed. Treadmill speed was determined by the Equine Therapy Centre staff, conforming to the speed the horse was used to in her regular treadmill sessions. Two handlers, one on each side, encouraged the horse to maintain a straight, neutral head-neck posture with the neck close to the horizontal and head close to vertical, using consistent and appropriate rein tension. A final capture involved a 10-second standing trial with the horse standing square in a straight, neutral head-neck posture on the treadmill.

The experimental saddle was then loaded with the additional weights. Considering that adding loads can influence saddle dynamics (Valentin *et al.*, 2010), the movement of the loaded experimental saddle was evaluated prior to collecting any measurements by the two SMS QSFs, the Master Saddle Maker, and the research team, including the PhD student and supervisors. For this part of the study, the two study horses walked and trotted in-hand on a concrete 40x4 m surface with the different loading increments secured to the saddle. This evaluation demonstrated that adding the weights to the experimental saddle initiated lifting at the back of the saddle for Horse 1 and excessive craniocaudal saddle movements for Horse 2 at trot. With all weights attached (9.6 + 22.2 + 12.6 + 8.8 kg), the saddle also started to slip considerably to the left for Horse 1 at trot. For both study horses, the saddle movements were most pronounced when all weights were attached. Considering the excessive movements of the experimental saddle when the weights were attached at trot, no further trialling or data collection was undertaken with the loaded experimental saddle.

4.2.7 Data processing and analysis

The reflective markers captured while Horse 1 halted, walked, and trotted on the treadmill with the experimental saddle were labelled in Qualisys Track Manager (version 2020.1, Qualisys AB, Gothenburg, Sweden). Data gaps smaller than ten frames were filled automatically by the Qualisys Track Manager using polynomial interpolation. The capture rate was then evaluated in the Qualisys Track Manager, indicating no residual gaps in the data capture of the standing, walk, and trot trials. The three-dimensional (3D) coordinates of all markers were exported in .TSV files and imported into MATLAB (version R2020b, The MathWorks, Natick, Mass., USA) to plot flexion-extension and lateral bending displacement measurements of the horse's mid-caudal thoracic back region throughout the standing, walk and trot trials, demonstrating that the optical motion capture could successfully be used to measure the movement and posture of the horse's mid-caudal thoracic region in a static and dynamic horse with the experimental saddle.

4.2.7.1 Processing of the static trial

A custom-made MATLAB script was used to plot the mean (±standard deviation) position of each back marker in the horse's median plane throughout the entire trial. The craniocaudal position between the back segments was calculated as the resultant vector between the X and Y-coordinates of two adjacent markers, as per Equation 4.1. The resultant vector between the X and Y-coordinates rather than the X-coordinates was used to represent the craniocaudal distance between the adjacent markers in order to compensate for the horse potentially standing slightly misaligned with the X-axis of the coordinate system during the standing trial.

$$\boldsymbol{Craniocaudal\ distance_{i,j}} = \sqrt{\left(\mathbf{x_i} - \mathbf{x_j}\right)^2 + \left(\mathbf{y_i} - \mathbf{y_j}\right)^2} \qquad \mathbf{(4.1)}$$

With i and j = two adjacent back segments

4.2.7.2 Processing of the dynamic trials

A custom-made MATLAB script was used to plot the mean (±standard deviation) flexion-extension and lateral bending displacements between the back segments during a stride cycle from all strides captured throughout the entire walk and trot trials. First, a 4th-order low-pass Butterworth filter with a cut-off frequency of 30 Hz was applied to remove high-frequency noise in the motion signals collected for both trials. The application of this filter conforms with other literature reporting similar measure outcomes of a horse's back movement collected with optical motion capture, such as the study by Hardeman *et al.* (2020). This filter was also deemed appropriate to attenuate high-frequency noise while maintaining the shape of the motion signal based on visual observation of the 4^{th}-order low-pass Butterworth filter with different cut-off frequencies, as is shown in Figure 4.4.

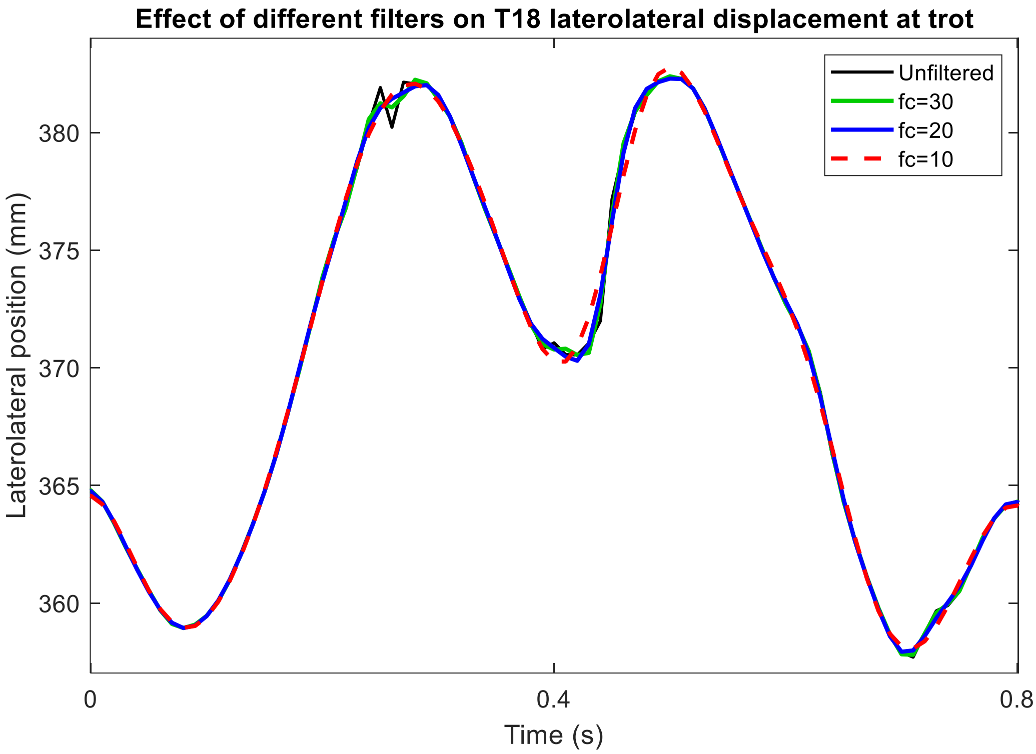


Figure 4.4 | The attenuation of noise in the laterolateral motion signal at T18 during one stride cycle at trot using a 4^{th}-order low-pass Butterworth filter with different cut-off frequencies (fc).

The flexion-extension and lateral bending displacements between the different back segments were then calculated according to the methods described by Faber *et al.* (2001b). As described in section 2.4.3, this method quantifies the degree of flexion-extension and lateral bend as the angle between the horizontal and the line through a back segment cranial and caudal to the back segment of interest in the horse's median and dorsal plane, respectively. In other words, this method does not quantify the true angle between spinal segments, called 'relative' or 'joint' angles (Robertson *et al.*, 2013), but rather the orientation of the back region between adjacent back segments within the coordinate system defined by the optical motion capture system, called 'absolute' or 'segment' angles (Robertson *et al.*, 2013). This calculation method requires a consistent horizontal surface, considering a change of the locomotory inclination would falsely change the flexion-extension angle within the same coordinate system. While other calculation methods quantifying the internal motion of the horse's back between different back segments have since been reported (Hardeman *et al.*, 2020; Byström *et al.*, 2021), the described calculation method was selected to allow comparison with the study results reported by de Cocq, van Weeren and Back (2004), who pioneered in measuring the degree of flexion-extension in the horse's back when loaded with a saddle and rider and used the calculation method described by Faber *et al.* (2001b). The following equations were used to calculate the flexion-extension and lateral bending displacements at T10, T13, and T18, illustrated in Figure 4.5:

$$\textbf{Flexion} - \textbf{extension}_{v2} = \textbf{rad2deg}(\textbf{atan}(\frac{z_{v3} - z_{v1}}{x_{v3} - x_{v1}})) \quad \textbf{(4.2)}$$

with v1, v2, and v3 = the proximal, middle, and distal vertebrae, respectively,

and x_i *and* z_i *= the x- and z-coordinates at the ith-sample number.*

$$\textbf{Lateral bending}_{v2} = \textbf{rad2deg}(\textbf{atan}(\frac{y_{v3} - y_{v1}}{x_{v3} - x_{v1}})) \quad \textbf{(4.3)}$$

with v1 and v3 = the proximal and distal vertebrae, respectively,

and x_i *and* y_i *= the x- and y-coordinates at the ith-sample number.*

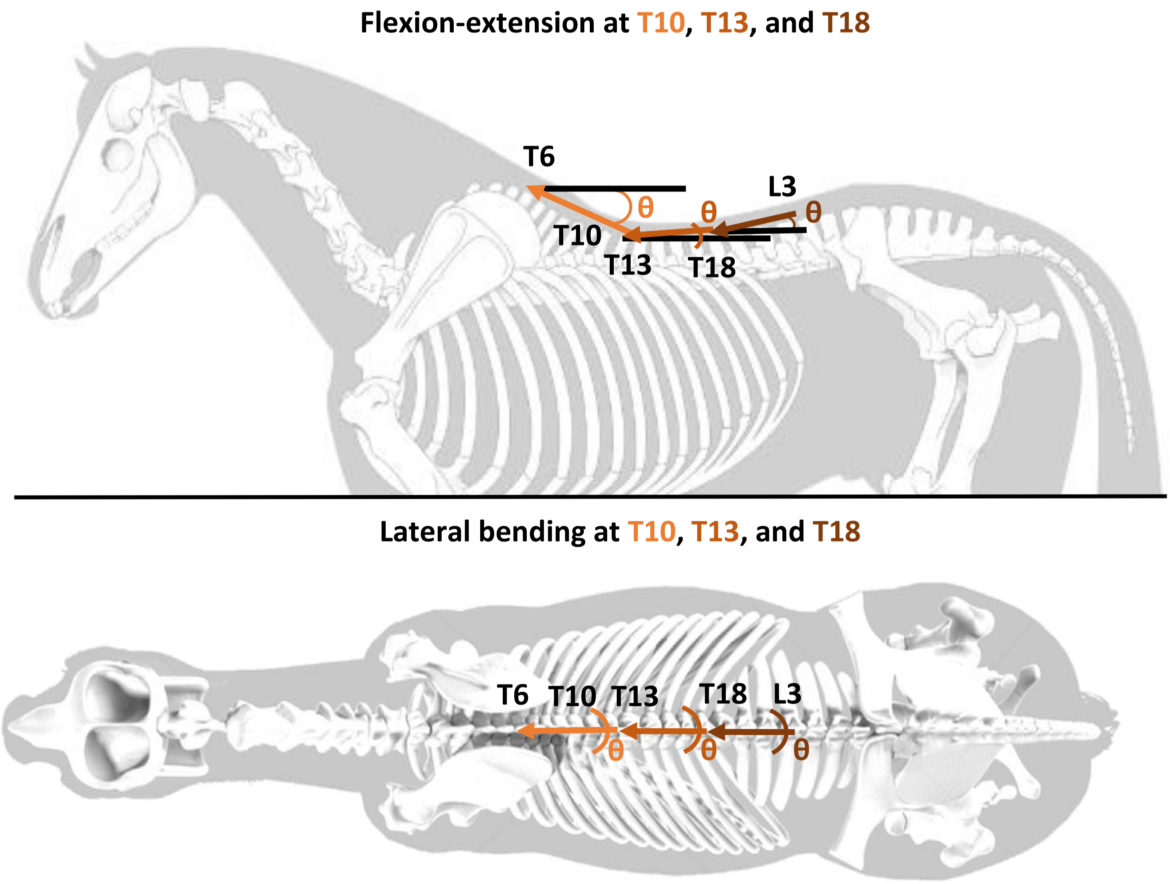


Figure 4.5 | An illustration of the calculated flexion-extension (on top) and lateral bending (below) angular displacements at T10, T13, and T18.

The angular displacements were then split into strides using the vertical displacement time series of the markers placed on the LTC and RTC, with the mid-stance phase of the left hindlimb initiating each stride cycle. At walk, the mid-stances of the left hindlimb coincide with the vertical displacement peaks of the LTC that are higher than those of the RTC, whilst these coincide with the vertical displacement troughs of the LTC that are higher than those of the RTC at trot (see Figure 4.6). A similar approach for stride splitting in trot has been described by Walker et al. (2010).

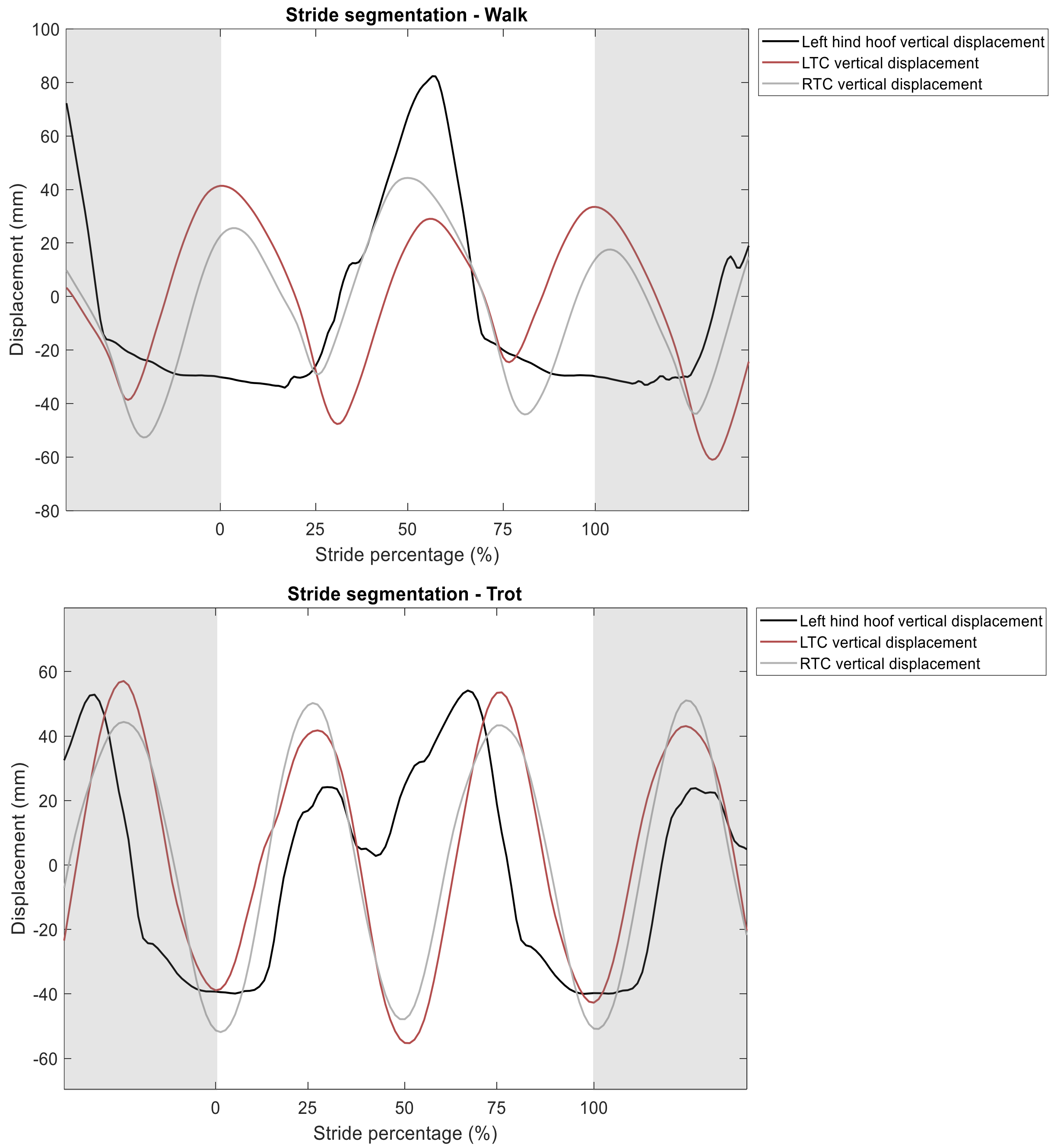


Figure 4.6 | One complete stride cycle starting and ending mid-stance phase of the left hindlimb, as indicated by the motion signals from the left/ right *tubera coxae* (LTC and RTC) and left hoof marker, is plotted in the white-shaded area. The grey-shaded areas show the continuation of the signals.

Quality control by visual inspection was performed to evaluate the accuracy of the stride segmentation protocol in each trial. The stride segmentation was plotted as lines on top of the time series of the LTC vertical displacement. The stride segmentation was deemed successful if the stride segments coincided with the higher peaks and troughs (at walk and trot, respectively) of the LTC, as shown in Figure 4.7. If stride segmentation was unsuccessful, the stride segmentation was repeated with changes to the minimal distance between peaks until successful.

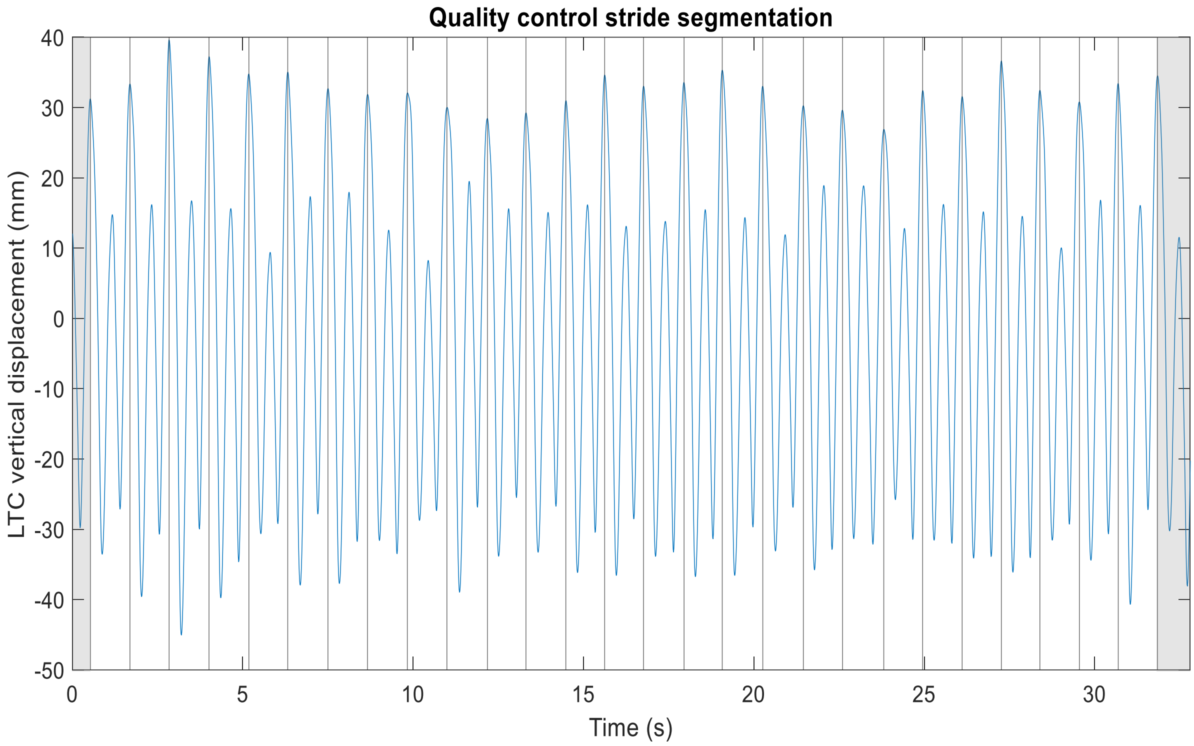


Figure 4.7 | The quality control of the stride segmentation. The vertical displacement of the left *tuber coxae* (LTC) was plotted with the vertical lines indicating the start of each stride segment. The grey-shaded areas represent the data points outside the first and last stride segments.

The strides were then normalised to 101 points using cubic spline interpolation, returning the angular displacements during stride cycles of different lengths corresponding to stride cycles with the same length (0-100%). An example of the effect of the cubic spline interpolation on the vertical displacement of the sacrum throughout two strides of different lengths is demonstrated in Figure 4.8.

The normalisation of the strides enabled the calculation of the mean (±standard deviation) of the flexion-extension and lateral bending displacements across the different stride cycles collected during the entire walk and trot trials. Splitting the time series into strides and normalising the stride cycles facilitated a presentation of the collected data that meets the scientific standards (Clayton and Schamhardt, 2001).

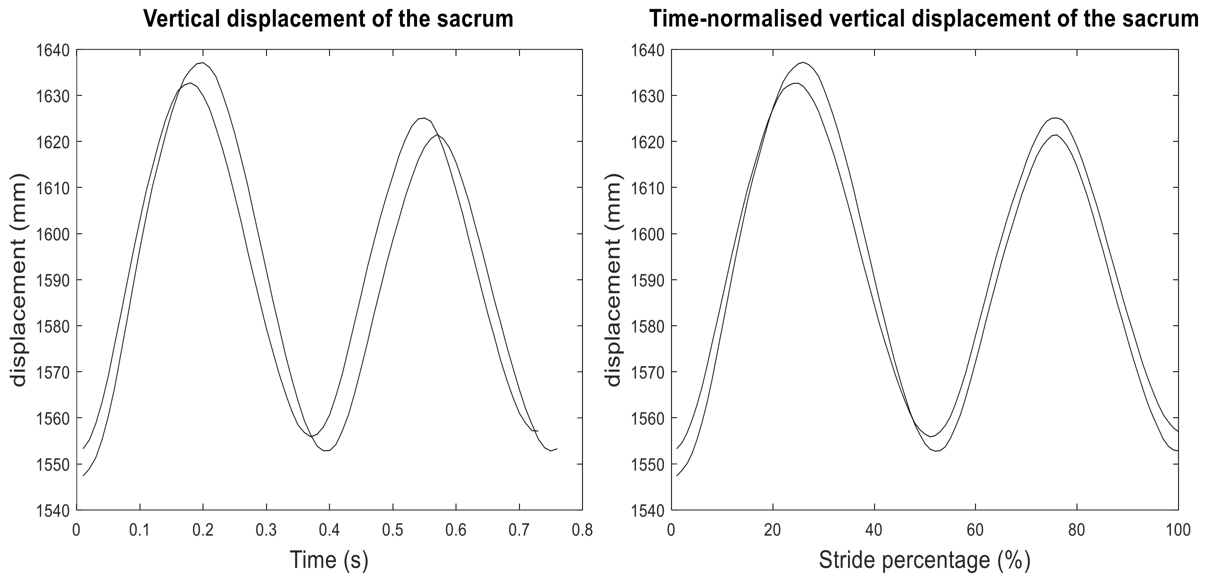


Figure 4.8 | The time-normalisation of a motion signal during two stride cycles of different lengths. This example shows the motion signal of the horse's sacrum vertical displacement at trot.

4.3 Results

Evaluation of the capture rate during the standing, walking, and trotting trials with the experimental saddle revealed that the back markers, including those affixed to the mid-caudal thoracic region, were traced throughout each trial. The successful marker tracing enabled the calculation of the mean (±standard deviation) position of the back markers throughout the standing trial, plotted in Figure 4.9, as well as the mean (±standard deviation) flexion-extension and lateral bending displacements at T10, T13, and T18 throughout the walk and trot trials, plotted in Figures 4.10-11. No optical motion capture measurements were collected with the loaded experimental saddle, considering that attaching weights to the experimental saddle initiated excessive saddle movement at the trot.

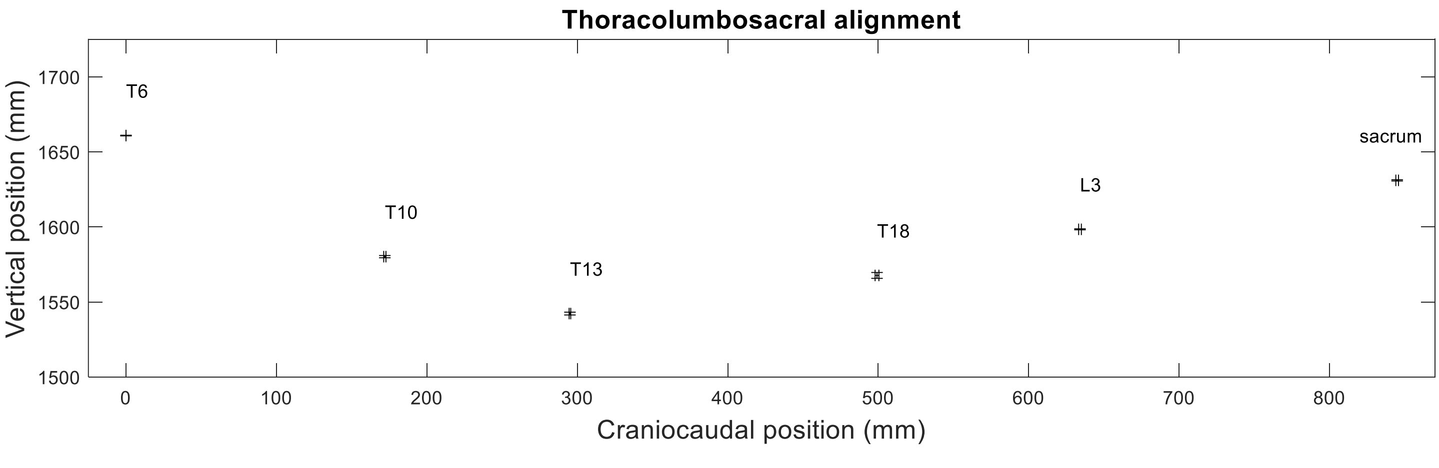


Figure 4.9 | The mean (±standard deviation) position of the back markers in the horse's median plane at halt with the experimental saddle during the 10-second trial.

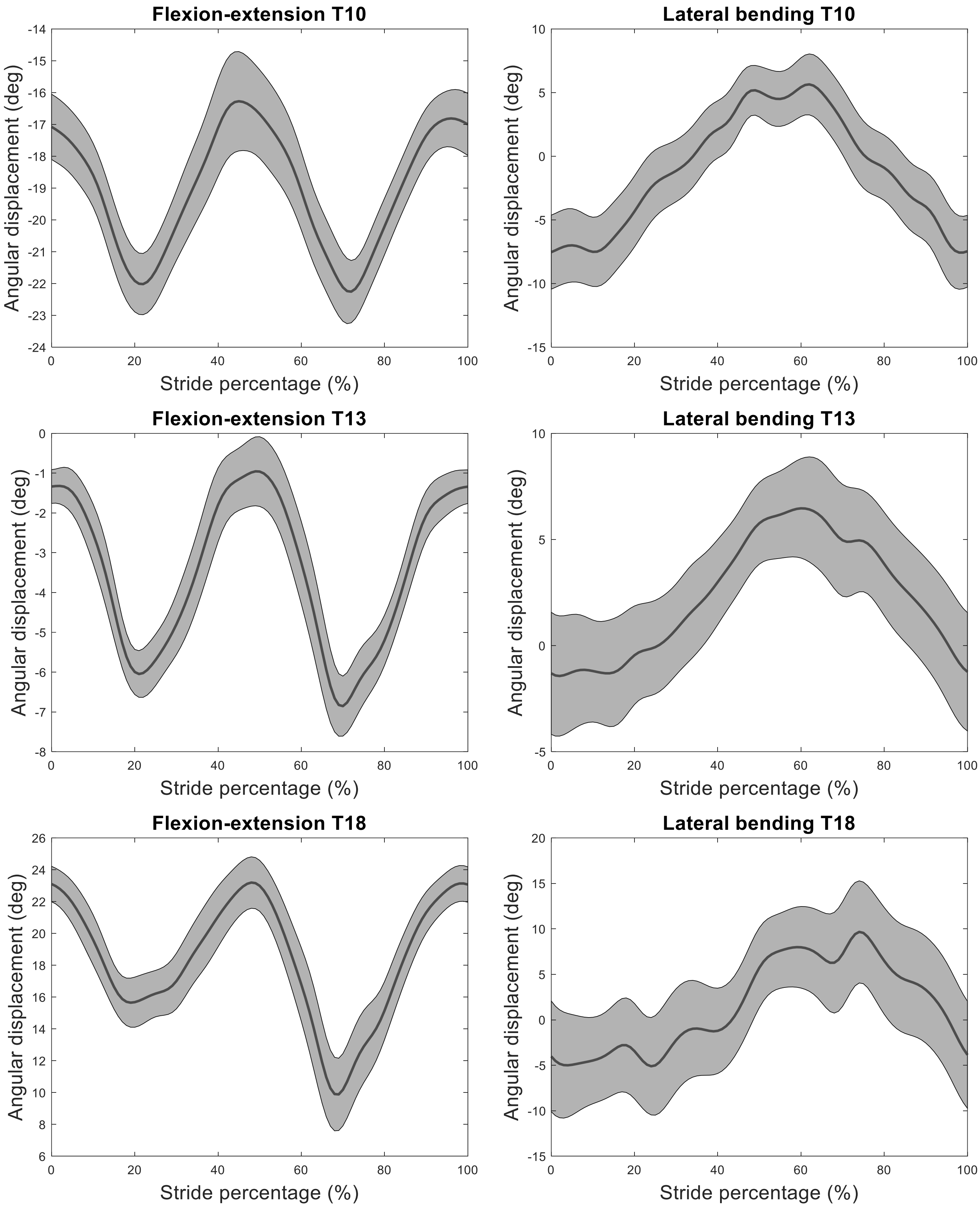


Figure 4.10 | The mean (±standard deviation) flexion-extension and lateral bending displacements at T10, T13, and T18 when walking with the experimental saddle during the 40-second trial.

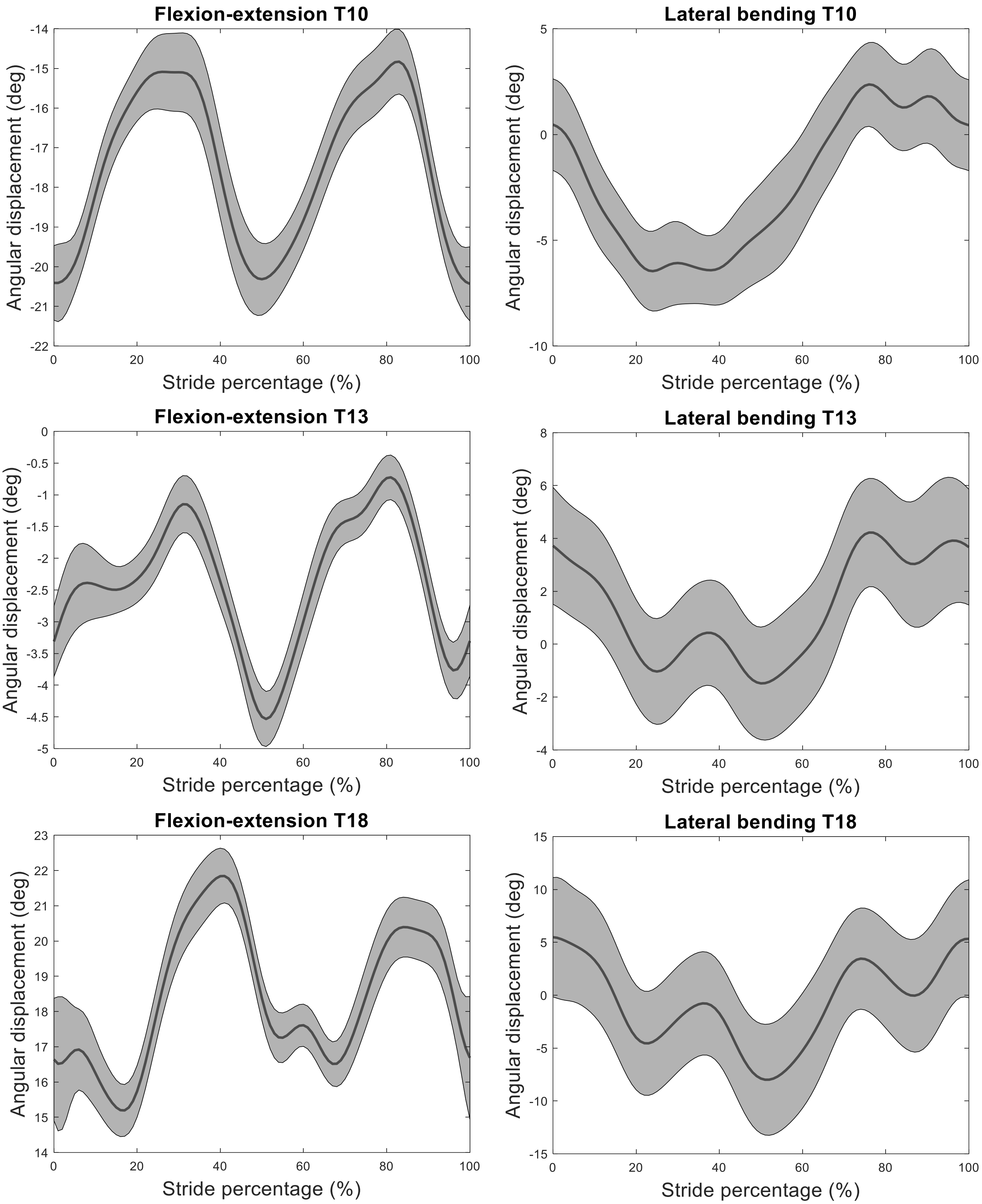


Figure 4.11 | The mean (±standard deviation) flexion-extension and lateral bending displacements at T10, T13, and T18 when trotting with the experimental saddle during the 40-second trial.

4.4 Discussion

This study explored the development of an experimental saddle without a seat that would allow optical motion capture of the horse's mid-caudal thoracic back region and to which passive weights could be attached, representing the mass of a light-weighted rider. The study findings revealed that the experimental saddle allows reliable optical motion capture of the horse's mid-caudal thoracic back region, based on successful tracking of the back markers in the Qualisys Track Manager throughout a 10-second standing and 40-second walking and trotting trial. Considering that attaching weights to the experimental saddle initiated excessive saddle movements at trot in both study horses, no measurements were taken with the loaded experimental saddle, and further trials with the loaded experimental saddle were aborted. Therefore, the study hypothesis was only partially met. The experimental saddle without additional weights allows reliable optical motion capture of the horse's mid-caudal thoracic region at halt, walk, and trot on a treadmill, but measurements to confirm this for the experimental saddle with additional weights could not be collected.

This study presents a research method that, for the first time in equine literature, facilitates optical motion capture measurements of the horse's mid-caudal thoracic region when loaded with a saddle. The loading dynamics of the horse's mid-caudal thoracic region is considered of particular interest in equine sports medicine, given the vital role of this body region in the horse's performance (van Weeren, McGowan and Haussler, 2010) and the high prevalence of back problems in this region (Townsend *et al.*, 1986; Zimmerman, Dyson and Murray, 2011; Clayton and Stubbs, 2016). Future research can use the design of the experimental saddle to complement the literature about the movement and posture of the horse's back when loaded with a saddle, including the mid-caudal thoracic region. However, previous literature studying how an unloaded saddle influences a horse's back movements revealed no statistical effect of the saddle on the flexion-extension displacements of the horse's lumbosacral back region when compared to walking or trotting without a saddle (de Cocq, van Weeren and Back, 2004) or in the laterolateral and dorsoventral ROM in the lumbosacral back region when compared to trotting without a saddle (Heim *et al.*, 2016). When studying the effect of a loaded saddle, on the other hand, statistically significant alterations were seen in the horse's lumbosacral flexion-extension displacements, revealing more extension in the horse's lumbosacral back region when loaded with a rider-equivalent mass (de Cocq, van Weeren and Back, 2004). While research is also warranted to advance our understanding of the influence a saddle without a rider has on the horse's movement patterns in the mid-caudal thoracic region, measurements of the horse's posture in the mid-caudal thoracic region when loaded with a saddle and a rider-equivalent mass would provide more relevant insights about the biomechanical demands of the horse's back when ridden.

This study did not provide quantitative measurements of the horse’s back movement and posture during the trial with the loaded experimental saddle. The continuation of the trial with the loaded experimental saddle had to be aborted due to the observation of excessive saddle movement at trot, causing concerns about the experimental saddle inducing back discomfort in the study horses. The excessive saddle movements were notable even with the lightest loading increment (9.6 kg) but most pronounced for the heavier loading increments (44.4 and 53.2 kg). The discrepancy in the loaded experimental saddle’s dynamic stability at walk and trot can be associated with the different locomotory patterns of the horse’s back between these gaits. A saddle’s movement patterns will always differ from those of the horse’s back, given that the relatively rigid construction of the saddle does not completely conform to the changes in the horse’s back shape (Clayton and Hobbs, 2017). The locomotory forces exerted on the saddle can initiate a momentum of the saddle relative to the horse’s back due to a certain degree of freedom between the saddle and the horse’s back, regardless of the presence of the girth. When a dampening mechanism accommodating the degrees of freedom between a saddle and horse is lacking and the saddle’s mass increments, an increase in the saddle’s momentum relative to that of the horse’s back is evident. The differentiation between the weighted experimental saddle’s dynamic stability at the walk and trot can be related to the different movement patterns of the horse’s trunk between the two gaits, with the dorsoventral and longitudinal acceleration amplitudes of the trunk being notably bigger at the trot compared to the walk (Barrey *et al.*, 1994). To optimise the dynamic stability of the loaded experimental saddle at the trot, a mechanism efficiently dampening the more excessive dorsoventral and longitudinal movement of the horse’s trunk is required.

Comparing the findings from this study with previous literature investigating how a loaded saddle influences a horse’s movement patterns, it was found that Valentin *et al.* (2010) also reported excessive saddle displacements when loads above 30 kg were applied to a saddle, which they tested in a pilot study. Consequently, Valentin *et al.* (2010) only applied loads of 30 kg in their empirical study. However, the studies by Van Oldruitenborgh-Oosterbaan, Barneveld and Schamhardt (1995) and de Cocq, van Weeren and Back (2004) did not report any excessive saddle displacements in their study. Personal communication with S. Van Oldruitenborgh-Oosterbaan confirmed that no notable dynamic instabilities were observed during their data collection using a saddle loaded with 90 kg of lead mass. However, it must be appreciated that the loaded saddle was stabilised on the horse’s back with an additional lunging roller in their experimental setup. In the study by de Cocq, van Weeren and Back (2004), the use of a lunging roller stabilising the loaded saddle was mentioned as well; their experimental setup with a horse loaded with a saddle with weights attached (75 kg) is depicted in Figure 4.12. Notably, Valentin *et al.* (2010) did not report the use of an additional girthing system to stabilise the loaded saddle in their experimental setup, potentially clarifying why they, as in this study, observed excessive saddle movements when weights were applied to the saddle, and why Van Oldruitenborgh-Oosterbaan, Barneveld and Schamhardt (1995) and de Cocq, van Weeren and Back (2004) did not. The use of an additional girth to stabilise the loaded saddle was not pursued in this study, considering the use of an additional girth crossing the midline of the horse's back would conflict with the purpose of the development of the experimental saddle as it would inhibit optical motion capture of the horse's mid-caudal thoracic back region. Furthermore, girth tension increases the forces exerted on the horse's back, doubling the forces exerted on the horse's back by the saddle's weight at halt (Jeffcott, Holmes and Townsend, 1999) and going up to four times the saddle's weight at trot (Fruehwirth *et al.*, 2004). It must thus be acknowledged that the pressures exerted on the horse's back when using an additional girth to affix the loaded saddle complex onto the horse's back will not be representative of those exerted by a saddle girthed with one traditional girth and with a rider-equivalent mass attached.

Figure 4.12 | The experimental setup in the study by de Cocq, van Weeren and Back (2004). The picture demonstrates one of their study horses loaded with a saddle with weights (75 kg) attached and a lunging roller stabilising the loads. This figure is used with permission from the publisher.

While the proposed experimental saddle has the potential to advance movement analysis of a horse's back in loaded conditions, several limitations must be considered. Attaching weights onto the experimental saddle requires additional stabilising mechanisms to minimise its dynamic instability on a trotting horse while not covering its midline. Contemplating alternative designs for the loaded experimental saddle, the rationale behind developing such a saddle should lead the decision-making. While attaching weights to a saddle might provide a more standardisable approach to studying the loading back dynamics in ridden horses than recruiting riders, elaborating on mechanical compensations to fasten the applied loads onto the horse's back might be a misleading simulation of a rider's load on the horse's back. Considering a rider's dynamics on the horse, riders use their legs as a quasi-elastic mechanism to couple their movement with that of the horse and dampen the horse's upper body movement (de Cocq *et al.*, 2010), whereas the passive weights can be considered as a point mass on the horse's back with no dampening capacities. Therefore, the use of the experimental saddle to investigate the loading back dynamics in the ridden horse lacks relevancy to equine practice as long as (a) a more appropriate simulation of a rider's load is missing or (b) the experimental saddle does not allow ridden purposes. Moreover, experimental setups using the experimental saddle will still be laboratory-bound since quantifying a horse's back kinematics, including postural measures, still relies on optical motion capture. This limitation adds to the insufficient transparency of the experimental saddle to sport-specific practices. Future research should take these considerations into account when further exploring how to advance our knowledge about the loading mechanisms of the back in ridden horses.

4.5 Conclusion

This study laid out the design and testing of an unloaded and loaded experimental saddle without a seat to enable optical motion capture of a horse's mid-caudal thoracic back region when loaded with a mass equivalent to that of a rider. It was found that the experimental saddle allows reliable optical motion capture of the horse's mid-caudal thoracic region based on successful tracking of skin-mounted markers affixed to anatomical landmarks representing the mid-caudal thoracic spinous processes in a horse at halt, walk, and trot on a treadmill. While this study thus represents a novel method that successfully facilitates measurements of the movement and posture in the horse's mid-caudal thoracic region when loaded with a saddle for the first time in equine literature, challenges were met when attaching loads (10-53 kg) equivalent to that of a light-weighted rider to the saddle. Excessive saddle movements were observed in the study horses at the trot, which was most pronounced with the heavier weight increments. Therefore, any further trialling or measurements with the loaded experimental saddle were aborted. These observations confirm that the effect of a rider's load on the horse's back cannot be simplified to a mere passive weight, lacking an efficient dampening mechanism to accommodate for the locomotory forces exerted on the saddle by the horse at the trot. Future research is encouraged to explore more efficient simulations of a rider's weight and research methods facilitating measurements of the movement and posture in the horse's mid-caudal thoracic region when loaded with a saddle and rider.

CHAPTER FOUR – PART B

4B The use of hybrid motion capture to measure a horse's back movement and posture

4.6 Introduction

Current literature investigating the horse's back movement when ridden uses optical motion capture or IMUs as motion capture tools, as was observed in the systematic review study in this thesis (Chapter 3). When using optical motion capture, a large number of optical motion cameras are required to collect measurements of the horse's back movement in field study conditions throughout an acceptable number of strides, considered as five strides or more for equine gait analysis (Clayton and Schamhardt, 2001, p. 56). Considering that optical motion cameras are high in cost, time-consuming to set up and generally do not withstand unpredictable weather conditions (Chèze, 2014), the use of optical motion capture for field measurements is often not viable. Alternatively, increasing the number of trials per study condition can compensate for a smaller number of optical motion cameras, though this introduces inter-trial variability in the motion signal. For example, in the study by de Cocq *et al.* (2009a), only six optical motion cameras were used to measure a horse's back movement, which allowed captures of one valid stride per trial. As a result, six trials were collected per study condition by de Cocq *et al.* (2009a) to reach an acceptable number of strides for their kinematical analysis (n=6). To facilitate steady-state measurements of the horse's back movement in ridden field conditions, alternative research methods are of interest.

In contrast to optical motion capture, IMUs are relatively low in cost, practical to use in field settings, and do not rely on a line of sight for motion capture (Pfau, Witte and Wilson, 2005). However, IMUs have not yet been established to accurately measure the posture of a horse's back, quantified as the alignment between back segments, whilst this is of interest in advancing our understanding of the biomechanical demands of the horse's back when ridden. The position or orientation of the IMUs, referred to as the IMUs' pose estimation, relative to each other is required for the calculation of alignment between the IMUs. Martin *et al.* (2014) demonstrated that the relative orientation between IMUs skin-mounted on the horse's back could be obtained for the pitch rotation, enabling the measurement of the flexion-extension angles of the horse's back at walk and trot. Martin *et al.* (2014) defined the initial pitch orientation of the IMUs on a horse at halt using the accelerometer data, equivalent to zero in a static subject, to orientate the IMU's vertical axis within the global coordinate system in which the vertical axis aligns with the direction of gravity. As discussed in Chapter 2 (Section 2.4.2), the orientation of the IMUs is derived from integrating the angular velocity measured with the IMU's gyroscope, which is prone to a certain level of bias, and integration of the gyroscope's bias results in a drift error in the obtained rotational motion signal (Kok, Hol and Schön, 2017). Martin (2015) applied a high-pass filter to compensate for the drift error in the integrated rotational motion signal and improve its accuracy, as did Pfau, Witte and Wilson (2005), Warner, Koch and Pfau (2010), Bosch *et al.* (2018) and Hatrisse *et al.* (2023) to compensate for the drift error in the double integrated linear motion signal. The high-pass filter has a zero-centring effect on the motion signal, implying that the absolute value of the signal is lost and, thereby, the definition of the orientation between IMUs (Martin, 2015). Furthermore, the high-pass filter also mitigates interstride differences, attenuating non-cyclical movement components (Serra Bragança *et al.*, 2020). Consequently, the IMUs have merely been used to quantify movement amplitudes of the horse's back and during steady-state locomotion in the literature. These considerations imply that additional information is required to estimate the position or orientation of skin-mounted IMUs relative to each other when using previously established inertial measurement systems quantifying a horse's back movement.

Hybrid motion capture combines the input from different motion capture systems and has been used in multiple industries already to overcome the limitations of the motion capture systems individually (Pons-Moll *et al.*, 2010; Bönig *et al.*, 2014; Jung, Kim and Lyou, 2017). The combination of IMUs with visual or optical input has previously been used to facilitate the pose estimation of IMUs (Kok, Hol and Schön, 2017). This study presents a preliminary investigation into a hybrid approach to measure a horse's back movement and posture during steady-state walk and trot locomotion, combining an inertial measurement system that has previously been established to quantify the linear displacements of a horse's back movement using skin-mounted IMUs (Pfau, Witte and Wilson, 2005) with optical motion capture. The proposed hybrid approach uses optical motion capture for an initial position estimation of the IMUs at the start of a trial and tracks the displacement of the back movement throughout the trial with the IMUs. A schematic illustration of this hybrid approach to measure a horse's back movement, including postural measurements, is provided in Figure 4.13.

The aim of this study was to evaluate the accuracy of the proposed hybrid approach in measuring a horse's back movement, including postural measurements. The study objectives were to quantify the level of error of the proposed hybrid approach against the gold standard optical motion capture in measuring flexion-extension and lateral bending displacements of the horse's back during steady-state walk and trot locomotion on a treadmill. Sport horses with different back conformation were recruited to test if the levels of error of the hybrid approach in measuring the horse's back movement were associated with conformation characteristics of the horse's back. It was hypothesised that the levels of errors found for the hybrid approach would be small enough to be of use in a clinical setting and that no correlations would be found between the identified levels of error and the study horses' back conformation.

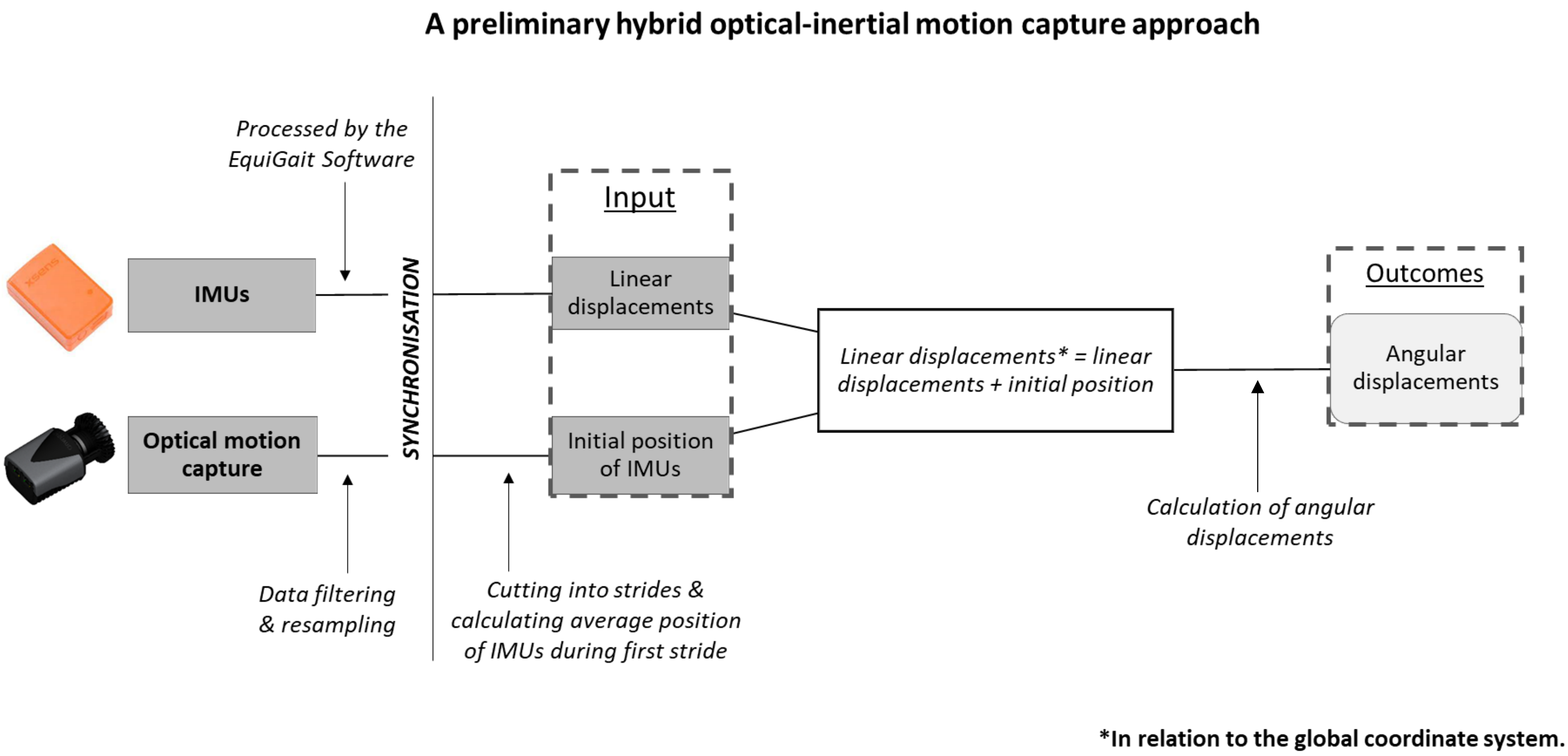


Figure 4.13 | A schematic illustration of the proposed hybrid optical-inertial motion capture approach. The motion signals from the inertial measurement units (IMUs) were processed through the EquiGait Software©, which applies the signal processing described by Pfau, Witte and Wilson (2005) to quantify the IMUs' linear displacements. The optical motion cameras capture the position of markers affixed to the IMUs in the global coordinate system.

4.7 Methods

This study was approved by the Ethical Committee at Hartpury University (ETHICS2020-228-LR). Informed, written consent from the horse owners was obtained before their horses participated in the study.

4.7.1 Study horses

Six horses (two mares and four geldings) with a mean age of 12±3 years and of different breeds were recruited. All horses regularly undertook treadmill exercise at Hartpury Equine Therapy Centre and were considered sound by their owner. The demographic details of the study horses are outlined in Table 4.2

Table 4.2. The demographic characteristics of the study horses.

	Age (years)	Breed	Sex
Horse 1	13	Welsh D	Mare
Horse 2	10	Holsteiner	Gelding
Horse 3	16	Dutch WB	Gelding
Horse 4	14	ISH	Mare
Horse 5	11	Welsh Cross	Gelding
Horse 6	8	Dutch WB	Gelding

ISH = Irish Sport Horse, WB = Warmblood.

4.7.2 Kinematic measurements – optical motion capture and IMUs

The kinematic data were obtained using an optical motion capture system (Qualisys AB, Göteborg, Sweden) and IMUs (MTx, Xsens, Enschede, Netherlands). The measurement systems collected data simultaneously, synchronised by two technicians who verbally counted the initiation for each capture.

Eight IMUs (4.7x3.0x1.1 cm) were affixed to the horse, on the bridle headpiece and the skin overlying the 5th, 13th, and 18th thoracic spinous process (T5, T13, and T18), the 2nd lumbar vertebra (L2), mid-*tubera sacrale* (sacrum), and on the LTC and RTC, respectively. The IMUs were attached to all horses by the same technician using double-sided tape. The IMUs were connected wirelessly to a computer running the EquiGait Software (Brickendon, Hertford, Hertfordshire, UK), which is built on the MT Manager Software (v4.8, Xsens, Enschede, Netherlands). Due to an unforeseen error in the hardware of the IMU placed on the 18th thoracic vertebra, IMU data at this level could not be retrieved. Consequently, only seven IMUs were used for data processing in this study. The placement of the seven IMUs on the horse is shown in Figure 4.14. The IMU data were collected with the IMUs sampling at 100 Hz. As discussed previously, this sampling frequency coheres to the Nyquist sampling theorem and to the sampling frequency range considered appropriate when using IMUs in equine movement analysis (Pfau and Reilly, 2021).

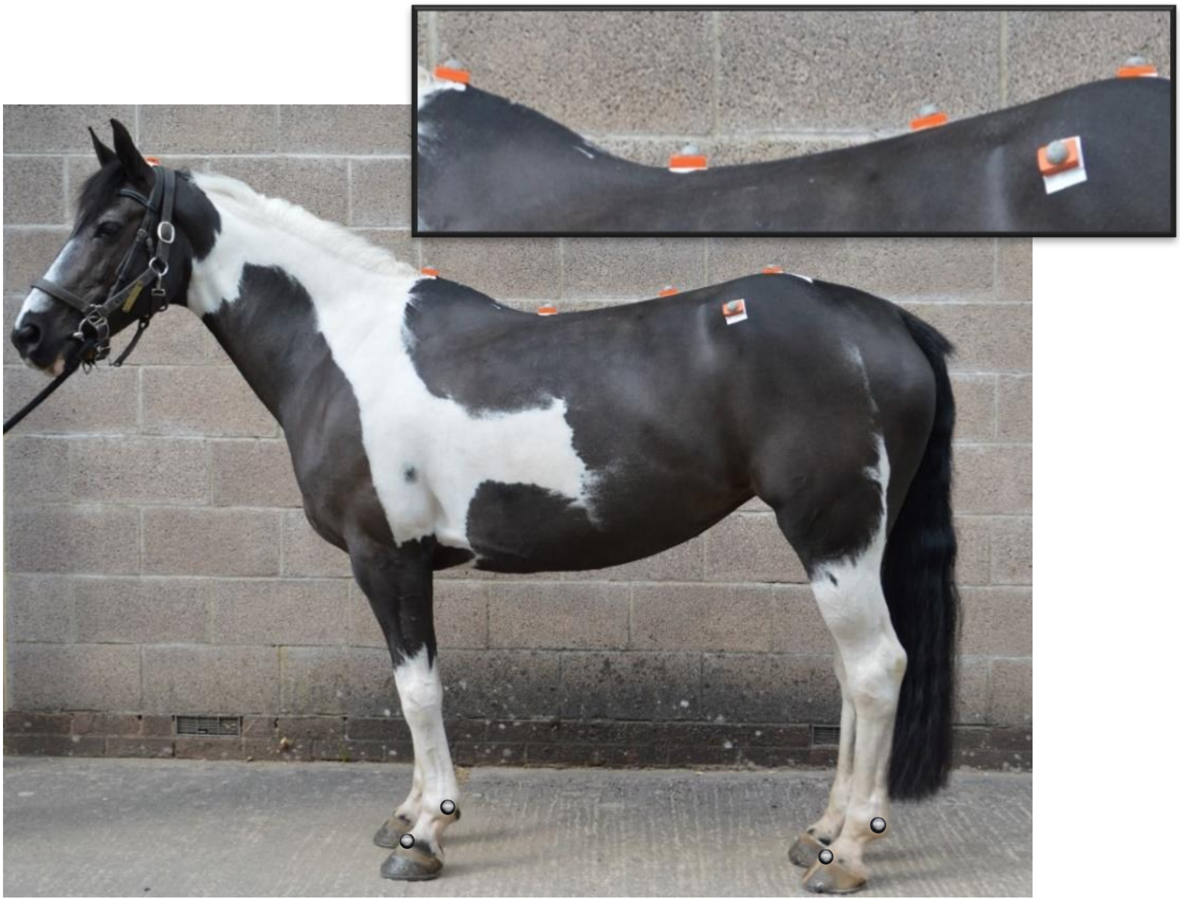


Figure 4.14 | Placement of the IMUs – with hemispherical markers on top – affixed to the horse's bridle at the level of the poll and to the skin overlying the anatomical landmarks of the horse's spinous process at thoracolumbar T5, T13, and L2, sacrum, LTC, and RTC, and of the reflective markers on the left front and hind coronal band and fetlock.

Hemispherical reflective markers (33 mm in diameter) were attached on top of the IMUs, as demonstrated elsewhere (Warner, Koch and Pfau, 2010; Bosch *et al.*, 2018), and spherical markers (19 mm in diameter) were attached to the skin overlying the left fore and hindlimb fetlock and coronal band using double-sided tape by the same technician. The movement of the markers was captured by nine motion capture cameras (Miqus M3, Qualisys AB, Göteborg, Sweden) placed around the treadmill within a 6 m range, as shown in Figure 4.15. One video camera (Miqus Video, Qualisys AB, Gothenburg, Sweden), placed between cameras 2 and 4, was used to enable retrospective visual observation of the trial. The cameras were daisy-chained and connected to a laptop running Qualisys Track Manager (version 2020.1, Qualisys AB, Gothenburg, Sweden). The optical motion capture system collected the data sampling at 240 Hz. This sampling frequency was chosen according to a previous study by Pfau, Witte and Wilson (2005), who validated the inertial measurement system used in the proposed hybrid approach against optical motion capture.

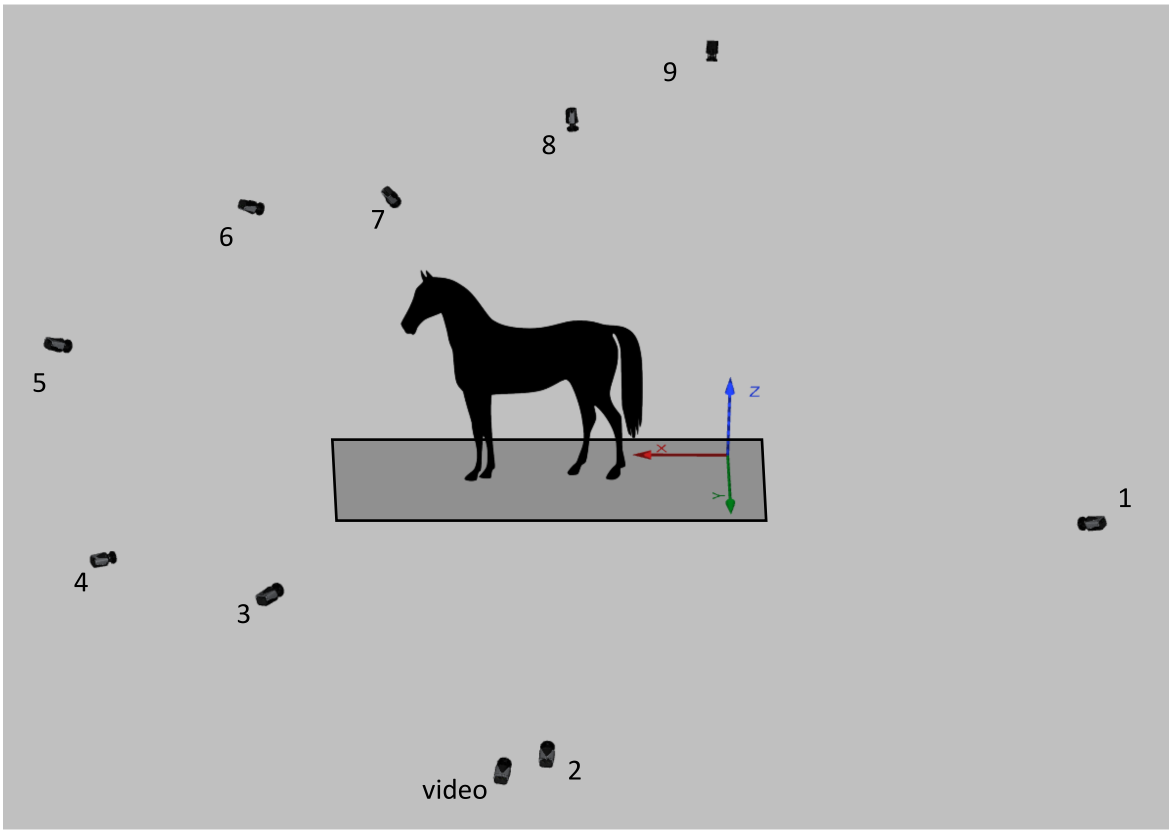


Figure 4.15 | The nine motion capture cameras and one video camera organised around the treadmill set-up. The coordinate system was located behind and on the right side of the horse's position on the treadmill.

A motion capture calibration of 20 seconds was performed at the start of the data collection. An L-shaped calibration frame and a calibration wand (601.8 mm) were used for the calibration, with the calibration wand being moved through the capture volume throughout the calibration capture. The calibration frame was positioned on the same spot for both calibrations, which was measured and identified carefully using a measuring tape. The long arm of the calibration frame was positioned close to the right-side border, positive in the direction of travel of the horse on the treadmill, whilst the short arm was parallel to the short side of the treadmill and positive to the left according to the horse's orientation on the treadmill. The definition of the global coordinate system followed the right-hand rule, according to the orientation of the local coordinate system of the IMUs, with the long arm of the calibration frame representing the global coordinate system's X-axis and the short arm the Y-axis (see Figure 4.15). The calibration outcomes demonstrated an average residual of the cameras ranging from 0.42 to 1.18 mm, and a standard deviation of the wand length of 0.66 mm.

4.7.3 Study protocol

All horses carried out a predefined protocol on the treadmill, which was no longer than five minutes. A 10-second standing capture was taken while the horse halted squarely on the treadmill with weight on all limbs. The horse then walked and trotted for 30 seconds to acclimate the horses to the treadmill speed, then for a 40-second data capture. The treadmill speed was determined for each horse individually by the Equine Therapy Centre staff, conforming to the speed each horse was used to in their regular treadmill sessions. Walking speed was the same for all horses (1.4 m/s) while trotting speed varied between 3 and 3.4 m/s (see Appendix A.VI for the speed for each horse). During all trials, the handlers encouraged the horse to maintain a straight, neutral head-neck posture (neck close to the horizontal and head close to vertical) using consistent and appropriate rein tension.

4.7.4 Data processing

The reflective markers were labelled in the Qualisys Track Manager. Data gaps smaller than ten frames were filled automatically by the Qualisys Track Manager using polynomial interpolation. The 3D coordinates of all markers in the global coordinate system, defined by the calibration of the optical motion capture system, were exported in .TSV files. The inertial measurements were processed in the EquiGait software, which computed each IMU's linear acceleration, velocity, and displacement in a right-handed Cartesian coordinate system where the X-axis aligns with the horse's line of progression, the Z-axis is aligned with the global coordinate system, and the Y-axis is orientated perpendicular to the X and Z axes (Pfau, Witte and Wilson, 2005; Warner, Koch and Pfau, 2010). The data from the optical motion capture system and the IMUs were imported into MATLAB (version R2020b, The MathWorks, Natick, Mass., USA), and custom-made MATLAB scripts were used to process the data further (see Appendix B).

4.7.4.1 Calculation of the back conformation characteristics

The 3D coordinates of the thoracolumbosacral markers captured by the optical motion capture system during the static captures were used to calculate the back conformation characteristics of the horses. One frame during which the horse was standing adequately square and still was selected from the standing capture in Qualisys, representing a photographic measurement which has previously been described for conformation measurements (Holmström, 2001). The selection of the frame was based on visual evaluation of the horse's posture during the trials, and a frame during which the horse was standing ultimately still, straight, and squarely in a neutral head-neck posture with its weight distributed over all limbs was selected. The 3D coordinates of the markers at that frame only were used for the measurements of the back conformation.

Wither height was calculated as the vertical position of the marker at T5, with an 11 mm correction for the height of the IMU on top of which the marker was placed throughout the selected standing capture. The back length was calculated as the craniocaudal length between the marker at T5 and the sacrum, calculated as the resultant transverse vector. The thoracolumbosacral angle was calculated as the angle between the craniocaudal vectors from T5 to T13 and sacrum to T13 and the dorsoventral vectors from T5 to T13 and sacrum to T13 throughout the selected standing capture (see equation 4.4). The quantified conformation characteristics of the horse's back wither height, back length, and thoracolumbosacral angle are depicted in Figure 4.16.

$$\textbf{Thoracolumbosacral angle} = 180^{\circ} - \theta_1 - \theta_2 \qquad \textbf{(4.4)}$$

$$With\ \theta_1 = rad2deg\left(atan\left(\frac{vertical\ distance\ T5{-}T13}{craniocaudal\ distance\ T5{-}T13}\right)\right)$$

$$With\ \theta_2 = rad2deg\left(atan\left(\frac{vertical\ distance\ T13{-}sacrum}{craniocaudal\ distance\ T13{-}sacrum}\right)\right)$$

With craniocaudal distances = the resultant transverse vectors between the markers

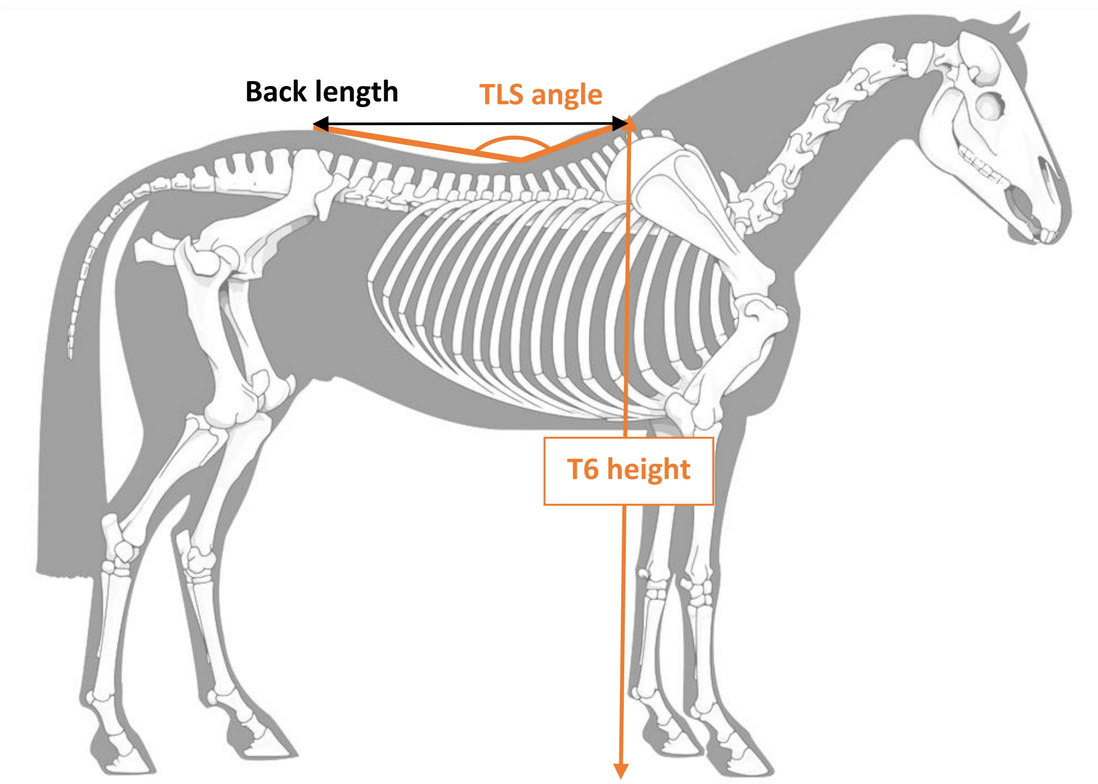


Figure 4.16 | A representation of the quantified conformation characteristics of the horse's back, including wither (T6) height, back length, and thoracolumbosacral (TLS) angle.

4.7.4.2 Filtering and resampling of the optical motion capture data

The motion signals collected with the optical motion capture system during the walk and trot trials were filtered using a 4th-order low-pass Butterworth filter to remove high-frequency noise. A cut-off frequency of 12 Hz was applied, coinciding with the cut-off frequency used in part A of this Chapter (30 Hz) for a sampling frequency of 100 Hz. To allow synchronisation with the IMUs' motion signals, the optical motion capture data were resampled to 100 Hz, being 5/12 times the original sampling rate (240 Hz), using the *resample* function in MATLAB which applies a finite impulse response (FIR) antialiasing low-pass filter. The low-pass filter was applied prior to downsampling the signal in order to mitigate any distortion of the motion signal due to filtering the data, referred to as aliasing of the signal (Al-Amri *et al.*, 2018; Fleron *et al.*, 2019). As the data from the IMUs were already filtered by processing it in the EquiGait software, no filter was applied to the displacement time series obtained from the IMUs. The filter applied to the displacement data by the EquiGait software is a high-pass Butterworth filter with a cut-off frequency of 0.5 Hz for mediolateral and 1 Hz for craniocaudal and dorsoventral movement, which attenuates the low-frequency components of the motion signal (Pfau, Witte and Wilson, 2005).

4.7.4.3 Time-synchronisation

To synchronise the time series obtained from the optical motion capture and the IMUs, the correlation coefficient was calculated between the LTC vertical velocity time series collected with both motion capture tools and a cross-correlation of the time series was performed. The index of the correlation peak yields the time lag between the capture of the two systems, which was within one second for all trials, and enabled alignment of the time series in time. The cross-correlation to time-synchronise the time series from a horse's movement collected with optical motion capture and IMUs has been used previously by Bosch *et al.* (2018). In this study, a velocity measure was chosen for the cross-correlation as those are not high-passed filtered by the EquiGait software and thus allow a more reliable synchronisation. The vertical velocity signal of the LTC from both systems was visually inspected before and after the time-synchronisation to ensure an accurate cross-correlation of the time series (see Figure 4.17). Once synchronised, the first and last stride were discarded of each capture in order to avoid filtering transients to affect the motion signals output, which could skew the comparison between motion capture systems and different filtering approaches (Warner, Koch and Pfau, 2010; Serra Bragança *et al.*, 2020).

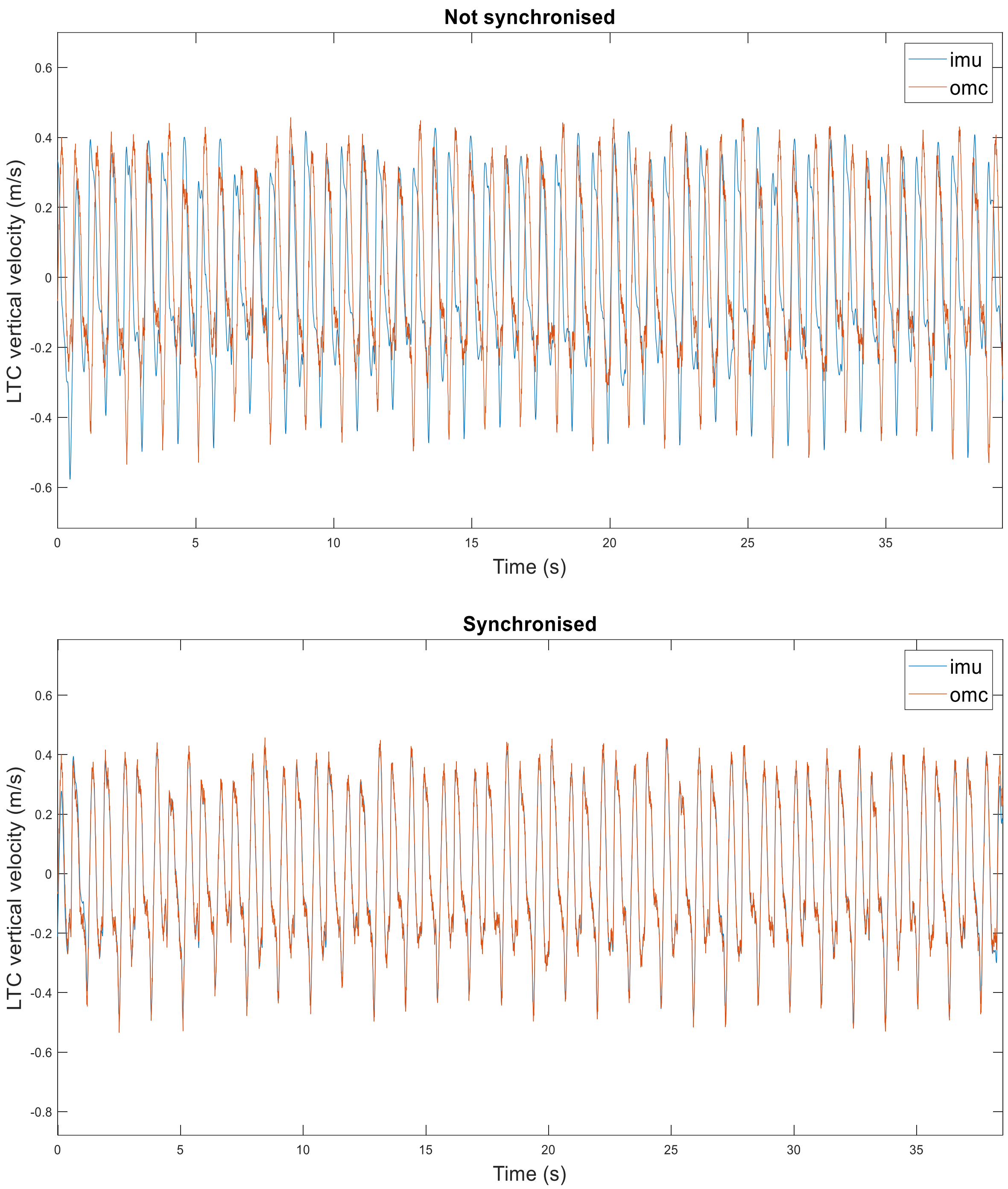


Figure 4.17 | The vertical velocity of the left *tuber coxae* (LTC) at walk captured by optical motion capture (omc) and an inertial measurement unit (imu) before and after time-synchronisation.

4.7.4.4 Position estimation of the IMUs

The position estimation of the IMUs in the global coordinate system of the optical motion capture system was obtained for each trial individually. The position of the IMUs throughout a trial was estimated using the coordinates of the markers placed on top of the IMUs collected with optical motion capture during the first included stride of that trial, referred to as the IMUs' initial position during that trial, and the linear displacement time series collected with the IMUs. Given that the inertial measurement system used for the proposed hybrid approach has been validated to track the linear displacement of a horse's back segments during steady-state locomotion (Pfau, Witte and Wilson, 2005; Warner, Koch and Pfau, 2010) but not during standing captures and transitions between gaits, the position estimation was performed at the start of each dynamic trial rather than via a static calibration, as is seen elsewhere (Martin, 2015; Hatrisse *et al.*, 2023). The first stride of the dynamic trials was used for the definition of the IMUs' initial position as a standardised time point for the position estimation.

The optical motion capture dataset was first cut into strides using the vertical displacement time series of the IMUs placed on the LTC and RTC, as described in Section 4.2.8. The mean of the 3D coordinates of the markers placed on top of the IMUs throughout the first stride was then calculated. The position estimation of the IMUs throughout the trial was completed by aligning the linear displacements obtained from the IMUs with their initial position, obtained with the optical motion capture system. The following equations were used for the position estimation of the IMUs along the three axes:

$$\textbf{Position along } \mathbf{X_{axis}} = \text{mean}(\mathrm{X}_{coordinates} \text{ throughout 1st stride}) + \mathrm{X}_{\text{displacement}} \quad \textbf{(4.5)}$$

$$\textbf{Position along } \mathbf{Y_{axis}} = \text{mean}(\mathrm{Y}_{\text{coordinates}} \text{ throughout 1st stride}) + \mathrm{Y}_{\text{displacement}} \quad \textbf{(4.6)}$$

$$\textbf{Position along } \mathbf{Z_{axis}} = \text{mean}(\mathrm{Z}_{\text{coordinates}} \text{ throughout 1st stride}) + \mathrm{Z}_{\text{displacement}} \quad \textbf{(4.7)}$$

With the XYZ coordinates being captured with the optical motion capture system

and the XYZ displacement being collected with the IMUs

A diagram of the position estimation of an IMU along the vertical axis is shown in Figure 4.18. The estimated position of the IMUs throughout the trial is sequentially described as the displacement time series collected using the hybrid approach.

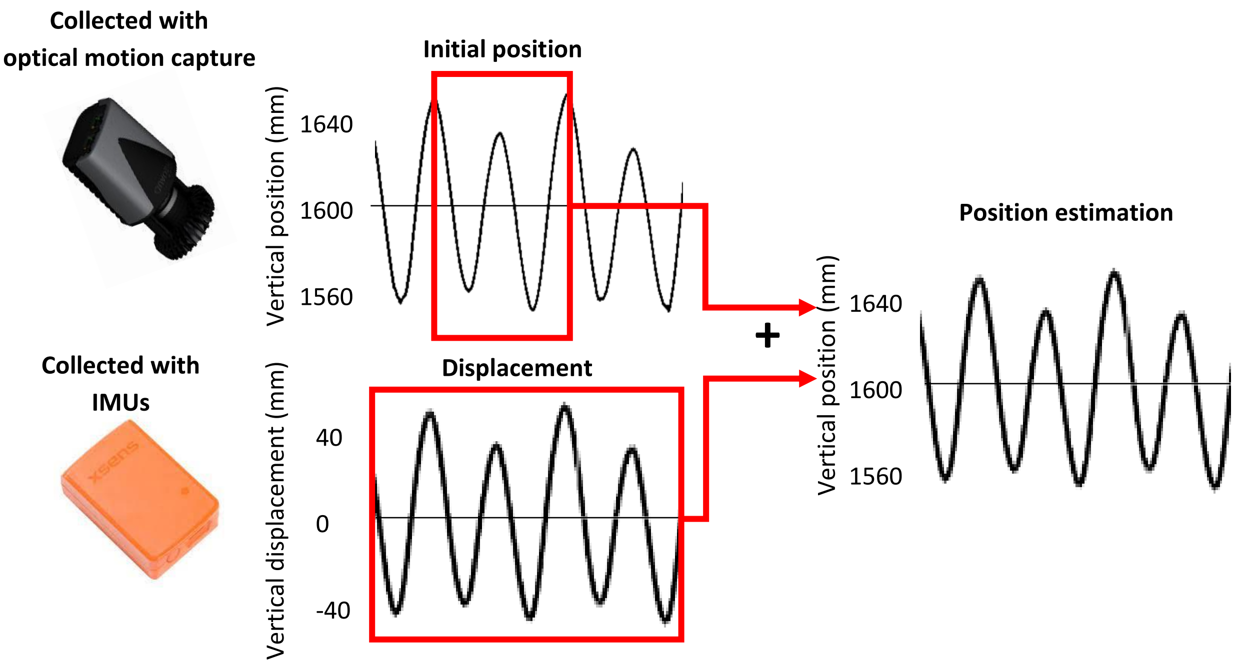


Figure 4.18 | A diagram of the position estimation of an inertial measurement unit (IMU) along the vertical axis using the sum of the mean vertical position of the marker on top of the IMU during the first stride of the capture and the vertical displacement of the IMU throughout the capture.

4.7.4.5 Calculation of the angular displacements

The flexion-extension and lateral bending displacements between T5-T13-L2 and T13-L2-sacrum were calculated using the displacement time series collected using optical motion capture and the hybrid approach. The flexion-extension and lateral bending displacements were calculated as described by Faber *et al.* (2001b), with the adaptation that the flexion-extension angles were calculated within the horse's median plane rather than in the *X-Z* plane of the global coordinate system (see Equations 4.8-9). This adaptation allowed a more accurate comparison between the two motion capture systems, considering that the IMUs quantify the linear displacements in a horse-based reference system (Warner, Koch and Pfau, 2010). Therefore, the craniocaudal distance between the back segments rather than the distance along the X-axis was used for the calculation of the flexion-extension displacements with the time series collected with the optical motion capture system. The error induced by the difference in the horse's versus global reference system, or the 'projection' of the angle in the global reference system, in the lateral bending displacements calculated with the displacement time series from the two motion capture systems were compensated for by zero-centring the angular displacement outcomes. The zero-centring of the lateral bending displacements was performed by calculating the mean lateral bending angle for each normalised stride and subtracting the mean angles from the continuous angular displacements throughout each stride (see Equation 4.10). The same method was used to split and normalise the strides as described in Section 4.2.8, initiating each stride cycle with the mid-stance phase of the left hindlimb. Figure 4.19 illustrates the calculated angles at T13 and L2.

$$\mathbf{Flexion-extension}_{v2} = \mathrm{rad2deg}(\mathrm{atan}(\frac{z_{v3} - z_{v1}}{craniocaudal\ distance_{v3-v1}})) \quad \mathbf{(4.8)}$$

with v1 and v3 = the proximal and distal vertebrae, respectively

$$\mathbf{Lateral\ bending}_{v2} = \mathrm{rad2deg}(\mathrm{atan}(\frac{y_{v3} - y_{v1}}{x_{v3} - x_{v1}})) \quad \mathbf{(4.9)}$$

with v1 and v3 = the proximal and distal vertebrae, respectively.

$$\mathbf{Zero-centred\ lateral\ bending_i} = \mathrm{lateral\ bending_i} - \mathrm{mean(lateral\ bending)} \quad \mathbf{(4.10)}$$

$$with\ i = stride\ number.$$

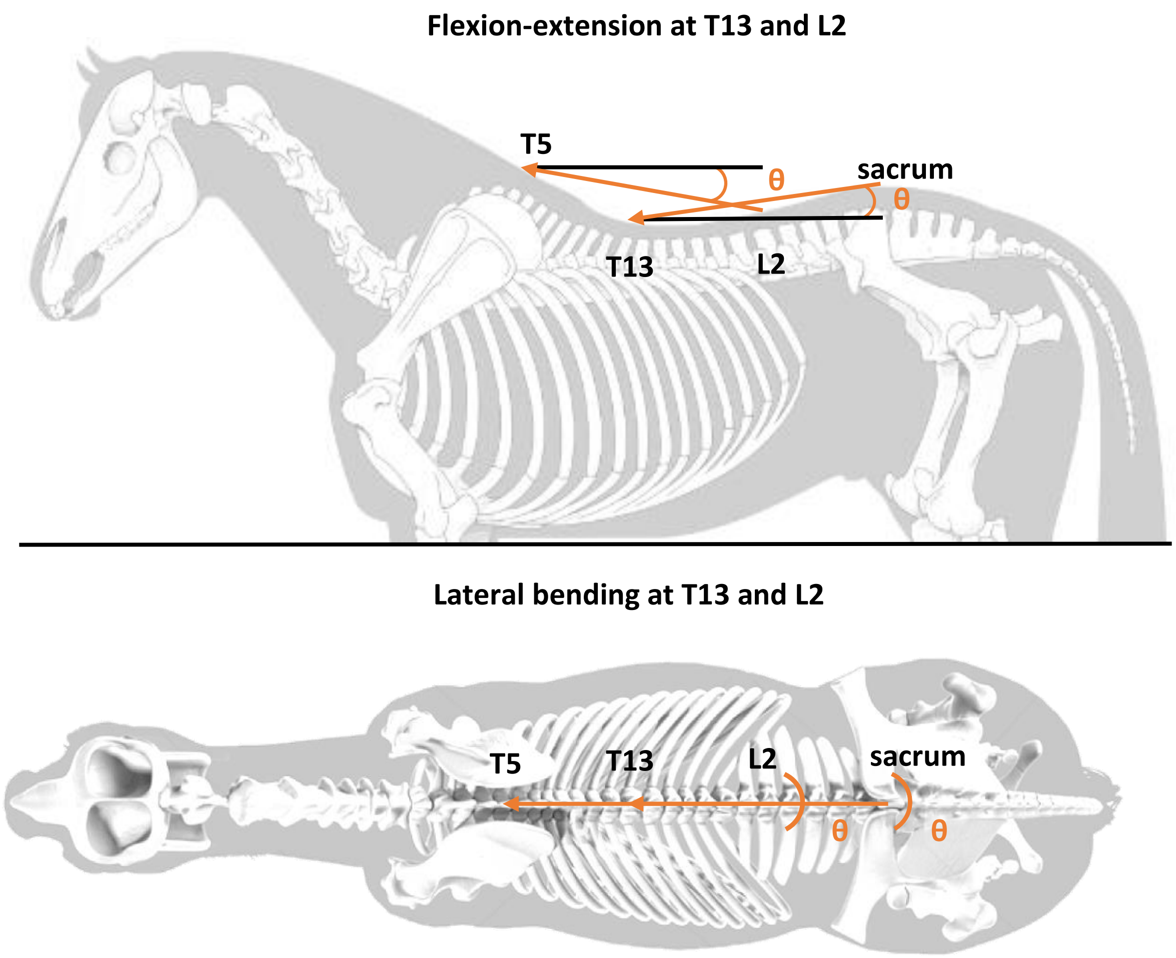


Figure 4.19 | The flexion-extension (on top) and lateral bending (below) angle at T13 and L2.

4.7.4.6 Excluding outliers

As aforementioned (see Section 2.4.2), the outcomes from the inertial measurement systems used to measure equine locomotion represent steady-state locomotion only due to the filtering methods applied to the motion signals. Therefore, a correct comparison between the hybrid approach and optical motion capture could only be made during steady-state locomotion. To detect and exclude stride cycles with movement outliers representing non-steady state locomotion in the collected data sets, for example due to a horse altering its position or rhythm on the treadmill, the moving-window method described by Mullineaux and Irwin (2017) was applied. This moving-window method entails two stages of outlier detection, with the first detecting stride cycles with spatial outliers at each time point using the median absolute deviation and the second detecting stride cycles with spatiotemporal outliers using moving window standard deviation with a size one. To account for the varying number of stride cycles, the confidence interval size of the median absolute deviation and moving window standard deviation were multiplied by the two-tailed t-statistic for a *p*-value of 0.0001 and 0.01, respectively. The movement outliers were identified within the angular displacement time series derived from the optical motion capture motion signals. The stride cycles with movement outliers detected using the moving-window method were then excluded from the time series obtained using optical motion capture and the hybrid approach.

4.7.5 Data analysis

The outcomes collected for comparison between the motion capture systems were the flexion-extension displacements and the zero-centred lateral bending displacements at T13 and L2 at walk and trot. The difference between the angular time series collected with the two motion capture systems was found to be abnormally distributed using the Shapiro-Wilk test in MATLAB ($p<0.05$). Therefore, non-parametric tests were used to evaluate the level of error of the hybrid approach against the optical motion capture and the correlation between the two, adhering to the accuracy outcomes described by Pfau, Witte and Wilson (2005). The statistical outcomes evaluated include the median difference in the angular displacements, the 25th and 75th percentile range (P25-P75) of the difference in the angular displacements, the ratio of the P25-P75 and the ROM of the angular displacements measured with optical motion capture (P25-P75/ROM), and the Spearman correlation (*R*) between the angular displacements. Additionally, correlation analysis was performed to evaluate any associations between the levels of error found for the hybrid approach in measuring the horse's back movement and the conformation characteristics of the horse's back. A Spearman correlation analysis was performed between the P25-P75/ROM and *R* measures of the angular displacements between the motion capture systems and the horse's wither height, back length, and thoracolumbosacral angle at walk and trot. An alpha level of .05 was adhered to for all statistical tests.

4.8 Results

Overall, 126 strides at walk and 183 strides at trot were evaluated. The stride time varied between 1.1 and 1.3 seconds at walk and 0.8 and 0.9 seconds at trot between the horses, coinciding with a stride frequency of 0.8-0.9 Hz at walk and 1.1-1.3 Hz at trot. The number of strides collected, as well as the speed and stride time, for each trial are demonstrated in Appendix A.VI.

4.8.1 The levels of error measuring flexion-extension displacements

The median and interquartile range of the difference in and the correlation between the flexion-extension displacements at T13 and L2 calculated using optical motion capture and the hybrid approach at walk and trot are reported in Table 4.3. The median difference values ranged from -0.2 to 0.3 degrees, while the P25-P75/ROM varied between 3.7 and 19.9%. The correlation between the two motion capture systems was very strong (*R*=0.90-1.00) for the flexion-extension displacements at T13 and L2 at walk and trot for all horses. The alignment of the flexion-extension displacements at both levels calculated with the two motion capture systems were comparable at walk and trot (see Figure 4.20).

Table 4.3. Level of error and correlation between the flexion-extension displacements calculated using optical motion capture and the hybrid approach.

	T13			L2		
	Median (P25, P75)	*R*	P25-P75/ ROM (%)	Median (P25, P75)	*R*	P25-P75/ ROM (%)
Walk						
Horse 1	-0.2 (-0.4, 0.0)	0.99*	4.5	-0.0 (-0.2, 0.2)	0.99*	5.3
Horse 2	0.0 (-0.4, 0.3)	0.96*	11.5	0.1 (-0.3, 0.4)	0.96*	11.1
Horse 3	0.0 (-0.2, 0.2)	0.99*	6.3	-0.1 (-0.3, 0.0)	1.00*	3.7
Horse 4	-0.1 (-0.3, 0.0)	0.99*	5.9	0.3 (0.1, 0.4)	0.99*	5.3
Horse 5	-0.2 (-0.3, 0.0)	0.99*	4.4	-0.1 (-0.3, 0.0)	0.99*	4.4
Horse 6	0.2 (-0.0, 0.3)	0.99*	5.2	0.2 (0.1, 0.4)	1.00*	4.0
Trot						
Horse 1	0.2 (0.0, 0.4)	0.98*	9.0	0.0 (-0.1, 0.1)	0.90*	14.1
Horse 2	0.1 (-0.2, 0.3)	0.95*	13.6	-0.0 (-0.3, 0.3)	0.90*	19.1
Horse 3	-0.2 (-0.4, -0.1)	0.98*	7.6	-0.0 (-0.3, 0.2)	0.93*	11.7
Horse 4	-0.0 (-0.2, 0.2)	0.98*	8.4	0.2 (0.0, 0.3)	0.96*	11.7
Horse 5	0.1 (-0.2, 0.3)	0.90*	19.9	-0.1 (-0.3, 0.1)	0.95*	13.3
Horse 6	-0.2 (-0.5, 0.1)	0.98*	8.3	0.1 (-0.1, 0.4)	0.94*	12.8

*P25, P75 = the 25th and 75th percentiles, P25-P75 = the interquartile range; ROM = range of motion. * = P<0.001.*

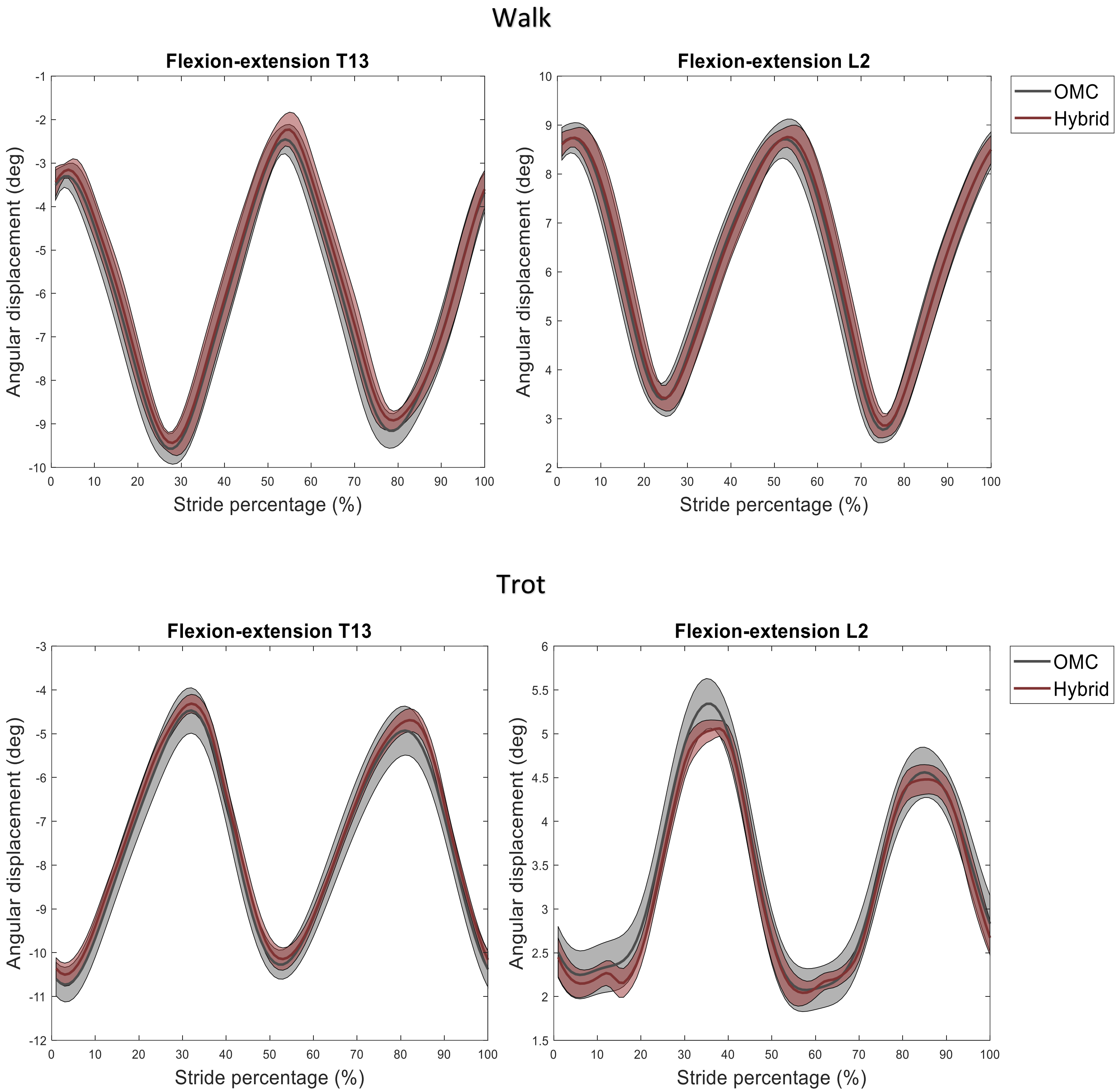


Figure 4.20 | An example of the mean (with standard deviation) flexion-extension displacements at T13 and L2 at walk and trot calculated with both motion capture systems. OMC = optical motion capture, Hybrid = the hybrid approach.

4.8.2 The levels of error measuring lateral bending displacements

The median and interquartile range of the difference in and the correlation between the lateral bending displacements at T13 and L2 calculated using optical motion capture and the hybrid approach at walk and trot are reported in Tables 4.4. A notable variability in the levels of error of the hybrid approach in measuring the lateral bending displacements was seen between horses, with the levels of error being consistently higher for the lateral bending measurements at L2. The median difference values ranged from -0.1 to 0.1 degrees, while the P25-P75/ROM varied between 5.2 and 23.3%. The correlation between the two motion capture systems in the lateral bending displacements at both levels and gaits varied from a strong to a very strong correlation (*R*=0.81-0.99). The alignment of the lateral bending displacements at both levels calculated with the two motion capture systems were comparable at walk and trot (see Figure 4.21).

Table 4.4. Level of error and correlation between the zero-centred lateral bending displacements calculated using optical motion capture and the hybrid approach.

	T13			L2		
	Median (P25, P75)	*R*	P25-P75/ ROM (%)	Median (P25, P75)	*R*	P25-P75/ ROM (%)
Walk						
Horse 1	-0.1 (-0.3, 0.2)	0.99*	5.9	0.0 (-0.2, 0.2)	0.94*	13.5
Horse 2	0.0 (-0.6, 0.6)	0.92*	16.3	-0.1 (-0.5, 0.5)	0.84*	23.3
Horse 3	-0.0 (-0.3, 0.3)	0.96*	11.6	0.1 (-0.2, 0.2)	0.88*	16.0
Horse 4	0.0 (-0.2, 0.2)	0.97*	7.3	0.0 (-0.2, 0.2)	0.97*	8.7
Horse 5	-0.0 (-0.2, 0.2)	0.99*	7.3	0.0 (-0.2, 0.1)	0.97*	8.9
Horse 6	-0.1 (-0.2, 0.3)	0.98*	6.4	0.0 (-0.3, 0.2)	0.81*	17.4
Trot						
Horse 1	0.0 (-0.2, 0.2)	0.97*	6.7	0.0 (-0.2, 0.2)	0.93*	11.7
Horse 2	-0.0 (-0.5, 0.4)	0.91*	13.2	-0.0 (-0.4, 0.4)	0.83*	19.1
Horse 3	0.1 (-0.1, 0.2)	0.93*	9.4	0.0 (-0.2, 0.2)	0.98*	9.2
Horse 4	0.0 (-0.2, 0.2)	0.95*	12.5	0.0 (-0.2, 0.2)	0.93*	14.8
Horse 5	-0.0 (-0.2, 0.2)	0.98*	5.8	-0.0 (-0.2, 0.2)	0.93*	13.7
Horse 6	0.0 (-0.3, 0.4)	0.95*	9.8	-0.1 (-0.5, 0.5)	0.81*	20.1

P25, P75 = the 25th and 75th percentiles, P25-P75 = the interquartile range; ROM = range of motion. P<0.001.

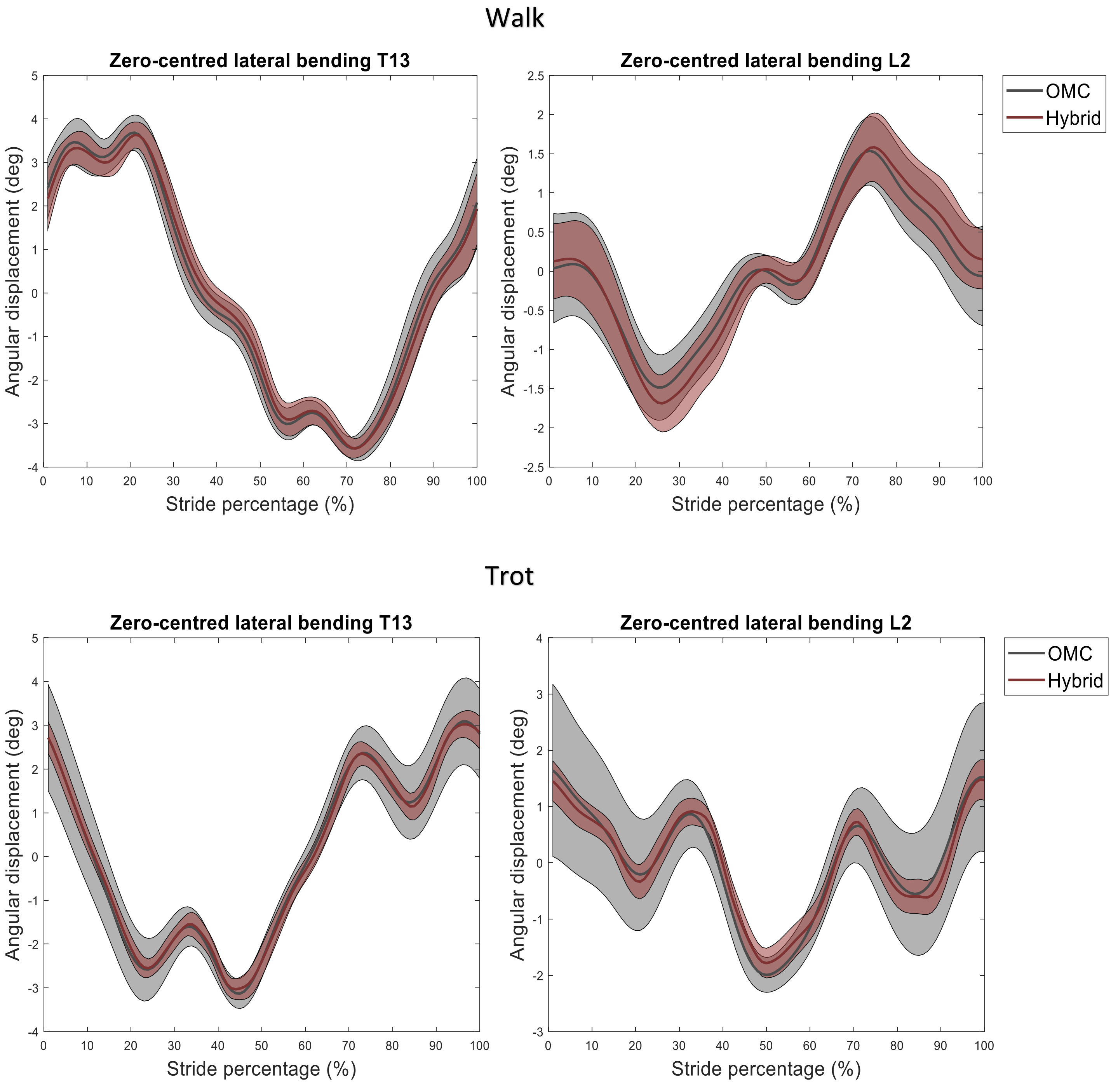


Figure 4.21 | An example of the mean (with standard deviation) zero-centred lateral bending displacements at T13 and L2 at walk and trot calculated with both motion capture systems. OMC = optical motion capture, Hybrid = the hybrid approach.

4.8.3 Association between the horse's back conformation and the levels of error of the hybrid approach in measuring the horse's back movement

The conformation characteristics of the horse's back are shown in Table 4.5. A variation of 27 cm in the wither height, 13 cm in the back length, and six degrees in the thoracolumbosacral angle were seen in the examined study horses. No correlations were found between the horse's back conformation and the levels of error of the hybrid approach in measuring the angular displacements (all $p \geq 0.05$), except for measuring the lateral bending displacements at walk at L2, for which significant correlations were found between the horse's back length and the correlation coefficient (R=-0.93, p=0.01) and the P25-P75/ROM (R=0.94, p=0.01) accuracy measures (see Figure 4.22).

Table 4.5. The horses' back conformation characteristics.

	Wither height (m)	Back length (m)	Thoracolumbosacral angle (degrees)
Horse1	1.55	0.87	151
Horse2	1.82	0.91	157
Horse3	1.74	0.89	155
Horse4	1.60	0.83	153
Horse5	1.61	0.78	154
Horse6	1.72	0.90	154

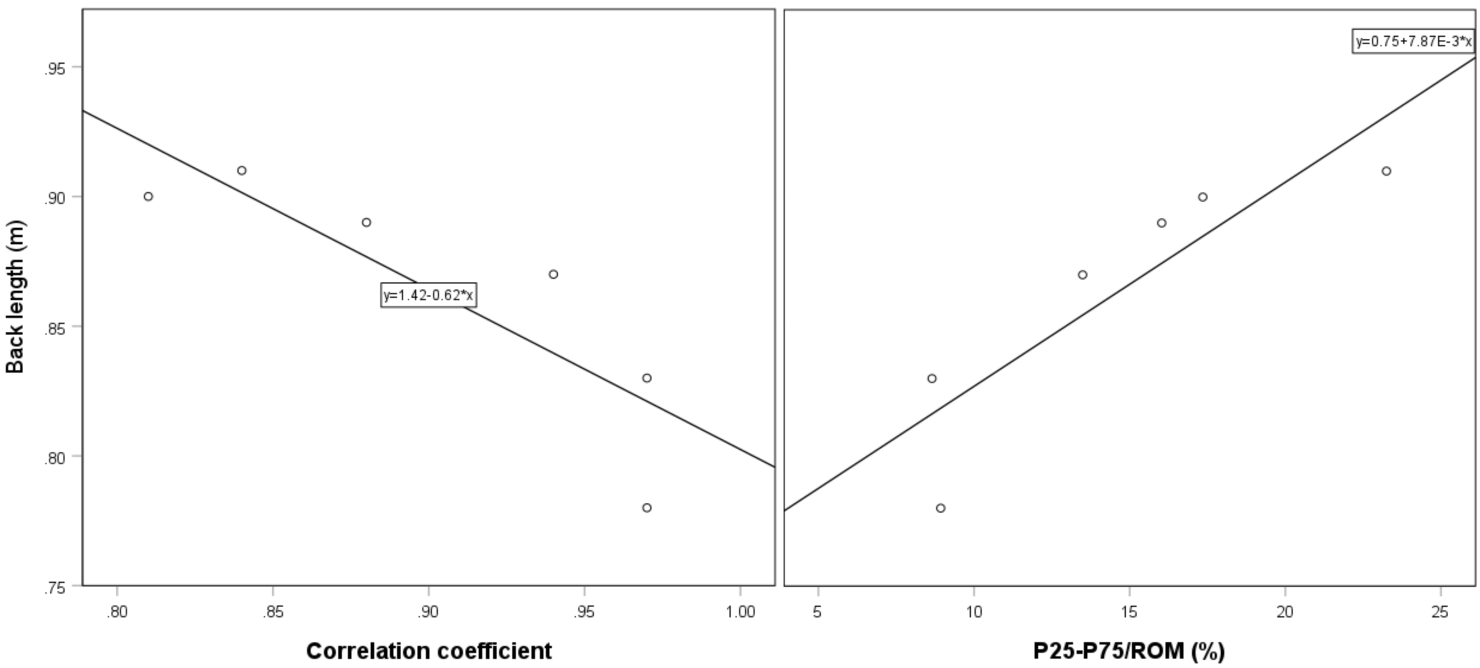


Figure 4.22 | Scatter plots of back length by the correlation coefficient (left) and P25-P75/ROM (right) between the two motion capture systems in measuring lateral bending at L2 at walk.

4.9 Discussion

This study aimed to evaluate the level of error of the proposed hybrid approach in measuring flexion-extension and lateral bending displacements of the horse's back at walk and trot against optical motion capture. The P25-P75/ROM of the level of error found for the proposed hybrid approach in measuring the angular displacements was within 20% for most horses, which was previously reported as the normal range of movement variability in flexion-extension and lateral displacement measurements of a horse's back when trotting on a hard-surfaced straight line (Hardeman *et al.*, 2020). The range of movement variability defined by Hardeman *et al.* (2020) was based on the variation between 12 different measurements of the whole back (withers-T15-sacrum) spread over up to 55 days in sport horses (n=12) that were in regular ridden work and considered sound by their owner and a veterinarian prior to the data collection. Additionally, the correlation between the two motion capture systems was higher than the correlation reported by Hardeman *et al.* (2020) for the whole back flexion-extension (ICC=0.51) and lateral bending (ICC=0.80) measurements. The median level of error found for the proposed hybrid approach in measuring the angular displacements was also found to be within clinical and statically significant changes in the flexion-extension (0.5 degrees) and lateral bending (0.3 degrees) ROM at walk and trot previously reported in horses with induced back pain (Wennerstrand *et al.*, 2009). However, the interquartile ranges exceeded these values for some of the horses. Given that the levels of error found for the proposed hybrid approach in measuring angular displacements of the horse's back were within the normal range of movement variability in a horse's back kinematics (Hardeman *et al.*, 2020), these levels of error can be considered small enough to be of use in clinical settings, confirming the first study hypothesis. However, the proposed hybrid approach might not be accurate enough to measure small differences in the horse's back movement, considering that the interquartile ranges for its level of errors went up to 0.6 degrees for the flexion-extension and 1.2 degrees for the lateral bending displacement measurements.

It was also hypothesised that there would be no correlation between the levels of error of the hybrid approach and the horse's back conformation. This second study hypothesis was rejected based on significant correlations between the horse's back length and the levels of error of the hybrid approach in measuring the lateral bending displacements at walk. These study findings indicate that the longer the horse's back, the more prominent the levels of errors of the hybrid approach in measuring the lateral bending displacements at L2 at walk. It must be noted that the highest levels of error of the hybrid approach were found for the lateral bending displacements at L2 at walk, as well. This observation coincides with that of Faber *et al.* (2001b), who examined the level of error in flexion-extension and lateral bending displacements of the horse's back at walk and trot measured using skin-mounted markers against bone-fixated markers with optical motion capture. Faber *et al.* (2001b) reported that the measurements using skin-mounted markers were least reliable in quantifying the lateral bending displacements in the caudal thoracic-lumbar region at walk and assigned those discrepancies to skin displacement and the 2D projection of the horse's spinal movement. As demonstrated previously in the appendicular skeleton, the skin displacement patterns are strongly and positively correlated with the horse's body size at walk and significantly less so at trot (van Weeren, van den Bogert and Barneveld, 1992). Therefore, it could be speculated that the more prominent discrepancies found between the two motion capture systems in measuring the lateral bending displacements at L2 at walk in the current study could have been caused by skin displacements in this region being more prominent at walk and in horses with a bigger body size. Furthermore, the placement of the hemispherical marker on top of the IMU and the discrepancies in motion signal processing, such as the application of the high-pass filter on the displacement outcomes from the IMUs, are likely to have influenced the role of skin displacement in the discrepancies between the motion capture systems.

While a combination of measurement tools in equine movement analysis is common (Egan, Brama and McGrath, 2019), the use of a hybrid motion capture approach combining optical motion capture with IMUs to measure a horse's back movement has not yet been reported in the equine literature. This study demonstrated that such a hybrid motion capture approach can overcome some of the limitations of the motion capture tools individually in measuring a horse's back movement. The hybrid approach proposed in this study facilitates position estimation of the IMUs relative to each other, enabling measurements of the horse's posture, and only relies on the line of sight from the optical motion cameras on IMU-mounted markers throughout one stride cycle. The high correlation values and relatively low levels of error of the hybrid approach can be considered encouraging for the use of this hybrid approach to measure a horse's back movement. However, several considerations have to be taken into account prior to applying the proposed hybrid approach in field conditions.

First of all, this study evaluated the levels of error of the hybrid approach against optical motion capture in horses walking and trotting on a treadmill, which was opted for to enable continuous comparison of the measurement outcomes during steady-state locomotion between the two motion capture systems with a relatively low number of optical motion cameras (n=9). The motion signals along the XY axes adopt cyclical motion patterns with minimal linear movement components when on a treadmill, whilst these are composed of linear movement components predominantly when overground by moving forwards/ sideways. The signal processing applied by the inertial measurement system used in this study defines the IMUs' displacements along the XY axes as cyclical movement regardless of whether the horse moves on a treadmill or overground (Pfau, Witte and Wilson, 2005; Warner, Koch and Pfau, 2010), whilst the optical motion capture tracks the movement of the markers in its capture volume and represents the actual locomotory patterns (Chèze, 2014). This discrepancy between the motion signals derived from the IMUs and the optical motion capture system might alter the levels of error of the hybrid approach against optical motion capture in measuring a horse's back movement in field conditions compared to on the treadmill. However, when calculating angular displacements, differential linear displacements are of interest. Differential linear displacements also demonstrate predominantly cyclical motion patterns regardless of whether the horse moves on a treadmill or overground. Therefore, it can be speculated that the difference in the levels of error of the hybrid approach when measuring a horse's back movement in field or on the treadmill would be trivial. Regardless, further research is required to establish the reliability of alike hybrid approaches to measure a horse's back movement in field conditions.

A second consideration to acknowledge when contemplating the use of the proposed hybrid approach in field conditions is its limitation in capturing movement variability. A certain degree of movement variability is attenuated in the displacement time series obtained with the IMUs, considering a high-pass filter is applied to these time series (Pfau, Witte and Wilson, 2005). No high-pass filter was applied to the optical motion capture time series, which means that they represent movement variability more accurately. Even though strides with movement outliers were targeted and excluded by the moving-window method described by Mullineaux and Irwin (2017), and the horse is considered to demonstrate a more steady-state gait while on a treadmill (Buchner *et al.*, 1994), notable differences were still observed between the two motion capture systems in measuring movement variability (see Figures 4.19-20). This distinction between the motion signals from the two motion capture systems is considered responsible for the larger motion capture errors identified in this study for the proposed hybrid approach in measuring the horse's back movement. Therefore, the proposed hybrid approach would be reliable for measurements of a horse's back during steady-state locomotion only, and any non-cyclical movement outliers can skew its outcomes.

The limitation of the proposed hybrid approach in measuring movement variability also entails that its validity in measuring the horse's back movement is highly dependent on the initial position estimation being representative of the entire trial. In this study, the first valid stride captured by the optical motion capture system was selected to standardise the composition of the IMUs' initial position. However, the selection of data points to define the IMUs' position in the optical motion capture coordinate system throughout a trial is random and can influence the validity of the hybrid approach when they represent a stride cycle with movement outliers. For these reasons, further development and evaluation of hybrid approaches encountering some of those considerations are recommended prior to their use in field conditions, which was considered outside the scope of this thesis.

Several technological challenges were faced during the data collection of this study and have to be addressed. At the time of the data collection, no synchronisation toolbox was at disposal to automatically synchronise the start and end of each capture. Synchronisation of the datasets was strived for by 'simultaneously' starting and ending the captures of the two systems by verbally counting down, which was within one second for all trials, and by retrospectively correcting for the time difference between the two datasets using previously established methods (Howard, Conway and Harrison, 2014; Bosch et al., 2018). A second technological challenge in this study's data collection was the technical issue with the IMU placed at T18 on the day of data collection. Given that no data could be retrieved from this IMU, the selection of thoracolumbar segments to quantify the horses' back kinematics was forced to be adjusted. As a result, the angular displacements were quantified between T5-T13-L2 and T13-L2-sacrum rather than between T5-T13-T18, T13-T18-L2, and T18-L2-sacrum, as originally planned. However, this study aimed to evaluate the levels of error of the hybrid approach in measuring angular displacements rather than to describe the physiological angular displacements between particular back segments. Therefore, the selection of back segments used in this study to calculate the angular displacements was deemed appropriate for the study's purpose.

4.10 Conclusion

This study presents a preliminary investigation into a hybrid optical-inertial motion capture approach to measure a horse's back movement and posture and evaluates the levels of error of the proposed hybrid approach in measuring angular displacements of the back in horses walking and trotting on a treadmill. The levels of error of the hybrid approach in measuring flexion-extension and zero-centred lateral bending displacements were considered small enough to be of use in a clinical setting, though it might not be accurate enough to detect small differences in a horse's back movement (smaller than 0.6 degrees for flexion-extension and 1.2 degrees for lateral bending displacements). Very strong correlations between the two motion capture systems were found for the flexion-extension displacements and strong-to-very-strong correlations for the zero-centred lateral bending displacements at walk and trot. Furthermore, the levels of error of the hybrid approach were significantly correlated with the horse's back conformation, indicating that the hybrid approach is less reliable in measuring the lateral bending displacements in the caudal thoracic-lumbar region at walk in horses with a longer back, which is potentially related to skin displacement. Overall, the study findings are encouraging for the use of hybrid optical-inertial motion capture in overcoming some of the limitations of the individual motion capture tools in measuring the horse's back movement. However, several considerations were addressed for the use of the proposed hybrid approach. Further development and evaluation of hybrid approaches encountering some of those considerations are recommended prior to their use to measure a horse's back movement and posture in field conditions.

CHAPTER FIVE

5 The biomechanical interaction between saddle, rider, and the horse's back, and how it relates to the horse's back functioning

5.0 Background

Understanding the biomechanical interaction between saddle, rider, and the horse's back can support equine practitioners and clinicians in their evidence-based decision-making when managing back health and functioning in the ridden horse in training and rehabilitation settings. Technological advances enabling measurements of the horse's kinematics and the forces exerted on the horse's back when ridden brought advances in the literature about this interaction with it, as seen in the systematic review in this thesis (Chapter 3). The systematic review identified typical movement and postural adaptations in the horse's back when loaded with a saddle and rider and identified saddle- and rider-related characteristics influencing these adaptations. However, the role of the saddle in the observed movement adaptations is not yet fully understood and warrants more quantitative evidence.

Another area warranting further investigation is the association between the horse's back functioning and the aforementioned movement and postural adaptations in the horse's back when loaded with a saddle and rider. As reviewed in Chapter 2, the horse's back functioning can be evaluated using functional assessments, which is common practice in the clinical field (McGowan and Cottriall, 2016; Haussler *et al.*, 2021a). Advances in the standardisation and methodological evaluation of those assessments (Tabor *et al.*, 2020) enable the integration of those functional assessments in the research field, too. Functional measures of the horse's back considered valid and reliable in current literature and accessible in the equine field include the evaluation of the horse's postural type (Paul, 2016; Tabor *et al.*, 2023), thoracolumbar epaxial muscle tone and reactivity (Merrifield-Jones, Tabor and Williams, 2019), thoracic epaxial musculature dimensions (Greve and Dyson, 2013b), and the thoracolumbosacral dorsoventral flexibility and coordination (Licka and Peham, 1998; Haussler *et al.*, 2021b). Evaluating how these functional measures relate with the horse's movement and postural adaptations when being loaded with a saddle and rider can provide new and clinically relevant insights about the relation between the horse's back functioning and the biomechanical demands of the horse's back when loaded with a saddle and rider.

This Chapter reports two experimental studies, investigating (1) the effect of a correctly fitting saddle without a rider on the horse's back movement at walk and trot and (2) the effect of saddle and rider on the horse's back posture at halt and movement at walk and in rising trot, and how these effects relate to functional measures of the horse's back.

CHAPTER FIVE – PART A

5A The effect of a saddle on the horse's back kinematics at walk and trot in-hand

5.1 Introduction

The saddle plays a crucial role in the horse-saddle-rider interaction, acting as an interface between the dynamic horse and rider complex (Greve and Dyson, 2013a). A saddle fitting correctly to the horse facilitates the horse's locomotor performance and minimises any saddle-related discomfort (Harman, 1999). Considering the close connection between the saddle and the horse's back, secured by the girth, the movement of the saddle is closely associated with that of the horse's back. Examining high-level dressage horses (n=7) ridden in sitting trot, Byström *et al.* (2009) found that the saddle's pitch and yaw rotations resemble those of the horse's mid-thoracic region at trot described by Faber *et al.* (2001a), in curve shape, temporal characteristics, and ROM. The saddle's roll rotation demonstrated more variable movement patterns, influenced by the rider's movement (Byström *et al.*, 2009). Galloux *et al.* (1994) further established that the saddle, without a rider, demonstrates more pronounced roll rotations at walk while more pronounced longitudinal and lateral displacements at trot, again coinciding with the horse's back movements. However, a saddle has a relatively rigid construction and will, therefore, not be able to fully adapt to the variable dynamics of the horse's back (Clayton and Hobbs, 2017). A previous study examining the lateral displacement of correctly fitting saddles relative to the midline of the horse's back in non-lame horses (n=7) when ridden reported lateral displacements up to 2.4 cm during rising trot and 2.0 cm during sitting trot, which was significantly associated with the pelvic movement of the horse and rider (Byström *et al.*, 2018). These findings confirm the close connection between the saddle and the horse's back, regardless of the small range of movement freedom and the interplay between the rider and the saddle.

While the horse and rider influence the saddle's movement, the saddle is expected to alter the horse's back movement to a certain degree as well – albeit minimal in correctly fitting saddles. However, de Cocq, van Weeren and Back (2004) reported no statistical differences in the lumbosacral flexion-extension angular displacements in riding school horses (n=9) at walk and trot without and with a saddle on a treadmill. Studying Franches-Montagnes stallions (n=27), Heim *et al.* (2016) also reported no statistical differences in the laterolateral and dorsoventral displacements in the horses' lumbosacral region when trotting without and with a saddle. Quantitative evidence on the effect of a saddle, without a rider, on the horse's back movement at walk and on the movement of the mid-caudal thoracic region at trot is still warranted and might reveal novel insights about how the saddle influences the horse's back movement. De Cocq, van Weeren and Back (2004) used optical motion capture to quantify the horse's back kinematics and considering that the anatomical landmarks of the mid-caudal thoracic back are occluded to the optical motion cameras by a saddle, only reported the kinematics of the lumbosacral back region. The use of skin-mounted inertial measurement units (IMUs) can overcome the limitation of optical motion capture in measuring movement of occluded body segments and has elsewhere been shown to allow measurements of the horse's mid-caudal thoracic back movement in saddled conditions (Martin *et al.*, 2017b). While Heim *et al.* (2016) used skin-mounted IMUs to quantify the horse's back kinematics without and with a saddle, including an IMU placed at thoracic level T12, they did not report any statistical findings about saddle-induced alterations in the horse's mid-caudal thoracic back region as '*data from this location was inconsistent*'. No further clarification as to why the IMU data at T12 could have been inconsistent was provided in this study. Given that other studies have since successfully used IMUs attached to the dorsal midline of the mid-caudal thoracic region with the saddle on (MacKechnie-Guire and Pfau, 2021a, 2021b), the placement of IMUs in this region and in saddled conditions is considered feasible in the case that the medial margins of the saddle panels are verified to allow enough space for the placement of the IMUs on the midline of the horse's mid-caudal thoracic region. Therefore, the use of skin-mounted IMUs enables measurements of the saddle-induced alterations in the horse's mid-caudal thoracic back movement.

The effect of a saddle on the horse's back includes this of the girth, which secures the saddle on the horse's back and can limit the horse's back movement by reducing thoracic excursions and the protraction and retraction of the thoracic limb (Murray *et al.*, 2013). The girth crosses the sternum and covers the thickest part of the m. *cutaneus trunci* (van Iwaarden, Stubbs and Clayton, 2012), forming a circular continuum with the saddle around the horse's chest via the girth straps. The position of this circular continuum aligns with the spinal levels being exposed to the highest peak pressures when ridden (Murray *et al.*, 2017), which is also the back region that demonstrates decreased roll and yaw ROM when ridden (MacKechnie-Guire and Pfau, 2021a, 2021b). It could be hypothesized that those movement adaptations in the horse's back are associated with the tactile stimulation exerted by the girth and saddle in this particular back region, resulting in a movement constraining effect. Further research reporting the locomotory adaptations induced by the saddle without a rider could provide novel insights into the role of the saddle, including this of the girth, in contrast to that of the rider in the movement adaptations of the horse's back when loaded with a saddle and rider.

This study aimed to quantify the horse's back kinematics, including the mid-caudal thoracic region, using skin-mounted IMUs without and with a correctly fitting saddle at walk and trot in-hand. The study objectives were to quantify the translational, rotational, and differential rotational ROM of the back in horses that were in active ridden work when walking and trotting on a straight line in-hand without and with a correctly fitting saddle. This selection of movement variables enables comparison with previous literature studying the horse's back movement adaptations to being loaded with a saddle and rider reporting translational, rotational, and differential rotational ROM. It was hypothesized that a saddle alters the horse's back kinematics at walk and trot, decreasing ROM in the cranial region underneath the saddle, in particular in the dorsal and transverse planes including roll and yaw movements, while inducing compensatory movement patterns in the more caudal regions.

5.2 Methods

This study was approved by Hartpury University Ethics Committee (ETHICS2020-46). Informed consent from the horse owners was obtained before their horse(s) participated in the study, who could withdraw their participation from the study up until the point of data collection.

5.2.1 Study horses

Eight horses of 10 (±4) years that were in active ridden work, competing at novice level or above, and considered sound by their owners and without any musculoskeletal injury within three months prior to data collection were recruited from the Hartpury loan and livery population. The demographic details of the study horses can be found in Table 5.1.

Table 5.1. The demographical characteristics of the study horses (n=8).

Horse	Age	Breed	Discipline	Sex	Height (m)	Competition level
Horse 1	7	Warmblood	Showjumping	Gelding	1.66	Discovery
Horse 2	14	Irish sport horse	Dressage	Mare	1.61	Elementary
Horse 3	7	Warmblood	Showjumping	Gelding	1.68	Newcomers
Horse 4	10	Holsteiner	Eventing	Gelding	1.78	Affiliated
Horse 5	17	Irish sport horse	Eventing	Mare	1.63	Novice
Horse 6	5	Warmblood	Dressage	Gelding	1.68	Novice
Horse 7	8	Warmblood	Showjumping	Gelding	1.70	Foxhunter
Horse 8	11	Warmblood	Showjumping	Gelding	1.72	Newcomers

5.2.2 Saddles

Horses were examined in their own saddle, girth, and bridle. The details of the saddles are provided in Table 5.2. Two Society of Master Saddlers Qualified Saddle Fitters (SMS QSF) evaluated the static and dynamic saddle fit of each horse following the SMS guidelines (Guire *et al.*, 2017; Society of Master Saddlers, 2021). The saddles were deemed to fit the horses correctly. Furthermore, the SMS QSFs considered that the medial margins of the saddle panels allowed enough space for the placement of the skin-mounted IMUs on the midline of the horse's back region 'underneath' the saddle by means of visual evaluation and manual palpation of the lateral edges of those IMUs. All girths were elastic at both ends, except for one, which was only elastic on one side. No saddle pads were used.

Table 5.2. The details of the saddles (n=8).

Horse	Saddle type	Brand	Size (inch)	Weight (kg)	Flocking/ filling
Horse 1	Jumping	Bates	17	7.85	Wool
Horse 2	Jumping	Silhouette	17½	6.84	Synthetic
Horse 3	Jumping	Equipe	17	7.12	Foam
Horse 4	Dressage	Anatomica	17½	8.55	Wool
Horse 5	Jumping	Albion	17½	8.5	Wool
Horse 6	Dressage	Amerigo	17	7.98	Wool
Horse 7	Jumping	Erreplus	17	8.18	Wool
Horse 8	Jumping	Equipe	17½	7.70	Foam

5.2.3 Kinematic measurements

Eight MTw IMUs (Xsens MTw Awinda, The Netherlands) with dimensions 47x30x11 mm were affixed to the horse, on the bridle headpiece and the skin overlying the horses' anatomical landmarks of the spinous process of the 5th thoracic vertebra (T5), the 13th thoracic vertebra (T13), the 18th thoracic vertebra (T18), the 3rd lumbar vertebra (L3), in between the left and right *tubera sacrale* (TS), and of the left and right *tubera coxae* (LTC and RTC), as illustrated in Figure 5.1. Double-sided tape was used to attach the IMUs onto the horse and the IMUs were placed by the same technician for all horses. The IMUs were connected wirelessly to a laptop running the EquiGait Software (Brickendon, Hertford, Hertfordshire, UK) and captured the horse's movement at a sampling rate of 100 Hz.

Figure 5.1 | The placement of the skin-mounted IMUs on the anatomical landmarks of the spinous processes T5, T13, T18, L3, and TS, and the LTC and RTC.

5.2.4 Study protocol

The data collection took place on a hard surface track (40x4 m) at the Equine Therapy Centre at Hartpury University. The horses walked up and down the track once prior to collecting data in two study conditions, without and with saddle. Data were then collected for a minimum of 10 strides with the horses walking and trotting in-hand in the two study conditions. All horses were led with their head and neck in a straight and natural position, i.e. with their neck close to the horizontal, by an experienced handler who led the horse from the left side. The horses walked and trotted at their own preferred speed.

5.2.5 Data processing

The inertial measurements were processed in the EquiGait software (Brickendon, Hertford, Hertfordshire, UK), according to previously published methods (Warner, Koch and Pfau, 2010). Within the software, each IMU's three-dimensional (3D) translational ROM (craniocaudal, laterolateral, dorsoventral) are computed as the displacements along the XYZ axes and the rotational ROM (roll, pitch, yaw) as the displacements around the XYZ axes in a horse-based right-handed coordinate system, with the X-axis being aligned with the horse's direction of travel, the Y-axis being perpendicularly orientated to the X- and Z-axes, and the Z-axis being aligned with gravity. The software output also includes the differential rotational ROM (differential roll, pitch, and yaw), calculated by subtracting the rotational signals of adjacent sensors from each other. The measurements taken from the EquiGait software for data analysis included both the translational and rotational ROM of the individual back segments (T5, T13, T18, L3, and TS), as well as the differential rotational ROM between the back segments (T5-T13, T13-T18, T18-L3, and L3-TS). Additionally, stride duration was extracted from the software and used as a surrogate measure to control for speed differences between the trials of the two study conditions (without and with a saddle). As explained elsewhere, the relation between stride duration and speed is inverse, with an increase in stride duration slowing down the speed given a consistent stride length (Barrey, 2001, p. 88).

5.2.6 Statistical analysis

The statistical analyses were performed in SPSS (IBM SPSS Statistics v29, New York, USA). The normality of the subtracted difference of the paired measures was tested using a Shapiro-Wilk test, which demonstrated normal distribution. The evaluation of the differences in the study horses' back kinematics and stride duration when walking and trotting with a saddle (and without a rider) compared to without a saddle was addressed using paired t-tests. An alpha level of .05 was adhered to for all statistical tests.

5.3 Results

The horse's stride duration did not significantly differ when walking without or with a saddle (mean ± standard deviation = 1.16±0.09 s and 1.14±0.06 s respectively, $t(7)=1.51$, $p=0.175$) nor when trotting without or with a saddle (mean ± standard deviation = 0.71±0.05 s and 0.70±0.04 s respectively, $t(7)=1.75$, $p=0.123$).

5.3.1 The translational ROM of the horse's back

At walk, a saddle was seen to significantly increase the craniocaudal ROM at T13, T18, and L3 (respectively +12.5%, $p<0.001$, d=1.923, +5.8%, $p=0.049$, d=0.840, and +3.3%, $p=0.019$, d=1.073). At trot, the saddle was seen to significantly decrease the laterolateral and dorsoventral ROM at T5 (respectively -16.7%, $p=0.027$, d=-0.989, and -5.1%, $p=0.008$, d=-1.283), whilst it significantly increased the craniocaudal ROM at T13 (+24.6%, $p=0.012$, d=1.182) and laterolateral ROM at T18 and L3 (respectively +14.6%, $p=0.019$, d=1.073, and 5.4%, $p=0.005$, d=1.403).

5.3.2 The rotational ROM of the horse's back

At walk, a saddle was seen to significantly decrease the roll ROM at T5 (-17.8%, $p=0.002$, d=-1.740), whilst it significantly increased the yaw ROM at T13 (+21.1%, $p=0.029$, d=0.967) and the pitch ROM at the sacrum (+4.3%, $p=0.038$, d=0.904). At trot, the saddle was seen to significantly decrease the roll ROM at T5 (-21.0%, $p=0.004$, d=-1.467), whilst it significantly increased the pitch ROM at T13 (+19.1%, $p=0.035$, d=0.923).

5.3.3 The differential rotational ROM of the horse's back

At walk, a saddle was seen to significantly decrease the differential yaw ROM at T5-T13 (-21.7%, $p=0.035$, d=-0.926), whilst it significantly increased the differential roll ROM at T13-T18 (+36.1%, $p=0.009$, d=1.452), and the differential yaw ROM at T18-L3 (+21.6%, $p=0.031$, d=0.952). At trot, the saddle was seen to significantly increase the differential yaw ROM at T13-T18 and T18-L3 (respectively +76.1%, $p=0.003$, d=1.538, and +28.6%, $p=0.025$, d=1.000), and the differential pitch ROM at T18-L3 (+15.6%, $p=0.029$, d=0.967).

The mean (standard deviation) and confidence intervals (95%) of the translational, rotational, and differential rotational ROM when walking and trotting without and with a saddle can be found in Tables 5.3, 5.4, and 5.5, respectively.

Table 5.3. The translational ROM of the horse's back when walking and trotting without and with a saddle.

Back region	Translational ROM	Without saddle			With saddle			Effect	
		M (SD)	95% CI		M (SD)	95% CI		*p*-value	*t*-value (7)
			LL	UL		LL	UL		
Walk									
T5	Craniocaudal (mm)	50.9 (5.9)	46.0	55.8	50.9 (6.0)	45.9	55.9	1.000	.00
	Laterolateral (mm)	45.8 (8.0)	39.0	52.5	44.6 (8.5)	37.5	51.8	.344	-1.01
	Dorsoventral (mm)	39.5 (7.5)	33.2	45.8	39.3 (6.5)	33.9	44.6	.849	-.20
T13	Craniocaudal (mm)	**44.8 (4.4)**	**41.1**	**48.4**	**50.4 (3.7)**	**47.3**	**53.5**	**<.001**	**5.44**
	Laterolateral (mm)	52.4 (11.5)	42.8	62.0	51.1 (11.1)	41.8	60.4	.397	-.90
	Dorsoventral (mm)	26.3 (5.7)	21.5	31.0	26.8 (6.2)	21.6	31.9	.763	.31
T18	Craniocaudal (mm)	**43.3 (6.1)**	**38.1**	**48.4**	**45.8 (4.7)**	**41.8**	**49.7**	**.049**	**2.38**
	Laterolateral (mm)	59.9 (7.7)	53.4	66.3	58.6 (8.3)	51.7	65.6	.257	-1.23
	Dorsoventral (mm)	47.3 (4.8)	43.2	51.3	47.8 (3.6)	44.7	50.8	.794	.27
L3	Craniocaudal (mm)	**39.9 (6.6)**	**34.3**	**45.4**	**41.1 (6.8)**	**35.4**	**46.8**	**.019**	**3.04**
	Laterolateral (mm)	59.3 (5.5)	54.6	63.9	56.9 (7.1)	50.9	62.8	.081	-2.04
	Dorsoventral (mm)	61.1 (5.9)	56.2	66.1	61.8 (3.9)	58.5	65.0	.755	.32
TS	Craniocaudal (mm)	44.0 (8.4)	37.0	51.0	45.4 (7.8)	38.8	51.9	.147	1.63
	Laterolateral (mm)	47.8 (6.3)	42.5	53.0	47.4 (7.4)	41.2	53.6	.723	-.37
	Dorsoventral (mm)	78.9 (7.9)	72.8	85.0	78.8 (4.1)	75.3	82.2	.925	-.06
Trot									
T5	Craniocaudal (mm)	30.0 (8.5)	22.9	37.1	31.8 (11.4)	22.2	41.3	.427	.84
	Laterolateral (mm)	**52.6 (14.0)**	**40.9**	**64.4**	**43.9 (14.7)**	**31.6**	**56.2**	**.027**	**-2.80**
	Dorsoventral (mm)	**78.5 (14.1)**	**66.7**	**90.3**	**74.5 (13.2)**	**63.5**	**85.5**	**.008**	**-3.63**
T13	Craniocaudal (mm)	**26.8 (8.6)**	**19.6**	**33.9**	**33.4 (10.0)**	**25.0**	**41.7**	**.012**	**3.34**
	Laterolateral (mm)	29.1 (10.8)	20.1	38.2	34.3 (13.8)	22.7	45.8	.072	2.12
	Dorsoventral (mm)	91.8 (15.4)	78.8	104.7	90.6 (13.5)	79.4	101.9	.239	-1.29
T18	Craniocaudal (mm)	20.8 (6.8)	15.1	26.4	21.5 (6.3)	16.3	26.8	.642	.49
	Laterolateral (mm)	**26.1 (8.0)**	**19.4**	**32.8**	**29.9 (7.6)**	**23.5**	**36.2**	**.019**	**3.04**
	Dorsoventral (mm)	91.6 (15.8)	78.4	104.9	90.1 (14.5)	78.1	102.2	.177	-1.50
L3	Craniocaudal (mm)	17.6 (5.7)	12.9	22.4	17.0 (5.8)	12.2	21.8	.140	-1.67
	Laterolateral (mm)	**28.0 (8.6)**	**20.8**	**35.2**	**29.5 (8.3)**	**22.6**	**36.4**	**.005**	**3.97**
	Dorsoventral (mm)	86.5 (16.3)	72.9	100.1	85.0 (15.7)	71.9	98.1	.244	-1.27
TS	Craniocaudal (mm)	19.5 (4.9)	15.4	23.6	18.6 (4.7)	14.7	22.5	.195	-1.43
	Laterolateral (mm)	25.0 (7.5)	18.7	31.3	24.5 (4.2)	21.0	28.0	.766	-.31
	Dorsoventral (mm)	79.1 (15.5)	66.2	92.1	77.6 (16.7)	63.3	91.2	.316	-1.08

The bold values indicate that the values were significantly influenced by study condition. ROM = ranges of motion, M = mean, SD = standard deviation, CI = confidence intervals, LL and UL = lower and upper limit, TS = between tubera sacrale.

Table 5.4. The rotational ROM of the horse's back when walking and trotting without and with a saddle.

Back region	Rotational ROM	Without saddle			With saddle			Effect	
		M (SD)	95% CI LL	95% CI UL	M (SD)	95% CI LL	95% CI UL	*p*-value	*t*-value (7)
Walk									
T5	Roll (°)	**21.3 (5.1)**	**17.1**	**25.6**	**17.5 (3.3)**	**14.7**	**20.3**	**.002**	**-4.92**
	Pitch (°)	7.1 (1.8)	5.6	8.7	6.8 (1.1)	5.9	7.8	.559	-.61
	Yaw (°)	11.5 (2.0)	9.9	13.2	11.6 (2.2)	9.7	13.5	.839	.21
T13	Roll (°)	12.7 (2.6)	10.5	14.9	11.9 (3.2)	9.3	14.6	.221	-1.34
	Pitch (°)	8.0 (.6)	7.3	8.6	7.7 (.7)	7.1	8.3	.404	-.89
	Yaw (°)	**7.1 (1.5)**	**5.9**	**8.3**	**8.6 (1.6)**	**7.3**	**9.9**	**.029**	**2.74**
T18	Roll (°)	11.5 (1.4)	10.4	12.7	11.7 (2.2)	9.9	13.5	.764	.31
	Pitch (°)	8.4 (.5)	8.0	8.8	8.7 (.6)	8.2	9.2	.137	.17
	Yaw (°)	4.4 (.9)	3.7	5.1	4.8 (.5)	4.8	4.4	.303	.11
L3	Roll (°)	14.4 (3.2)	11.8	17.1	14.6 (2.8)	12.2	17.0	.763	.31
	Pitch (°)	8.3 (1.1)	7.4	9.3	8.6 (1.1)	7.7	9.5	.057	2.28
	Yaw (°)	6.1 (1.7)	4.7	7.5	6.1 (1.4)	4.9	7.3	.988	.02
TS	Roll (°)	16.7 (2.3)	14.7	18.7	15.9 (1.9)	14.3	17.4	.147	-1.63
	Pitch (°)	**6.9 (1.0)**	**6.1**	**7.7**	**7.2 (1.0)**	**6.4**	**8.1**	**.038**	**2.56**
	Yaw (°)	7.5 (2.2)	5.7	9.3	7.5 (1.7)	6.1	8.9	.907	-.12
Trot									
T5	Roll (°)	**21.4 (6.6)**	**15.9**	**26.9**	**16.9 (4.3)**	**13.3**	**20.4**	**.004**	**-4.15**
	Pitch (°)	7.7 (1.8)	6.1	9.2	7.1 (1.8)	5.6	8.6	.341	-1.02
	Yaw (°)	9.5 (1.9)	7.8	11.1	9.6 (2.9)	7.2	12.0	.900	.13
T13	Roll (°)	10.5 (1.0)	9.6	11.3	10.6 (3.1)	8.0	13.2	.932	.09
	Pitch (°)	**4.7 (2.8)**	**2.4**	**7.0**	**5.6 (2.8)**	**3.3**	**8.0**	**.035**	**2.61**
	Yaw (°)	5.6 (1.5)	4.3	6.9	6.3 (1.3)	5.2	7.4	.145	1.64
T18	Roll (°)	12.2 (3.1)	9.6	14.8	13.3 (2.9)	10.9	15.7	.094	1.94
	Pitch (°)	3.6 (1.4)	2.5	4.8	4.1 (1.5)	2.8	5.4	.451	.80
	Yaw (°)	4.1 (.9)	3.4	4.9	4.5 (.5)	4.1	5.0	.307	1.10
L3	Roll (°)	12.1 (1.7)	10.7	13.5	12.5 (1.6)	11.2	13.8	.366	.97
	Pitch (°)	5.6 (2.2)	3.8	7.4	5.4 (1.8)	3.9	7.0	.393	-.91
	Yaw (°)	3.9 (.6)	3.4	4.3	4.1 (1.1)	3.2	5.0	.531	.66
TS	Roll (°)	19.0 (2.9)	16.5	21.4	19.6 (3.0)	17.1	22.1	.319	1.07
	Pitch (°)	4.8 (1.7)	3.3	6.3	4.6 (1.6)	3.3	5.9	.492	-.73
	Yaw (°)	4.7 (1.4)	3.5	5.9	5.1 (1.7)	3.7	6.5	.139	1.67

The bold values indicate that the values were significantly influenced by study condition. ROM = ranges of motion, M = mean, SD = standard deviation, CI = confidence intervals, LL and UL = lower and upper limit, TS = between tubera sacrale.

Table 5.5. The differential rotational ROM of the horse's back when walking and trotting without and with a saddle.

Back region	Diff. rotational ROM	Without saddle			With saddle			Effect	
		M (SD)	95% CI LL	95% CI UL	M (SD)	95% CI LL	95% CI UL	*p*-value	*t*-value (7)
Walk									
T5-T13	Diff. Roll (°)	12.5 (3.3)	9.7	15.3	11.1 (2.2)	9.3	13.0	.382	-.93
	Diff. Pitch (°)	6.7 (1.1)	5.8	7.6	6.2 (1.3)	5.1	7.3	.365	-.97
	Diff. Yaw (°)	**6.9 (1.9)**	**5.2**	**8.5**	**5.4 (2.2)**	**3.5**	**7.2**	**.035**	**-2.62**
T13-T18	**Diff. Roll (°)**	**7.2 (1.6)**	**5.7**	**8.6**	**9.8 (2.4)**	**7.6**	**12.0**	**.009**	**3.84**
	Diff. Pitch (°)	3.8 (.9)	3.0	4.7	3.7 (.8)	3.0	4.4	.619	-.52
	Diff. Yaw (°)	7.5 (1.1)	6.5	8.5	9.1 (2.9)	6.4	11.8	.151	1.65
T18-L3	Diff. Roll (°)	10.7 (8.3)	3.8	17.6	10.2 (5.0)	6.0	14.4	.736	-.35
	Diff. Pitch (°)	4.6 (4.9)	0.5	8.7	4.4 (3.4)	1.6	7.2	.691	-.42
	Diff. Yaw (°)	**3.7 (.4)**	**3.4**	**4.0**	**4.5 (.9)**	**3.7**	**5.2**	**.031**	**2.69**
L3-TS	Diff. Roll (°)	10.9 (1.8)	9.4	12.4	10.2 (1.5)	9.0	11.4	.306	-1.11
	Diff. Pitch (°)	6.1 (1.4)	5.0	7.2	5.9 (1.2)	4.9	6.9	.563	-.61
	Diff. Yaw (°)	3.4 (1.2)	2.5	4.4	3.4 (1.1)	2.5	4.3	.536	-.65
Trot									
T5-T13	Diff. Roll (°)	21.0 (7.9)	14.4	27.6	18.3 (4.5)	14.5	22.0	.243	-1.28
	Diff. Pitch (°)	8.7 (2.4)	6.6	10.7	9.4 (2.5)	7.3	11.5	.578	.58
	Diff. Yaw (°)	7.4 (2.7)	5.2	9.7	6.7 (3.8)	3.5	9.8	.436	-.83
T13-T18	Diff. Roll (°)	10.7 (4.4)	7.1	14.4	10.9 (3.8)	7.7	14.1	.855	.19
	Diff. Pitch (°)	5.1 (1.8)	3.6	6.7	6.1 (1.6)	4.8	7.4	.117	1.79
	Diff. Yaw (°)	**4.6 (1.6)**	**3.3**	**5.9**	**8.1 (2.6)**	**5.9**	**10.2**	**.003**	**4.35**
T18-L3	Diff. Roll (°)	11.7 (4.3)	8.0	15.3	12.5 (4.3)	8.9	16.2	.209	1.38
	Diff. Pitch (°)	**4.5 (1.4)**	**3.3**	**5.7**	**5.2 (1.7)**	**3.8**	**6.6**	**.029**	**2.74**
	Diff. Yaw (°)	**2.8 (.7)**	**2.3**	**3.4**	**3.6 (.8)**	**2.9**	**4.2**	**.025**	**2.83**
L3-TS	Diff. Roll (°)	19.1 (3.0)	16.6	21.6	19.4 (3.2)	16.7	22.0	.838	.21
	Diff. Pitch (°)	5.6 (1.3)	4.5	6.7	5.8 (1.2)	4.8	6.8	.497	.72
	Diff. Yaw (°)	3.3 (1.0)	2.4	4.1	3.2 (1.0)	2.4	4.0	.805	-.26

The bold values indicate that the values were significantly influenced by study condition. Diff = differential, ROM = ranges of motion, M = mean, SD = standard deviation, CI = confidence intervals, LL and UL = lower and upper limit, TS = between tubera sacrale.

5.4 Discussion

This study investigated how a correctly fitting saddle alters a horse's back kinematics when walking and trotting in-hand, with the purpose of gaining a better understanding of the role a correctly fitting saddle plays in the horse's back movement adaptations when loaded with a saddle and rider. The findings observed in this study provide evidence to confirm the study hypothesis. Walking and trotting with a saddle, compared to without, was observed to significantly decrease ROM in the cranial back region underneath the saddle (T5-T13), in the dorsal and transverse planes in particular, and increase ROM in the more caudal thoracic and lumbosacral segments (T13, T18, L3, and TS).

The decreased ROM in the horse's cranial back region underneath the saddle support that the saddle and girth can have a movement constraining effect in this region, as suggested elsewhere (Murray *et al.*, 2013). This region coincides with the region where the saddle and girth form a circular continuum around the horse's thorax and where the back is exposed to the highest pressures when loaded with a saddle only (de Cocq *et al.*, 2009b). As established in the systematic review, back regions exposed to higher pressures tend to demonstrate reduced ROM while adjacent back regions then seem to compensate by demonstrating increased ROM, which is supported by the findings from this study. The increase in ROM in the adjacent regions can be considered a result of the biotensegrity of the spine where changes in the dynamics of a particular spinal region induce changes in adjacent spinal regions through means of mechanical transmission via the anatomical connections (Levin, 2002). The most prominent movement adaptations in the more caudal back region are the differential roll and yaw movements, coinciding with the movement direction that demonstrated the most prominent decreased ROM in the more cranial back region. Those saddle-related movement adaptations should be taken into consideration in saddle fitting practice and when evaluating the horse's back movement when loaded with a saddle.

The findings from this study are in line with those reported by de Cocq, van Weeren and Back (2004) who reported no significant differences in the lumbosacral flexion-extension ROM, surrogate of the L3-TS differential pitch ROM reported in this study, in riding school horses walking and trotting without and with a saddle on a treadmill. Comparing our study results with those reported by Heim *et al.* (2016), who examined Franches-Montagnes stallions (n=27), this study as well reported no statistically significant differences in the laterolateral and dorsoventral ROM in the lumbosacral region when the horses trotted without or with a saddle, except for a small significant increase (+5.4%) in the laterolateral ROM at level L3. In comparison to the studies by de Cocq, van Weeren and Back (2004) and Heim *et al.* (2016), this study reported the 3D translational, rotational, and differential rotational ROM of the entire back region and examined actively competing sport horses. Therefore, this study brings original knowledge of the effect of a saddle on the horse's back kinematics.

The movement adaptations observed in this study in horses walking and trotting with a saddle are comparative with those previously reported in the ridden horse, in that the ROM decrease and increase in similar back regions in both conditions. Fruehwirth *et al.* (2004) reported a decrease in ROM at the withers in horses ridden at walk and in sitting trot and MacKechnie-Guire and Pfau (2021a, 2021b) reported a decrease in the roll and yaw ROM in the cranial thoracic region underneath the saddle in elite sport horses ridden in sitting trot, compared to when unridden. Furthermore, de Cocq *et al.* (2009a) found increased flexion-extension and lateral bending ROM in the lumbosacral region in riding school horses (n=12) when ridden in sitting or rising trot while MacKechnie-Guire and Pfau (2021a, 2021b) found increased differential roll, pitch, and yaw ROM in the thoracolumbar region in elite sport horses when ridden in sitting trot, compared to when trotting unridden. Given that the findings from this study demonstrate that a saddle, without a rider, induces comparative movement adaptations to when being ridden, these findings support that the saddle plays a significant role in the movement adaptations of the horse's back when ridden as well.

While this study provides evidence emphasizing the role of the saddle in the back dynamics of the horse, the results presented in this study should not be overinterpreted in the context of the horse-saddle interaction in ridden conditions. Firstly, the horse-saddle interaction alters when the rider is involved in the interaction. Previous research has, for example, demonstrated that the rider stabilises the saddle's movement and pressure distribution on the horse's back, with the centre of pressure showing less ROM (Fruehwirth *et al.*, 2004). Secondly, some of the movement alterations identified in this study were small (<20% difference), questioning the clinical relevance of these alterations assigned to the saddle, although all significant results demonstrated a large effect (d≥0.80) according to the interpretation of the effect sizes (Cook, Cook and Therrien, 2018). Additionally, it is appreciated that it has not yet been evaluated how a saddle influences the soft tissue artefact in the horse's back and that this might have confounded the reported movement outcomes. These considerations should be acknowledged when interpreting the saddle-induced alterations in the horse's back movement, certainly where the reported differences are relatively small.

This study selected a wide range of variables, enabling comparison with previous literature reporting translation, rotational, or differential rotational ROM of the horse's back when loaded with a saddle and rider. However, caution must be taken when interpreting the biological significance of some of those outcomes. Notably high roll ROM are observed in the results from this study, particularly at wither level, when compared to those reported by Faber *et al.* (2000, 2001a), who measured the rotational ROM of the thoracolumbosacral spine in horses walking and trotting, respectively, on a treadmill with bone-fixated markers. As discussed in Chapter 2 (section 2.4.3), the soft tissue artefact induces a certain level of error in the skin-mounted measurements. Goff *et al.* (2010) previously demonstrated that skin-mounted IMUs tend to overestimate the rotational ROM of the horse's pelvis, particularly the roll ROM at the trot. The results from this study seem to support this finding reported by Goff *et al.* (2010) for the thoracolumbar spine, too. Therefore, the absolute values of the roll ROM measured by skin-mounted IMUs appear to be affected by skin movement inducing rotational movement errors, and should thus be interpreted with caution.

Another limitation of this experimental study is the relatively small sample size (n=8), limiting the extrapolation of these study findings to the general equine population. This study also only reported kinematic measures, which implies that no further associations can be made between the observed movement adaptations and the horse's back functioning. Finally, this study only considered straight-line walk and trot locomotion, and the saddle might alter the biomechanics of the horse's back movement differently while on a circle or in canter. Further research is required to confirm the findings from this study in a bigger study sample and within different research settings in order to advance our understanding of the horse-saddle interaction.

5.5 Conclusion

This study quantified the effect of a correctly fitting saddle without a rider on the horse's back kinematics at walk and trot in-hand. It was found that a correctly fitting saddle without a rider alters the horse's back kinematics, with decreased ROM being observed in the more cranial thoracic back segments (T5-T13), particularly in the horse's dorsal and transverse planes, and increased ROM in the more caudal back segments (T13 up to the sacrum) at walk and trot. The movement adaptations seen to being loaded with a saddle only were comparative to those previously reported in the literature for being ridden in that it decreases and increases ROM in similar back regions, providing evidence for the role of the saddle in the movement adaptations of the horse's back when ridden. It is suggested that the horse-saddle interaction should always be taken into consideration when observing ridden performance, as should the reported saddle-related movement adaptations in saddle fitting practice. More research is warranted to establish extrapolation of those study findings to the general equine population as well as to the horse-saddle interaction in ridden conditions.

CHAPTER FIVE – PART B

5B The effect of a saddle and rider on the horse's back posture and movement in relation to functional measures of the horse's back

5.6 Introduction

Optimal back function is recognised to play a vital role in the locomotor apparatus and, consequently, the welfare and performance of the ridden horse (van Weeren, McGowan and Haussler, 2010). However, subclinical back dysfunctions are common in ridden horses, and can evolve into clinical back problems if not identified and managed appropriately (Haussler, 1999b). Back problems form a significant concern in the equine industry, both for welfare and performance related motivations, and more research has been called upon to advance our understanding of the pathomechanisms and optimal management of back problems in the ridden horse (van Weeren, McGowan and Haussler, 2010; Greve and Dyson, 2013a). It is thus of interest to establish research methods that reliably evaluate a horse's back functioning and are relevant for the ridden horse, facilitating the identification of back dysfunctions in this population. Additionally, understanding how the functioning of a horse's back relates to the postural and movement adaptations in the horse's back when being ridden can support the differentiation between more optimal and suboptimal, or 'functional' and 'dysfunctional', adaptations, and reveal indicators of a suboptimal ratio between the horse's physical capacities and the biomechanical demands of the ridden horse's back. Such understanding could eventually support clinical decision-making when managing back problems in the horse, targeting an optimal ratio between the horse's physical capacities and biomechanical demands to prevent the development of back dysfunctions (see Chapter 1). With more functional assessments being standardised and integrated into the equine literature (Tabor *et al.*, 2018, 2020), the evaluation of back functioning has become more accessible for quantitative research, enabling investigations into the relation between the functioning of a horse's back and the postural and movement adaptations in the horse's back when being ridden.

As was seen in the systematic review study (Chapter 3), research studying the effect of a saddle and rider on the horse's back biomechanics continues to grow and includes measurements of the horse's back posture and movement. An area of specific relevance for the ridden horse's back functioning is the study of the effect saddle and rider have on the horse's back posture. An optimal posture refers to the posture where the alignment between vertebral segments causes minimal stresses and strains upon the surrounding musculoskeletal structures at halt or during locomotion (Clayton, 2016a), protecting the supporting spinal structures against pathological mechanisms (Paulekas and Haussler, 2009). Studying the effect of a saddle and rider's load on a horse's back posture in riding school horses (n=9), de Cocq, Van Weeren, and Back (2004) found that the horse's lumbosacral region is more extended in all gaits when loaded with a rider-equivalent mass (75 kg) compared to when unloaded. When ridden in sitting and rising trot as well, the horse's lumbosacral region demonstrates more extension in comparison to when trotting unridden, though only less flexion when ridden in sitting trot in comparison to when trotting unridden, as was examined in riding school horses (n=12) ridden by one rider (84 kg) of intermediate level (de Cocq *et al.*, 2009a). If occurring repetitively, a more extended back posture may lead to the development of back problems, considering its association with higher stresses acting upon the surrounding musculoskeletal structures (Jeffcott, 1980; Zimmerman, Dyson and Murray, 2012). Consequently, core strengthening exercises are encouraged in the interest of maintaining or restoring spinal health in ridden horses, helping the horse to resist postural disturbances and maintain a neutral posture, referred to as 'postural control' (Stubbs and Clayton, 2008; Clayton, 2016a). However, how measures of the horse's back functioning relate to the effect saddle and rider have on the horse's back posture has not yet been studied. Furthermore, de Cocq, Van Weeren, and Back (2004) and de Cocq *et al.* (2009a) only reported dynamic measurements. Quantitative evidence for the effect of a saddle and rider's load on the horse's back posture at halt is thus warranted in order to extrapolate their study findings to static conditions.

Studying the literature about the effect of saddle and rider on the horse's back movement, a trend has been observed for roll and yaw ROM to decrease in the more cranial back region underneath the saddle and increase between the more caudal segments in different directions, although more quantitative evidence is required to confirm those movement adaptations when ridden at walk and in rising trot. The decreased ROM in the more cranial segments are likely related to a movement constraining effect of the saddle in this region (see Chapter 5A). As suggested by de Cocq *et al.* (2009a), the increased ROM between the more caudal back segments can indicate both a mobilising and a destabilising effect on the horse's back. As expanded on in Chapter 2, a destabilising mechanism refers to the incapacity to control the ongoing spinal movements within the physiological movement zones, which can have clinical consequences due to the excessive stresses on the surrounding musculoskeletal structures when crossing the physiological barriers (Haussler, 2016). Conversely, a mobilising mechanism refers to an increase in spinal ROM within the physiological movement zones and is associated with more optimal spinal functioning (Haussler, 2016). It is thus not yet clear if the increased ROM in the more caudal back regions when the horse is ridden indicate a destabilising or mobilising mechanism. Evaluating how those movement adaptations relate to the horse's back functioning can reveal new insights into the ridden horse's back dynamics.

This study aimed to investigate the effect of a saddle and rider on the horse's back posture at halt and on the horse's back movement when ridden at walk and in rising trot in a sample population of veterinary-approved sound competition horses without recent injury. While such study population can be described as 'functional' horses that are deemed fit for ridden purpose, subclinical back dysfunctions are common in performance horses (Haussler, 1999b; Wennerstrand, 2008), and a certain variation in functional measures of the horse's back was anticipated in this population. A second aim of this study was thus to investigate how the effects of a saddle and rider on the horse's back posture and movement relate to functional measures of the horse's back. Identifying associations between the postural and movement adaptations in a horse's back to being ridden and functional measures of the horse's back in this study population will reveal new insights into the role of subtle back dysfunctions in the back dynamics of the 'functional' ridden horse, which is considered most relevant to daily-life equine practice. The study objectives were to evaluate (1) the horse's back posture with a saddle and rider compared to without at halt, (2) the differential rotational ROM between back segments when ridden at walk and in rising trot in comparison to when walking and trotting unridden in-hand, and (3) the association between the postural and movement adaptations when being loaded with a saddle and rider and the functional measures of the back in veterinary-approved sound competition horses without recent injury. It was hypothesized that (1) the horse's back posture would be more extended with a saddle and rider's load compared to without, (2) the postural adaptations would be associated with functional measures of the horse's back, (3) the differential rotational ROM in the lumbosacral region would increase when ridden at walk and in rising trot, and (4) the movement adaptations would be associated with functional measures of the horse's back.

5.7 Methods

This study was approved by the Ethical Committee at Hartpury University (ETHICS2021-41). Informed, written consent from the horse owners was obtained before participating in the study, who could withdraw their participation from the study up until the point of data collection.

5.7.1 Study horses

Twenty sport horses of different disciplines were recruited from the Hartpury loan and livery population and external yards close to Hartpury University (within 30 minutes of driving) on a voluntary basis. All horses were seven years or older (10±3 years) and actively competing at novice up to elite level. Horses with days lost from training due to injury within the last three months before data collection were not included. All horses were considered sound and fit for ridden work by their owners as well as by a Veterinary Surgeon, who assessed the horses within seven days prior to the data collection – this assessment included a visual observation of the horses walking and trotting in a straight line on a hard level surface. The horses' demographic details can be found in Table 5.6.

Table 5.6. The demographic characteristics of the study horses (n=20).

Horse	Age	Breed	Discipline	Sex	Weight (kg)	Competition level
Horse 1	7	Warmblood	Eventing	Gelding	525-550	Intermediate **
Horse 2	11	Irish sport horse	Eventing	Mare	525-550	Novice/ 1m10
Horse 3	7	Warmblood	Dressage	Gelding	525-550	Prix St Georges
Horse 4	15	Wurttemberger	Showjumping	Gelding	600	1m20
Horse 5	12	Spanish purebred	Dressage	Mare	532	Medium
Horse 6	9	Swiss sport horse	Eventing	Mare	520	CIC**
Horse 7	7	Warmblood	Showjumping	Gelding	580	Disc/Newcomer
Horse 8	16	Warmblood	Dressage	Gelding	625-650	Intermediate 1-2
Horse 9	11	Irish sport horse	Dressage	Mare	500-525	Medium
Horse 10	9	Warmblood	Dressage	Gelding	650	Medium
Horse 11	13	Selle français	Eventing	Gelding	679	Novice/ 1m30
Horse 12	8	Hanoverian	Dressage	Gelding	650-675	Medium
Horse 13	14	Irish sport horse	Showjumping	Gelding	710	1m15
Horse 14	10	Selle français	Eventing	Gelding	600	BE100
Horse 15	10	Warmblood	Showjumping	Gelding	600-625	Newcomers
Horse 16	12	Warmblood	Dressage	Mare	550-575	Medium
Horse 17	9	Irish sport horse	Showjumping	Mare	550	Discovery
Horse 18	8	Hanoverian	Dressage	Mare	550-575	Medium
Horse 19	7	Warmblood	Dressage	Gelding	650-675	Preliminary
Horse 20	13	Irish sport horse	Showjumping	Mare	600	1m30

5.7.2 Study riders

The riders training and competing the study horses were recruited to ride their own horse in the study, thus representing established horse-rider partnerships. The riders (19 female and 1 male) had 16±5 years of riding experience, were 170±6 cm in height, and had a body mass of 63±7 kg, which was within 7-14% of their horse's body mass.

5.7.3 Saddles

Horses were ridden with their own saddle, girth, and bridle. Two SMS QSFs evaluated the static and dynamic saddle fit of each horse following the SMS guidelines (Guire *et al.*, 2017; Society of Master Saddlers, 2021), which were deemed correctly fitting for all included study horses. A high withered saddle cloth with 5 cm cut out its midline at the cranial and caudal ends to enable placement of the IMUs at the level of the withers and L1 was used for all horses. An additional woollen saddle half pad, of which 5 cm at the cranial and caudal ends of the midline were cut out as well, was used for some of the horse-saddle-rider combinations, which was determined by the SMS QSFs in function of saddle fit. The details of the saddles are shown in Table 5.7. A mix of girth models was used, including non-elastic (n=10) girths or girths that were elastic on both ends (n=10).

Table 5.7. The details of the horses' their own saddles.

Horse	Saddle type	Brand	Size (inch)	Model
Horse 1	Jumping	Devoucoux	17½	Chiberta
Horse 2	Dressage	Monarch	17½	Monarch
Horse 3	Dressage	Albion	17	K2 dressage adjusta
Horse 4	Jumping	Hulsebos	17	Twin-flap long straps
Horse 5	Dressage	Zaldi	17	Spanish dressage
Horse 6	Jumping	Stubben	17½	Mono-flap
Horse 7	Jumping	Bates	17	Twin-flap
Horse 8	Dressage	Albion	17½	Fabrento
Horse 9	Dressage	Fairfax	17½	Original/ standard
Horse 10	Dressage	Albion	17½	Slk ii adjusta
Horse 11	Jumping	Jeffries	17½	Elite jump
Horse 12	Dressage	Custom	17½	Dressage
Horse 13	Jumping	Prestige	17	Mono-flap
Horse 14	Jumping	D+R line	17	Twin-flap
Horse 15	Jumping	Childerick	17½	Twin-flap
Horse 16	Dressage	Bates	17	Twin-flap
Horse 17	Jumping	Devoucoux	17½	Twin-flap
Horse 18	Dressage	Custom	17½	Mono-flap
Horse 19	Dressage	Louisa Cuomo	16	Twin-flap
Horse 20	Jumping	Equide	17½	Twin-flap

5.7.4 Functional back assessment

A functional back assessment was performed for each horse, adhering to the functional assessments described in Section 2.2 (pp. 43-49). Firstly, the horses' postural type was evaluated by an experienced Association of Chartered Physiotherapists in Animal Therapy (ACPAT) registered Veterinary Physiotherapist by side-view inspection of the horse's posture, with the horse standing square on a level surface in a natural position with the head and neck straight, the neck close to the horizontal and the head slightly in front of the vertical. The postural types were defined as sway-backed, S-backed, or straight-backed, based on their spinal alignment and muscle balance in the different body regions, as described by Paul (2016) and Tabor *et al.* (2023). The template of the postural type assessment can be found in Appendix A.I. The Physiotherapist was trained to use this template prior to evaluating the horses' postural types.

Secondly, the same Physiotherapist evaluated the horses' epaxial muscular tone and tenderness in the thoracolumbar region following the scoring system described by Merrifield-Jones, Tabor and Williams (2019). The Physiotherapist followed a standardised protocol for the muscle tone and reactivity palpation, applying moderate pressure along the thoracolumbar region, on the left and the right side, with the dominant hand's index finger while the horse stands on a level surface with weight on the four limbs.

The Physiotherapist then assessed the horse's back flexibility and coordination by means of the rounding reflex. The Physiotherapist performed the rounding reflex by applying firm digital pressure bilaterally along the intermuscular groove between the biceps femoris and semitendinosus muscles at a level lateral to the base of the tail while the horse halted on a level surface and had weight on the four limbs, as described by Haussler (2018). The rounding reflex was repeated three times for each horse, and the Physiotherapist assigned an overall score for the horse's back flexibility and coordination throughout the reflexes based on the scale published by Haussler *et al.* (2020).

The horse's thoracic epaxial musculature dimensions were then measured using a FlexiCurve ruler (Jakarflex 100 cm Crystal Edge, Jakar International, Elstree, Herts., UK) by one of the SMS QSF. The same SMS QSF performed the measurements for all horses. The FlexiCurve ruler was placed around the horse's dorsum at thoracic levels T8 and T13, and the outline of the underside of the ruler was drawn onto an A2 graph paper. All horses were standing square on a level surface in a neutral HNP whilst the FlexiCurve ruler measurements were taken. The measures of the horses' epaxial musculature dimensions were the asymmetries between the left and right extremes of the Flexicurve ruler's outline three and fifteen cm down the vertical at each level, and the ratio between the width three and fifteen cm ventral to the dorsal midline at each level, as described elsewhere (Greve and Dyson, 2013b).

5.7.5 Postural and kinematic measurements

Eight MTw IMUs (Xsens MTw Awinda, The Netherlands) with dimensions 4.7x3.0x1.1 cm were affixed to the horse, on the skin overlying the horses' anatomical landmarks of the spinous process of the 6th thoracic vertebra (T6), the 1st lumbar vertebra (L1), the 3rd lumbar vertebra (L3), the 5th lumbar vertebra (L5), and the 3rd sacral vertebra (S3), the sternum (or on the middle of the girth for the ridden study condition), and the LTC and RTC. Double-sided tape was used to attach the IMUs onto the horse, and the IMUs were placed by the same technician for all horses. Hemispherical reflective markers (33 mm in diameter) were attached on top of the skin-mounted IMUs, as illustrated in Figure 5.2, which were used for the postural measurements of the horse's back. Furthermore, eight spherical reflective markers (19 mm in diameter) were attached to the skin overlying the horses' nasal peak, poll (bridle), left and right dorsal margin spina scapula, and fetlocks of the four limbs to enable retrospective observation of the horse's position at halt for the postural measurements.

Figure 5.2 | The placement of the skin-mounted IMUs, with hemispherical markers on top, placed on the anatomical landmarks at T6, L1, L3, L5, and S3 and the LTC and RTC.

The IMUs were connected wirelessly to a laptop running the EquiGait Software (Brickendon, Hertford, Hertfordshire, UK) and captured the horse's movement at a sampling rate of 100 Hz. Optical motion cameras (Miqus M3, Qualisys AB, Göteborg, Sweden) were set-up surrounding a defined capture volume (2x6 m) in a riding arena (see Figure 5.3). The cameras (n=8-10) were daisy-chained and connected to a laptop running Qualisys Track Manager (version 2020.1, Qualisys AB, Gothenburg, Sweden), capturing at a sampling rate of 100 Hz. The optical motion capture system was calibrated at the beginning of each data collection day and when recommended by the Qualisys Track Manager. The average residual of the cameras was 1.11 (±0.33) mm, and the average standard deviation of the wand length was 1.60 (±0.20) mm among the performed calibrations.

Figure 5.3 | The volume (2x6 m) to be captured by the optical motion cameras (encircled in yellow). The coordinate system was located on the right side of the volume.

5.7.6 Study protocol

The data collection was spread over four days, which all took place in the same covered arena with a soft, sand-waxed surface (Andrews Bowen, Lancashire, UK) at Hartpury University. Prior to data collection, the horses followed a ridden, self-described warm-up protocol, including walk, trot, and canter on both the left and right rein for 15 minutes. Once warmed-up, the horses walked and trotted on the left and right rein in a straight line, which was defined using spherical cones 2 m apart along the study track (36x2 m) and located 2.5 m from the arena wall, in two study conditions: unridden and ridden. In the unridden study condition, the horses walked and trotted in-hand in their own bridle, led by an experienced handler from the horse's left side, in an unrestricted posture. In the ridden study condition, the horses were ridden at walk and in rising trot by their own rider "*on the bit*" whilst engaging the hindquarters and demonstrating regular paces, according to the Fédération International Equestre (FEI) dressage guidelines (FEI, 2022). A horse is said to be on the bit when '*the neck is more or less raised… accepting the bridle with a light and consistent soft submissive contact. The head should remain in a steady position, as a rule slightly in front of the vertical, with a supple poll as the highest point of the neck*' (FEI, 2022, p. 1). The horse's posture during a trial was visually observed and evaluated in agreement between an international British Horse Society registered Coach (BHSI Coach) and the ACPAT Veterinary Physiotherapist, both present throughout the data collection days. If the horse's posture was inconsistent during a trial, the trial was excluded and repeated. For each study condition, two trials were captured on the left and right rein in each gait and a minimum of 10 strides was collected per trial. The speed consistency between the unridden and ridden trials was controlled for using timing gates (laser activated timers). If the trial speed was not within 0.3 m/s of the speed of the other trials within each gait, the trial was repeated, as was seen elsewhere (de Cocq *et al.*, 2009a).

The horses halted straight within the optical motion cameras' capture volume on the study track in the two study conditions (without and with saddle and rider). The position of the horses on the study track and in the optical motion cameras' capture volume during the standing trials is shown in Figure 5.3. In the study condition without saddle and rider, the horses halted straight and square in-hand with their neck straight and close to the horizontal. For the trials without saddle and rider, the horses were handled in their own bridle by an experienced handler. In the study condition with saddle and rider, the horses halted according to the FEI dressage guidelines (FEI, 2022), stating the horse should '*stand attentive, engaged, motionless, straight and square with the weight evenly distributed over all four legs. The neck should be raised with the poll as the highest point and the noseline slightly in front of the vertical. While remaining "on the bit" and maintaining a light and soft contact with the athlete's hand... The halt must be shown for at least 3 seconds*' (FEI, 2022, p. 2). The horse's posture at halt was visually observed and evaluated in agreement between the BHSI Coach and the ACPAT Veterinary Physiotherapist. The sequence of the study conditions was randomised for both the dynamic and static captures.

5.7.7 Data processing – standing trials

The horses' back posture without and with saddle and rider was computed using the optical motion capture data from the standing trials. The reflective markers were labelled in the Qualisys Track Manager and one frame during which the horse halted adequately straight, square and still was selected from each capture in Qualisys, which was selected based on the notes of each trial throughout the data collection and the position of the reflective markers placed on the limbs, head, and bridle. The 3D coordinates of the back markers during that frame were exported in TSV files and imported into MATLAB (version R2020b, The MathWorks, Natick, Mass., USA). Custom-made MATLAB scripts were used to calculate postural measurements of the horse's back (see Appendix C). The calculated postural measurements include the thoracolumbosacral (TLS) angle, being the angle between segments T6, L1, and S3 in the horse's median plane, and the angle between the individual back segments, being the angles between segments T6-L1, L1-L5, and L3-S3 angles in the horse's median plane. The angles were calculated as per Equations 5B.1-5B.4 and are illustrated in Figure 5.4.

$$\textbf{TLS angle} = 180^\circ - \theta_1 - \theta_2 \qquad \textbf{(5B.1)}$$

$$With\ \theta_1 = rad2deg\left(atan\left(\frac{vertical\ distance\ T6-L1}{craniocaudal\ distance\ T6-L1}\right)\right)$$

$$With\ \theta_2 = rad2deg\left(atan\left(\frac{vertical\ distance\ L1-S3}{craniocaudal\ distance\ L1-S3}\right)\right)$$

With craniocaudal distances = the resultant transverse vectors between the markers

$$\boldsymbol{\theta_{T6-L1}} = \mathrm{rad2deg}(\mathrm{atan}(\frac{\mathrm{vertical\ distance\ T6-L1}}{\mathrm{craniocaudal\ distance\ T6-L1}})) \qquad \textbf{(5B.2)}$$

$$\boldsymbol{\theta_{L1-L5}} = \mathrm{rad2deg}(\mathrm{atan}(\frac{\mathrm{vertical\ distance\ L1-L5}}{\mathrm{craniocaudal\ distance\ L1-L5}})) \qquad \textbf{(5B.3)}$$

$$\boldsymbol{\theta_{L3-S3}} = \mathrm{rad2deg}(\mathrm{atan}(\frac{\mathrm{vertical\ distance\ L3-S3}}{\mathrm{craniocaudal\ distance\ L3-S3}})) \qquad \textbf{(5B.4)}$$

With craniocaudal distances = the resultant transverse vectors between the markers

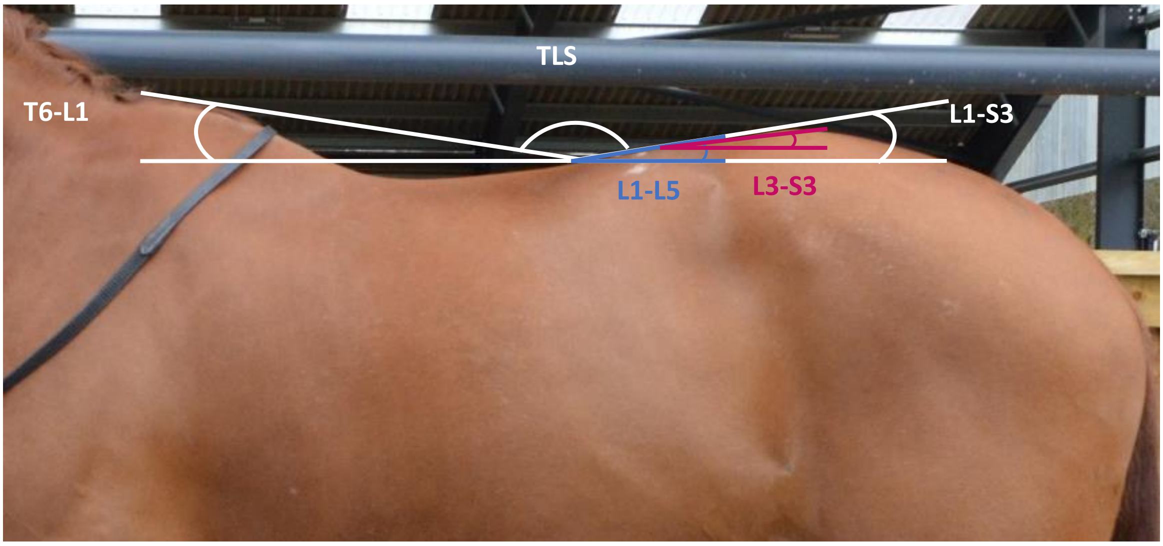


Figure 5.4 | An illustration of the postural measurements. TLS = thoracolumbosacral angle and T6-L1, L1-L5, and L3-S3 = the angles between the according back segments in the horse's median plane.

5.7.8 Data processing – dynamic trials

The inertial measurements were processed in the EquiGait software (Brickendon, Hertford, Hertfordshire, UK), using previously published methods (Pfau, Witte and Wilson, 2005). The differential roll, pitch, and yaw ROM between back segments T6-L1, L1-L3, L3-L5, and L5-S3 were extracted from the software for each study condition (unridden and ridden), gait (walk and trot), and rein (left and right). The data processing of the differential rotational ROM within the software included subtraction of the rotational motion signals of adjacent sensors, with the rotational motion signals being computed following a Cardan-Euler sequence orientated in a Cartesian coordinate system with roll as the first rotation, pitch as the second, and yaw as the third.

5.7.9 Statistical analysis

The statistical analyses were performed in SPSS (IBM SPSS Statistics v29, New York, USA). The normality of the difference of the paired postural and movement measures (measure in the unridden study condition – measure in the ridden study condition) and the scale functional measures (the thoracic epaxial musculature asymmetries and dimensions ratios) were tested using a Shapiro-Wilk test. Normal distribution was found for the tested measures. The effect of the study condition (without and with saddle and rider) on the horses' back posture at halt and movement at walk and trot was tested using linear mixed modelling. Separate models were carried out for each postural and movement measure at each gait, with the related outcome measures defined as dependent variables, study condition (unridden and ridden) as a fixed factor, and horse (subject) as a random factor. For the kinematic measures, rein (left or right rein) was added as a fixed factor and speed as a covariant, which was also added in the model as a fixed factor. A post hoc analysis was carried out to evaluate the differences in the postural and movement measurements between study conditions, reporting Bonferroni-adjusted *p*-values.

Where there was a statistical effect of study condition in the above described models, additional models were carried out including the interaction between the functional measures of the horse's back and the study condition. Only the functional measures showing a significant correlation ($p \leq 0.05$) with the differentiated postural and movement measures (measure in the unridden study condition – measure in the ridden study condition, with the trials on the different reins pooled) were entered into the model, which was tested for each measure using a Pearson Correlation test for the scale variables and a Spearman Correlation test for the ordinal variables. Where correlated, the functional measures thoracolumbar epaxial muscle tone and reactivity and the rounding reflex scores were defined as fixed factors, and the thoracic epaxial musculature asymmetries and dimensions ratio as covariates, which were then added to the model as fixed factors in interaction with study condition. Postural type, being a nominal parameter, was entered into each model, though excluded again if statistically insignificant in the model. A similar approach was applied to control for the rider-horse body mass ratio influencing the effect saddle and rider have on the horse's back posture and movement. Where the rider-horse body mass ratio showed a significant correlation ($p \leq 0.05$) with the differentiated postural and movement measures, tested with a Pearson correlation given normal distribution, it was defined as a covariate and entered into the model as a fixed factor in interaction with study condition. This selection and construction of the models was chosen to facilitate a reliable and valid interpretation of the association between the effect saddle and rider have on the horse's back posture and movement and the horse's back functioning. An alpha level of .05 was adhered to for all statistical tests.

5.8 Results

5.8.1 The horse's back posture without and with saddle and rider at halt

5.8.1.1 The horse and measurement inclusion

The postural measurements from one horse were excluded due to the horse-rider combination not standing according to the FEI guidelines, resulting in a sample size of 19 horses for the data analysis of the postural measurements. Out of these 19 horses, six horses were identified as a sway-backed postural type, six horses as straight-backed, and seven horses as S-backed. The group median (percentiles 25, 75) of the 19 horses' epaxial muscle tone and reactivity in the thoracolumbar region was 10 (6, 13) on a scale of 20, indicating a normal-to-increased muscle tone and reactivity in the study sample.

5.8.1.2 The postural measurements

The linear mixed models for the postural measurements of the horse's back at halt are given in Table 5.8, and the horses' TLS alignment with and without saddle and rider at halt is illustrated as a scatterplot in Figure 5.5. The horse's TLS angle significantly decreased with a saddle and rider compared to without (without saddle and rider = 166.7±2.2°, with saddle and rider = 162.2±2.9°, p<0.001), indicating a more extended back posture with a saddle and rider at halt. A significant interaction was found between the effect saddle and rider have on the TLS angle and the horse's postural type (p=0.022) and epaxial muscle tone and reactivity in the thoracic region (p=0.034). The interaction plot demonstrates that the extending effect saddle and rider have on the horse's TLS alignment is more prominent in horses with an S-backed postural type compared to horses with a sway- or straight-backed postural type (see Figure 5.6). The correlation analysis between the horse's epaxial muscle tone and reactivity in the thoracic region and the effect saddle and rider have on the horse's TLS angle demonstrated a positive correlation; the higher the muscle tone and reactivity, the more prominent the extending effect saddle and rider have on the TLS alignment (R=0.558, p=0.013).

The angles between segments T6-L1, L1-L5, and L3-S3 significantly increased with a saddle and rider compared to without (without saddle and rider = 7.7±1.6°, 10.9±1.7°, and 4.0±2.1°, with saddle and rider = 10.0±2.0°, 12.7±2.4°, and 6.5±2.4°, all p<0.001), also indicating a more extended alignment between the segments with a saddle and rider at halt. However, no significant interactions (all p>0.05) were found between the functional measures nor the rider-horse body mass ratio and the effect of study condition on the alignment between segments T6-L1, L1-L5, and L3-S3.

Table 5.8. The linear mixed models for the horse's back posture at halt.

Parameter	Factors	df	F	*p*-value	Post-hoc study condition		
					p-value	95% CI	
						LL	LL
<u>TLS angle</u>	Study Condition * Postural type * Tx muscle tone/ reactivity	1 4 12	208.12 4.65 3.31	<.001 .022 .034	<.001	-5.55	-4.07
<u>T6-L1 angle</u>	Study Condition	1	64.34	<.001	<.001	1.72	2.94
<u>L1-L5 angle</u>	Study Condition	1	16.26	<.001	<.001	.89	2.83
<u>L3-S3 angle</u>	Study Condition	1	103.35	<.001	<.001	2.01	3.05

*CI = confidence interval, LL = lower limit, UL = upper limit, Tx = thoracic. * = interaction between study condition and specified factor. The underlined parameters indicate that the values were significantly influenced by study subject.*

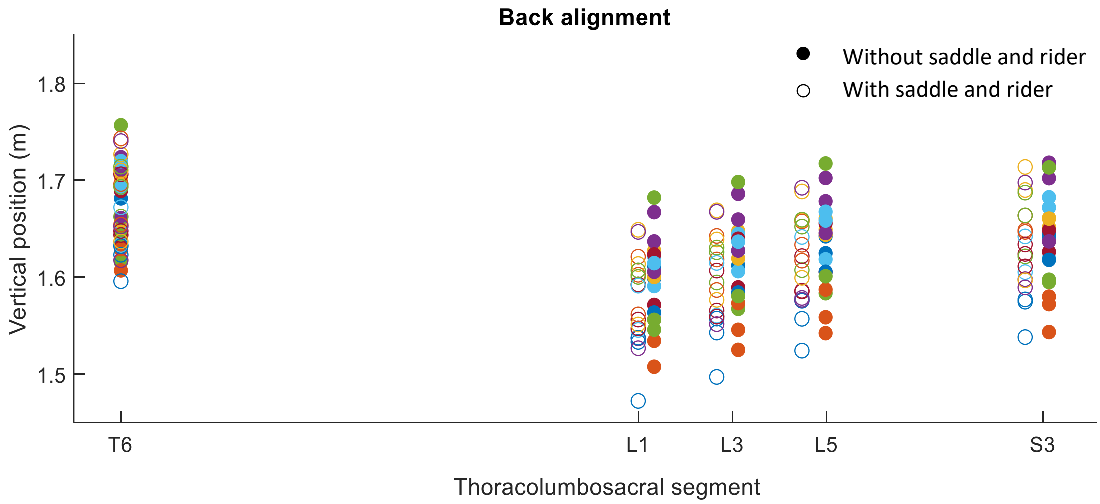


Figure 5.5 | A scatterplot of the back alignment of the individual horses without and with saddle and rider at halt, with the craniocaudal position of the segments aligned relative to the withers.

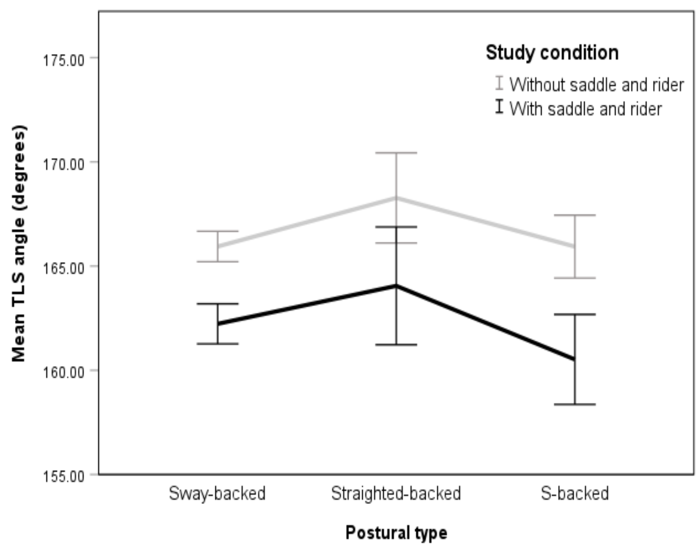


Figure 5.6 | The interaction plot between the study condition effect on the thoracolumbosacral (TLS) alignment and the horse's postural type. The error bars represent a confidence interval of 95%.

5.8.2 The ROM of the horse's back when walking unridden and ridden

5.8.2.1 Horse and measurement inclusion

The kinematic measures from three horses were excluded due to the horse-rider combinations not riding in an appropriate working posture. One horse showed a consistently elevated head and neck posture, another horse walked with the head notably behind the vertical, and another horse demonstrated an inconsistent head and neck posture during the walk trials, resulting in a sample size of 17 horses for the data analysis of the kinematic measures at walk. Out of these 17 horses, five horses were identified as a sway-backed postural type, four horses as straight-backed, and eight horses as S-backed. The group median (percentiles 25, 75) of the 17 horses' epaxial muscle tone and reactivity in the thoracolumbar region was 10 (6, 13) on a scale of 20, indicating a normal-to-increased muscle tone and reactivity in the study sample.

A mean (±standard deviation) of 21±4 strides was collected for each horse on each rein and in the two study conditions (unridden and ridden) at walk. The speed did not statistically differ when walking on the left or right rein (left rein = 1.49±0.14 m/s, right rein = 1.50±0.15 m/s, p=0.355) nor when walking unridden or ridden (unridden = 1.49±0.14 m/s, ridden = 1.51±0.15 m/s, p=0.207).

5.8.2.2 The differential rotational ROM

The linear mixed models for the differential rotational ROM of the horse's back at walk are given in Table 5.9, and the mean differential rotational ROM in the unridden and ridden study conditions are illustrated in Figure 5.7.

At walk and at T6-L1, being ridden significantly decreased the differential roll ROM (unridden = 27.9±6.2°, ridden = 24.2±4.3°, p=0.010), while it did not significantly influence the differential pitch ROM (p=0.805) and significantly increased the differential yaw ROM (unridden = 13.5±2.8°, ridden = 16.0±3.8°, p<0.001). Speed significantly influenced the differential pitch ROM as well (p=0.041). A significant interaction was found between the effect of study condition on the differential roll ROM and the horse's postural type (p=0.024) and between the effect of study condition on the differential yaw ROM and the epaxial musculature asymmetry at T8, 15 cm ventral to the midline (p<0.001). The interaction plot between the effect of study condition on the differential roll ROM and postural type demonstrates that being ridden decreased the differential roll ROM more in the horses with an S-backed postural type in comparison to the other postural types (see Figure 5.8). The correlation analysis between the horse's epaxial musculature asymmetry at T8, 15 cm ventral to the midline, and the effect saddle and rider have on the differential yaw ROM demonstrated a negative correlation, indicating that the bigger the asymmetry, the less the differential yaw ROM will increase when ridden (R=0.819, p<0.001).

At L1-L3, being ridden significantly increased the differential roll, pitch, and yaw ROM (unridden = 8.1±3.0°, 2.3±0.6°, and 2.8±0.6°, ridden = 12.3±3.0°, 3.8±1.3°, and 5.9±2.0°, respectively, all p<0.001). A significant interaction was found between the effect of study condition on the differential roll ROM and the horse's postural type (p=0.024) and epaxial musculature asymmetry at T13, 3 cm ventral to the midline (p<0.001) and between the effect of study condition on the differential pitch and yaw ROM and the rider-horse body mass ratio (both p<0.001). The interaction plot between the effect of study condition on the differential roll ROM and postural type demonstrates that being ridden increases the differential roll ROM less in the horses with an S-backed postural type in comparison to the other postural types (see Figure 5.9). The correlation analysis between the epaxial musculature asymmetry at T13, 3 cm ventral to the midline, and the effect of study condition on the differential roll ROM demonstrated a positive correlation; the bigger the asymmetry, the less the differential roll ROM will increase when ridden (R=0.585, p=0.017). The correlation between the rider-horse body mass ratio and the effect of study condition on the differential pitch and yaw ROM was positive as well; the higher the ratio, the more the differential pitch and yaw ROM will increase when ridden (R=0.598 and 0.667, p=0.005 and 0.012, respectively).

At L3-L5, being ridden significantly increased the differential roll, pitch, and yaw ROM (unridden = 7.4±2.5°, 3.3±1.1°, and 2.9±0.6°, ridden = 8.3±2.0°, 4.3±1.5°, and 3.9±1.1°, respectively, all p<0.001). A significant interaction was found between the effect of study condition on the differential roll ROM and the horse's postural type (p=0.005) and the epaxial musculature dimensions ratio at T13 (p<0.001) and between the effect of study condition on the differential pitch ROM and the rider-horse body mass ratio (both p<0.001). The interaction plot between the effect of study condition on the differential roll ROM and postural type demonstrates that being ridden increases the differential roll ROM less in the horses with an S-backed postural type in comparison to the other postural types (see Figure 5.10). The correlation analysis between the epaxial musculature dimensions ratio at T13 and the effect saddle and rider have on the differential roll ROM demonstrated a positive correlation; the higher the ratio, the more the differential roll ROM will increase when ridden (R=0.698, p=0.003). The correlation analysis between the rider-horse body mass ratio and the effect saddle and rider have on the differential pitch ROM demonstrated a positive correlation as well; the higher the ratio, the more the differential pitch ROM will increase when ridden (R=0.609, p=0.012).

At L5-S3, being ridden significantly increased the differential roll ROM (unridden = 8.3±2.5°, ridden = 12.1±3.8°, p<0.001) but not the differential pitch and yaw ROM (p>0.05). Speed significantly influenced the differential yaw ROM (p=0.037). No significant interactions were found between the functional measures nor with the rider-horse body mass ratio and the effect of study condition on the differential roll ROM.

Table 5.9. The linear mixed models for the horse's back movement at walk.

Level	ROM	Factors	df	F	*p*-value	Post-hoc study condition		
						p-value	95% CI	
							LL	LL
T6-L1	**Diff. Roll**	**Study Condition**	1	7.21	.010	**.010**	**-4.34**	**-.62**
		Rein	1	.12	.734			
		Speed	1	.69	.412			
		* Postural type	4	3.54	.024			
	Diff. Pitch	Study Condition	1	.05	.828	.828	-.75	.93
		Rein	1	.00	.960			
		Speed	1	4.45	.041			
	Diff. Yaw	**Study Condition**	1	138.81	<.001	**<.001**	**1.98**	**3.29**
		Rein	1	.22	.641			
		Speed	1	1.28	.262			
		*T8_15 asymmetry	2	39.59	<.001			
L1-L3	**Diff. Roll**	**Study Condition**	1	134.16	<.001	**<.001**	**3.87**	**5.11**
		Rein	1	.00	.999			
		Speed	1	.16	.691			
		* Postural type	4	3.65	.024			
		* T13_3 asymmetry	2	16.09	<.001			
	Diff. Pitch	**Study Condition**	1	18.11	<.001	**<.001**	**1.22**	**1.78**
		Rein	1	.13	.719			
		Speed	1	.12	.730			
		* Rider/ horse body mass	2	17.70	<.001			
	Diff. Yaw	**Study Condition**	1	7.87	.007	**<.001**	**2.53**	**3.46**
		Rein	1	.00	.974			
		Speed	1	3.87	.056			
		* Rider/ horse body mass	2	14.72	<.001			
L3-L5	**Diff. Roll**	**Study Condition**	1	43.42	<.001	**<.001**	**.38**	**1.14**
		Rein	1	.59	.445			
		Speed	1	1.81	.185			
		* Postural type	4	5.43	.005			
		* T13_3/15 width ratio	2	29.18	<.001			
	Diff. Pitch	**Study Condition**	1	13.62	<.001	**<.001**	**.61**	**1.22**
		Rein	1	.01	.934			
		Speed	1	.02	.891			
		* Rider/ horse body mass	2	10.53	<.001			
	Diff. Yaw	**Study Condition**	1	65.89	<.001	**<.001**	**.78**	**1.30**
		Rein	1	.46	.502			
		Speed	1	1.02	.318			
L5-S3	**Diff. Roll**	**Study Condition**	1	125.86	<.001	**<.001**	**3.11**	**4.46**
		Rein	1	.30	.586			
		Speed	1	.92	.923			
	Diff. Pitch	Study Condition	1	.15	.701	.701	-.37	.54
		Rein	1	.01	.933			
		Speed	1	3.82	.056			
	Diff. Yaw	Study Condition	1	2.08	.156	.156	-.07	.42
		Rein	1	.02	.885			
		Speed	1	4.55	.037			

*CI = confidence interval, LL = lower limit, UL = upper limit, ROM = ranges of motion. Diff. = differential. Tx = thoracic. * = interaction between study condition and specified factor. The underlined parameters indicate that the values were significantly influenced by study subject, and the bold values indicate that the parameter was significantly influenced by study condition.*

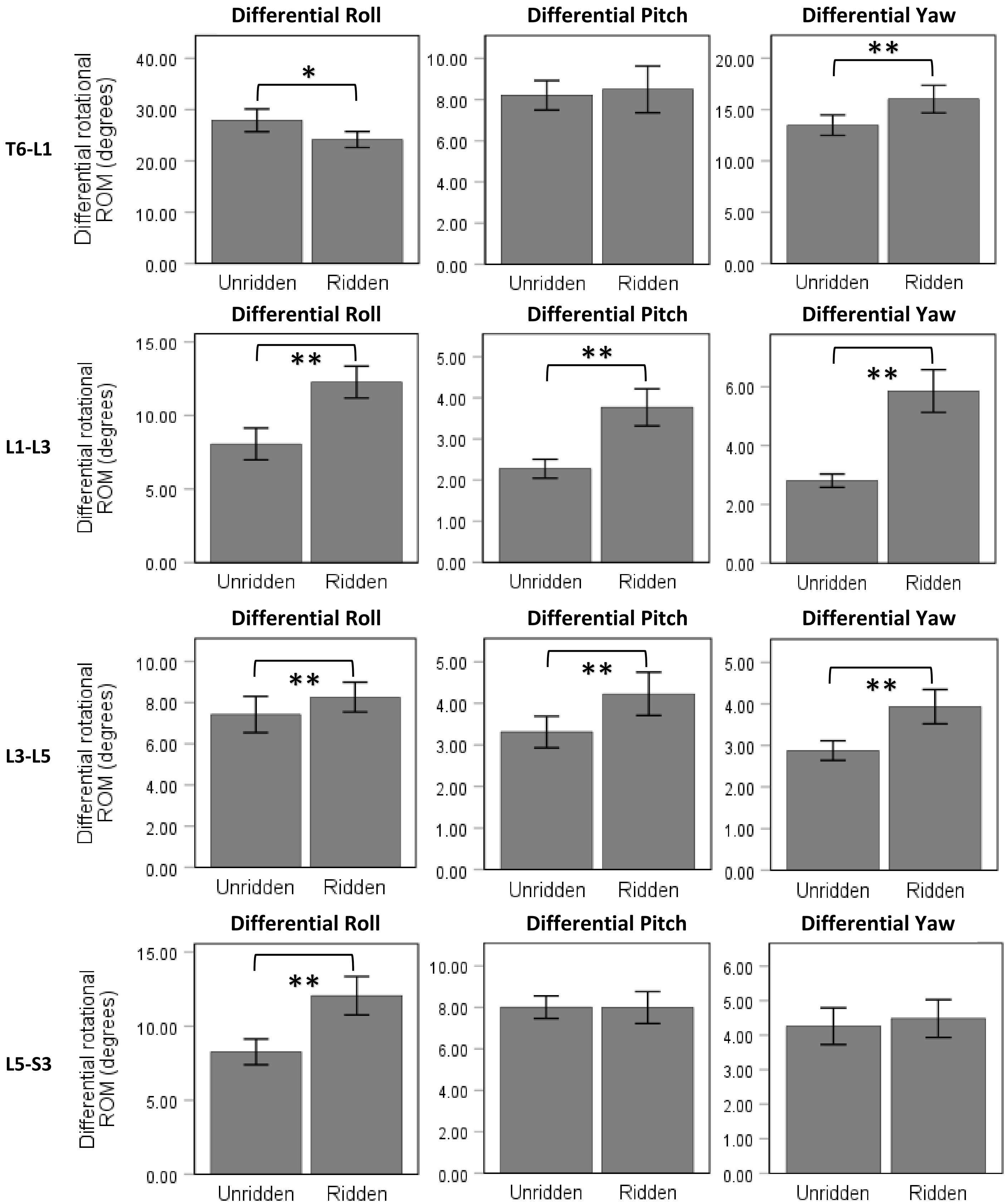


Figure 5.7 | The differential rotational ROM at walk in the unridden and ridden study conditions, with reins pooled. Error bars represent a 95% confidence interval. * and ** = the difference between ridden conditions is significant ($p<.05$ and $p<.001$, respectively).

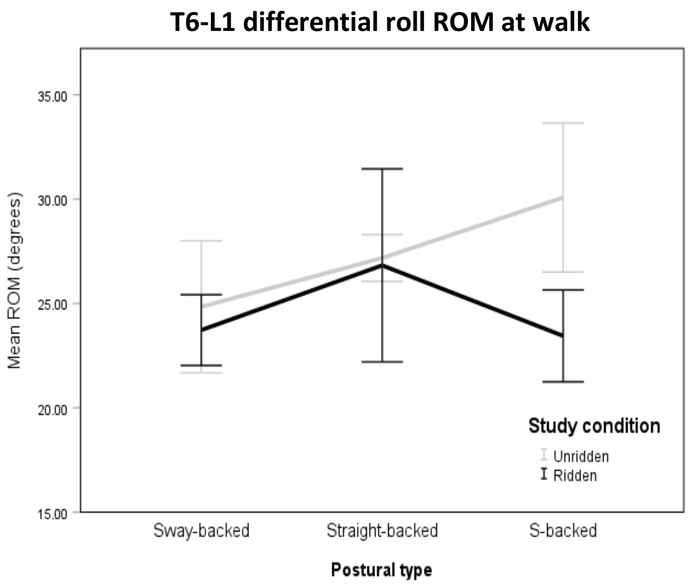


Figure 5.8 | The interaction plot between the effect of study condition on the differential roll ROM at T6-L1 at walk and the horse's postural type. The error bars represent a confidence interval of 95%.

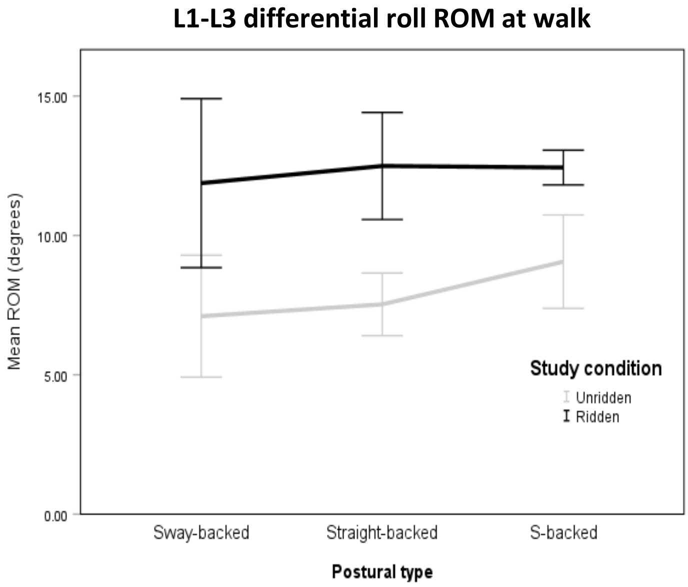


Figure 5.9| The interaction plot between the effect of study condition on the differential roll ROM at L1-L3 at walk and the horse's postural type. The error bars represent a confidence interval of 95%.

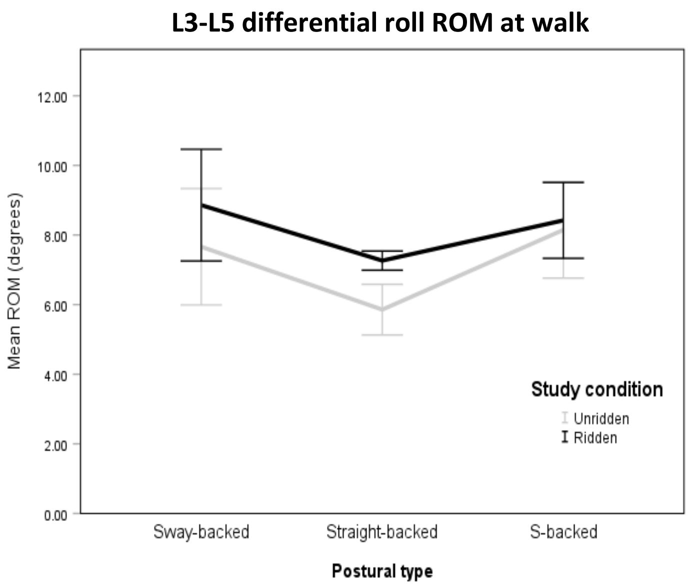


Figure 5.10 | The interaction plot between the effect of study condition on the differential roll ROM at L3-L5 at walk and the horse's postural type. The error bars represent a confidence interval of 95%.

5.8.3 The ROM of the horse's back when trotting unridden and ridden

5.8.3.1 The horse and measurement inclusion

The kinematic measures from two horses were excluded due to the horse-rider combinations not riding in an appropriate working posture. Again, one horse showed a consistently elevated head and neck posture, another horse walked with the head notably behind the vertical. As a result, a sample size of 18 horses was retained for the data analysis of the kinematic measures at trot. Out of these 18 horses, five horses were identified as a sway-backed postural type, five horses as straight-backed, and eight horses as S-backed. The group median (percentiles 25, 75) of the 18 horses' epaxial muscle tone and reactivity in the thoracolumbar region was 10 (6, 13) on a scale of 20, indicating a normal-to-increased muscle tone and reactivity in the sample size.

A mean (±standard deviation) of 28±4 strides in trot was collected for each horse on each rein and in the two study conditions (unridden and ridden). The speed did not statistically differ when trotting on the left or right rein (left rein = 3.39±0.37 m/s, right rein = 3.42±0.37 m/s, p=0.150) nor when trotting unridden or ridden (unridden = 3.39±0.39 m/s, ridden = 3.41±0.36 m/s, p=0.617).

5.8.3.2 The differential rotational ROM

The linear mixed models for the differential rotational ROM of the horse's back at trot are given in Table 5.10, and the mean differential rotational ROM in the unridden and ridden study conditions are illustrated in Figure 5.11.

At T6-L1, being ridden at trot significantly decreased the differential roll, while it significantly increased the differential pitch and yaw ROM (unridden = 30.5±12.7°, 9.0±2.6°, and 11.1±1.9°, ridden = 26.0±4.6°, 10.9±4.6°, and 12.0±4.1°, p<0.001, p<0.001, and p=0.048, respectively). A significant interaction was found between the effect of study condition on the differential roll and yaw ROM and the horse's thoracolumbar epaxial muscle tone and reactivity (p<0.001 and p=0.003, respectively) and between the effect of study condition on the differential pitch ROM and the horse's postural type (p=0.029). The correlation analysis between the thoracolumbar epaxial muscle tone and reactivity and the effect saddle and rider have on the differential roll and yaw ROM demonstrated a positive correlation; the higher the muscle tone and reactivity, the more the differential roll ROM will decrease (R=0.515, p=0.034) and the differential yaw ROM will increase (R=0.742, p<0.001) when ridden. The interaction plot between the effect of study condition on the differential pitch ROM and postural type demonstrates that the increase in the differential pitch ROM when ridden is minimal in the horses with a sway-backed postural type and bigger in horses with a straight-backed postural type in comparison to horses with an S-backed postural type (see Figure 5.12).

At L1-L3, being ridden at trot did not significantly influence the differential roll ROM (p=0.099), though it significantly increased the differential pitch and yaw ROM (unridden = 3.3±1.3° and 3.0±1.1°, ridden = 4.4±1.6° and 3.5±1.3°, respectively, both p<0.001). A significant interaction was found between the effect of study condition on the differential pitch ROM and the horse's rounding reflex score (p<0.001) and between the effect of study condition on the differential yaw ROM and the horse's postural type (p=0.034) and lumbar epaxial muscle tone and reactivity (p=0.043). The correlation analysis between the rounding reflex score and the study condition effect on the differential pitch ROM demonstrated a positive correlation; the better the horse's rounding reflex score, the more the differential pitch ROM will increase when ridden (R=0.647, p=0.005). The correlation between the lumbar epaxial muscle tone and reactivity and the effect of study condition on the differential yaw ROM demonstrated a positive correlation as well; the higher the muscle tone and reactivity, the more the differential yaw ROM will increase when ridden (R=0.484, p=0.042). The interaction plot between the effect of study condition on the differential yaw ROM and postural type demonstrates that being ridden increases the differential yaw ROM more in the horses with a sway-backed postural type in comparison to the other postural types (see Figure 5.13).

At L3-L5, being ridden at trot did not significantly influence the differential roll and yaw ROM (p=0.244 and 0.137, respectively), though it significantly increased the differential pitch ROM (unridden = 3.5±0.9°, ridden = 4.3±1.3°, p<0.001). Speed significantly influenced the differential roll and yaw ROM (p=0.022 and 0.002, respectively). No significant interactions were found with the effect of study condition on the differential pitch ROM and the functional measures or rider-horse body weight ratio.

At L5-S3, being ridden at trot significantly increased the differential roll and yaw ROM, while it significantly decreased the differential pitch ROM (unridden = 13.9±4.3°, 3.2±1.0°, and 6.0±1.1°, ridden = 14.9±5.1°, 3.4±1.0°, and 5.3±1.1°, p<0.001, p<0.001, and p=0.023, respectively). A significant interaction was found between the effect of study condition on the differential roll ROM and the horse's postural type (p=0.047) and rounding reflex score (p=0.018) and between the effect of study condition on the differential yaw ROM and the horse's thoracic epaxial muscle tone and reactivity (p=0.038). The interaction plot between the effect of study condition on the differential roll ROM and postural type demonstrates that being ridden increases the differential roll ROM more in the horses with an S-backed postural type in comparison to the other postural types (see Figure 5.14). The rounding reflex score was negatively correlated with the study condition effect on the differential roll ROM; the better the score, the less the differential roll ROM will increase when ridden (R=0.507, p=0.032). The epaxial muscle tone and reactivity in the thoracic region was positively correlated with the study condition effect on the differential yaw ROM; the higher the muscle tone and reactivity, the more the differential yaw ROM will increase when ridden (R=0.461, p=0.054).

Table 5.10. The linear mixed models for the horse's back movement at trot.

Level	ROM	Factors	df	F	*p*-value	Post-hoc study condition *p*-value	95% CI LL	95% CI LL
T6-L1	**Diff. Roll**	**Study Condition**	1	29.44	<.001	**<.001**	**-7.24**	**-3.32**
		Rein	1	.10	.759			
		Speed	1	.22	.639			
		* TLx muscle tone/ reactivity	12	10.54	<.001			
	Diff. Pitch	**Study Condition**	1	27.47	<.001	**<.001**	**1.34**	**3.01**
		Rein	1	.01	.925			
		Speed	1	.20	.658			
		* Postural type	4	3.35	.029			
	Diff. Yaw	**Study Condition**	1	4.14	.048	**.048**	**.01**	**1.96**
		Rein	1	.82	.370			
		Speed	1	.27	.604			
		* TLx muscle tone/ reactivity	12	4.75	.003			
L1-L3	Diff. Roll	Study Condition	1	2.84	.099	.099	-.13	1.51
		Rein	1	1.26	.267			
		Speed	1	2.74	.103			
	Diff. Pitch	**Study Condition**	1	52.78	<.001	**<.001**	**.68**	**1.20**
		Rein	1	.13	.720			
		Speed	1	.51	.480			
		* Rounding reflex	8	5.69	<.001			
	Diff. Yaw	**Study Condition**	1	27.83	<.001	**<.001**	**.33**	**.74**
		Rein	1	.06	.817			
		Speed	1	3.41	.071			
		* Postural type	4	3.67	.034			
		* Lx muscle tone/ reactivity	12	2.80	.043			
L3-L5	Diff. Roll	Study Condition	1	1.39	.244	.244	-.25	.96
		Rein	1	.16	.689			
		Speed	1	5.50	.022			
	Diff. Pitch	**Study Condition**	1	44.47	**<.001**	**<.001**	**.58**	**1.08**
		Rein	1	.16	.688			
		Speed	1	.25	.620			
	Diff. Yaw	Study Condition	1	2.28	.137	.137	-.06	.40
		Rein	1	.40	.532			
		Speed	1	10.88	.002			
L5-S3	**Diff. Roll**	**Study Condition**	1	16.83	<.001	**<.001**	**.75**	**2.20**
		Rein	1	.40	.533			
		Speed	1	.06	.810			
		* Postural type	4	3.02	.047			
		* Rounding reflex	8	3.31	.018			
	Diff. Pitch	**Study Condition**	1	26.34	<.001	**<.001**	**-.96**	**-.42**
		Rein	1	.04	.834			
		Speed	1	.22	.645			
	Diff. Yaw	**Study Condition**	1	5.50	.023	**.023**	**.03**	**.40**
		Rein	1	1.43	.239			
		Speed	1	.16	.693			
		* Tx muscle tone/ reactivity	12	2.56	.038			

*CI = confidence interval, LL = lower limit, UL = upper limit, ROM = ranges of motion. Diff. = differential. TLx = thoracolumbar, Lx = lumbar, Tx = thoracic. * = interaction between study condition and specified factor. The underlined parameters indicate that the values were significantly influenced by study subject, and the bold values indicate that the parameter was significantly influenced by study condition.*

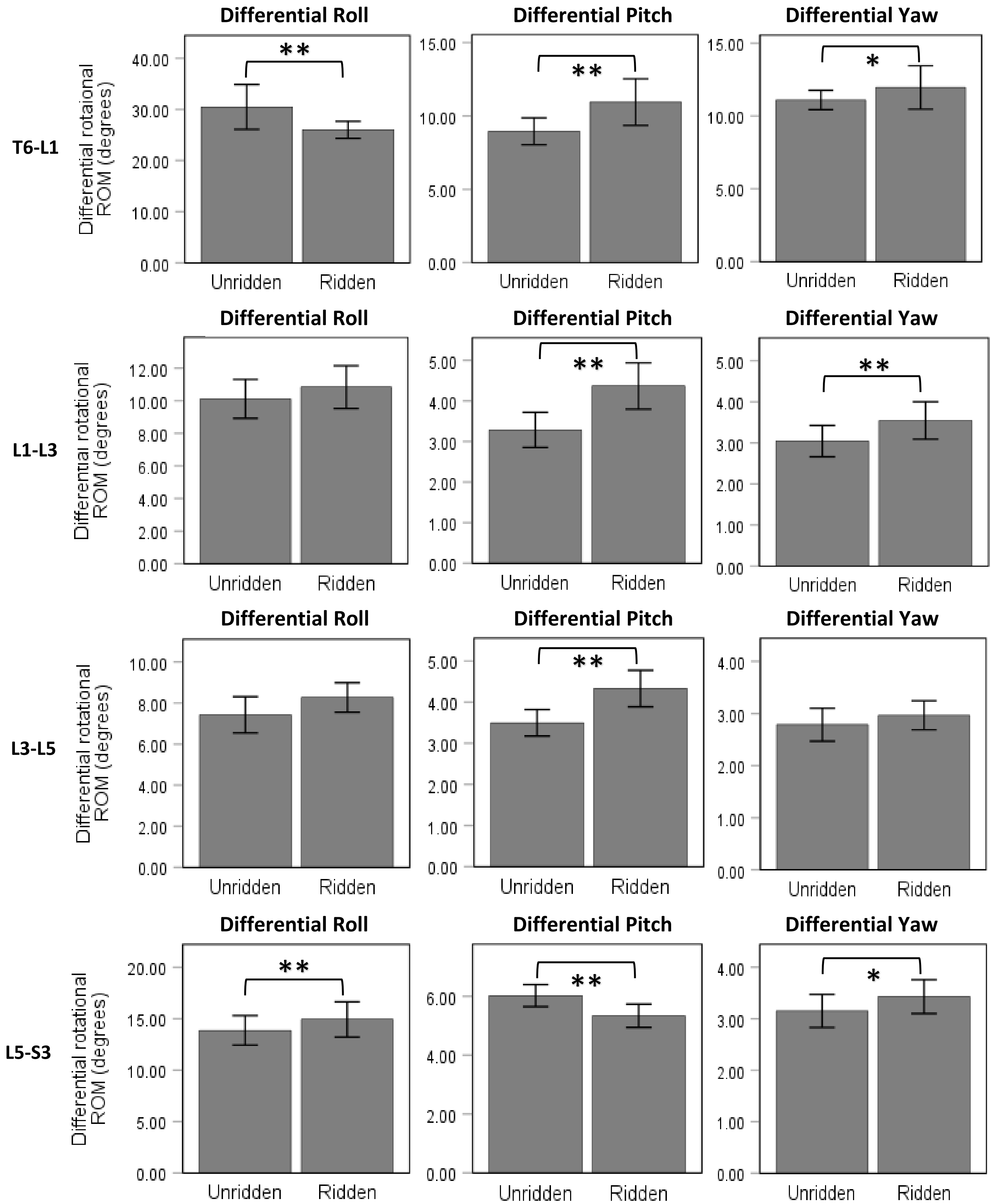


Figure 5.11 | The differential rotational ROM at trot in the unridden and ridden study conditions, with reins pooled. Error Bars represent a 95% confidence interval. * and ** = the difference between ridden conditions is significant (p<.05 and p<.001, respectively).

T6-L1 differential pitch ROM at trot

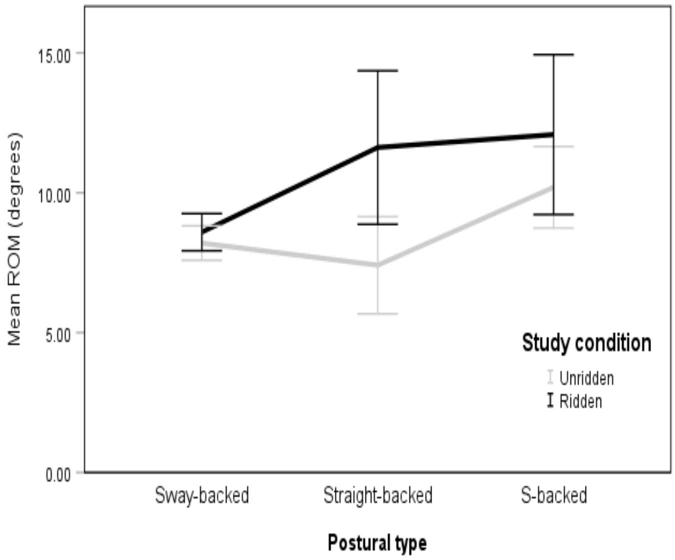


Figure 5.12 | The interaction plot between the effect of study condition on the differential pitch ROM at T6-L1 at trot and the horse's postural type. The error bars represent a confidence interval of 95%.

L1-L3 differential yaw ROM at trot

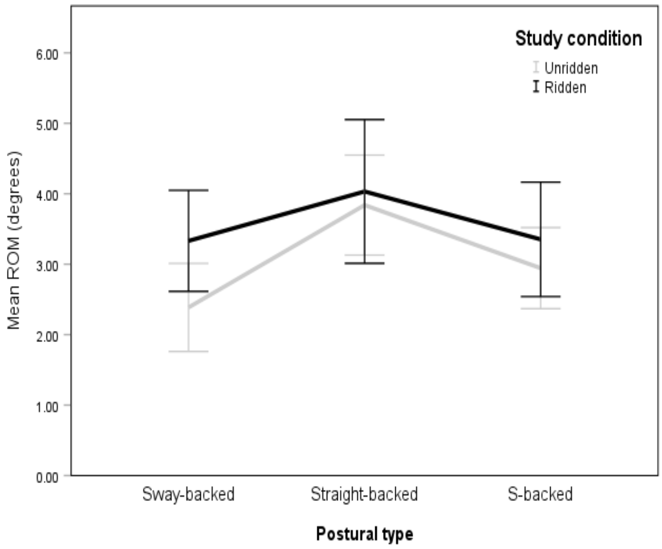


Figure 5.13 | The interaction plot between the effect of study condition on the differential yaw ROM at L1-L3 at trot and the horse's postural type. The error bars represent a confidence interval of 95%.

L5-S3 differential roll ROM at trot

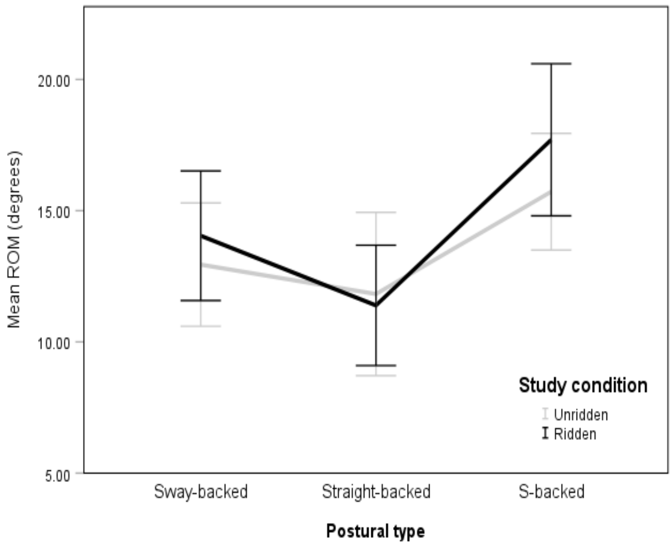


Figure 5.14 | The interaction plot between the effect of study condition on the differential roll ROM at L5-S3 at trot and the horse's postural type. The error bars represent a confidence interval of 95%.

5.9 Discussion

This study investigated how being ridden alters a horse's back posture at halt and movement at walk and trot in sport horses that were in active ridden work and evaluated how these alterations relate to functional measures of the horse's back. The findings from this study met the study hypotheses that (1) saddle and rider induce a more extended back posture at halt, (2) being ridden at walk and in rising trot increases ROM in the lumbosacral region compared to when unridden, and (3) these postural and movement adaptations in the horse's back when being ridden are associated with functional measures of the horse's back.

5.9.1 The alterations in the horse's back posture and movement when ridden

The results reported in this study support previous studies reporting the effect of a saddle and rider's load on the horse's back posture. Based on clinical evidence, Jeffcott (1979) and Townsend, Leach and Fretz (1983) already suggested that a saddle and rider's load can have an extending effect on the horse's back. De Cocq, Van Weeren, and Back (2004) and de Cocq *et al.* (2009a) provided quantitative evidence for this observation, reporting an increase in the degree of extension in the horse's lumbosacral region in all gaits when loaded with a rider-equivalent mass (75 kg) and when ridden in sitting and rising trot, respectively. This study confirmed that a saddle and rider's load also increase the degree of extension in the horse's back posture at halt, which was evident in all back regions but most evident in the lumbosacral region, coinciding with the anatomical spinal region with the most prominent physiological flexion-extension ROM (Denoix, 1999). In this study, the horses halted in a 'competition' posture. The competition posture has previously been associated with a more actively engaged abdominal and *iliopsoas* musculature given the horse demonstrates more flexion in the lumbar region when ridden in this posture compared to a free posture (Rhodin *et al.*, 2009, 2018). It could therefore be speculated that the horse's abdominal and *iliopsoas* musculature were engaged regardless of the observed increase in extension in this study, supporting the idea that the horse's back needs superior levels of muscular strength and postural control to accommodate the load of a saddle and rider (Clayton, 2012, 2016a).

The results reported in this study are also in line with previous studies reporting increased ROM in the lumbosacral back region when ridden compared to unridden; de Cocq *et al.* (2009a) reported a significant increase in flexion-extension and lateral bending ROM in the lumbosacral region when the horse is ridden in rising trot compared to when trotting unridden. MacKechnie-Guire and Pfau (2021a) found an increase in the differential roll, pitch, and yaw ROM in the caudal-thoracic and lumbar region (T18-L3) when the horses were ridden in sitting trot compared to unridden. While Martin *et al.* (2016) did not find statistical differences in the differential pitch region in the lumbar region when ridden in rising trot compared to when unridden, they compared the ROM during the sitting and rising phase of the rising trot compared to the step cycles unridden and only examined a small study sample (n=3) of riding school horses, potentially clarifying the differentiation with their study findings.

This study investigated how being ridden alters the horse's back kinematics at walk and in rising trot, providing novel insights about the horse's back dynamics when ridden in the different gaits. Studying the statistics of the reported kinematic measures, the most prominent alterations when being ridden at walk were seen for the differential roll and yaw ROM, whilst at trot, the most prominent alterations were seen for the differential pitch ROM. In both gaits, the back region just caudal to the saddle (L1-L3) demonstrated the most prominent ROM increases. At walk, axial rotation and lateral bending facilitate the transmission of forces between the appendicular and axial skeleton with generally low muscle activity, following the alternation of the footfalls with two or three limbs having contact with the ground simultaneously (Rhodin, 2008). It can be suggested that the prominent alterations in the horse's differential roll and yaw ROM when ridden at walk represent a locomotor adaptation to efficiently transmit the additional forces induced by saddle and rider between the axial and appendicular skeleton. At trot, the horse's body is supported by a diagonal pair of limbs during the stance phase, providing stability and limiting twisting movements of the horse's back whilst the muscular activity of the trunk muscles controls the pitch movement of the back (Rhodin, 2008; Hobbs, Richards and Clayton, 2014). The prominent alterations seen in the differential pitch ROM of the horse's back when ridden in rising trot support that epaxial and hypaxial muscular strength and neuromotor control are required to control for the modulation induced by saddle and rider in the horse's back movement (Clayton, 2012, 2016a), providing dynamic stability to the increased ROM.

5.9.2 How the functional measures and the rider-horse body mass ratio relate to the alterations in the horse's back posture and movement when ridden

Different postural and locomotory adaptations to being ridden were seen in the horses with different postural types. At halt, saddle and rider were seen to have a more pronounced extending effect on the back posture in S-backed horses compared to the sway- or straight-backed horses. Typical to the sway-backed horses is that their back posture is already in a sub-maximal extended position due to their weaker abdominal musculature (Paul, 2016; Tabor *et al.*, 2023), potentially clarifying why the extending effect of saddle and rider is less pronounced in sway-backed horses compared to in S-backed horses. Typical to straight-backed horses is their hypertonic abdominal musculature (Paul, 2016; Tabor *et al.*, 2023), which lacks in the S-backed horses and might aid the straight-backed horse in counteracting the extending effect of saddle and rider on their back posture. At walk, a clear differentiation was observed in the effect of being ridden on the differential roll ROM between the S-backed horses in comparison to the sway- and straight-backed horses, with the S-backed horses demonstrating a much more pronounced decrease in the thoracolumbar (T6-L1) roll ROM and, coincidentally, less increased roll ROM in the lumbosacral region when ridden. At trot, the straight-backed type horse demonstrated the most prominent increase in the thoracolumbar differential pitch ROM when ridden, while the sway-backed type horses demonstrated a more prominent increase in the lumbar differential yaw ROM and the S-backed type horses a combination of a more prominent increase in the thoracolumbar differential pitch ROM and in the lumbosacral differential roll ROM. Given the differences in alignment and muscle balance (Paul, 2016; Tabor *et al.*, 2023), the observation of different movement patterns in the horses with different postural types is evident and should be taken into consideration when evaluating the effect saddle and rider have on the horse's back movement or when managing movement dysfunctions in ridden horses in equine practice.

Despite the fact that the horses included in this study all represented 'functional' sport horses that were actively competing without a recent injury and considered sound by a veterinary surgeon, the functional assessment of the horse's back identified some level of muscle dysfunctions in the study horses, which related to the outcomes of the ridden examination. Firstly, the epaxial muscle tone and reactivity in the horse's thoracolumbar region significantly interacted with the horse's posture at halt and the horse's back movement when ridden at trot. As previously established (see Section 2.1.4), back pain is associated with poor postural and neuromotor control due to neurogenic deactivation of the stabilising trunk musculature (Stubbs, 2011; Clayton, 2012; McGowan and Hyytiäinen, 2017). The findings from this study provide quantitative evidence that the presence of back pain in the horse, assessed by the increased epaxial muscle tone and reactivity, results in altered postural and neuromotor control with the horses demonstrating more pronounced alterations in their back posture and movement patterns when ridden. More specifically, the extending effect of a saddle and rider's load on the horse's back posture at halt is more pronounced in horses with higher epaxial muscle tone and reactivity, in the thoracic region in particular, indicating altered postural control in these horses. Previous literature already reported an association between the presence of back pain and a more extended posture in the horse, at halt (Tabor, Mann and Williams, 2018), walk, and trot (Wennerstrand *et al.*, 2009). This study also found that horses with higher thoracolumbar epaxial muscle tone and reactivity demonstrate increased differential yaw ROM when ridden at trot. Also discussed in Chapter 2, compensatory lateral movements are observed in the unridden horse when back pain is present (Jeffcott *et al.*, 1982; Wennerstrand *et al.*, 2004, 2009). It is hypothesised that the more pronounced increase in differential yaw ROM across the back segments in horses with higher epaxial muscle tone and reactivity when (un)ridden indicates a lack of neuromotor control to stabilise the lateral dynamic demands at trot, requiring eccentric activity of the trunk musculature to stabilise the inertially driven spinal movements (Robert *et al.*, 2002; Wakeling *et al.*, 2007). The lack of a significant interaction between the horse's epaxial muscle tone and reactivity and the horse's back movement when ridden at walk might relate to the back requiring less muscular stabilisation at the walk in comparison to the trot (Zsoldos *et al.*, 2010; Kienapfel *et al.*, 2018).

The functional measures of the horse's thoracic epaxial musculature dimensions demonstrated significant interactions with the horse's back movement when ridden at walk only. More asymmetry in the thoracic epaxial musculature dimensions related to less pronounced increases in the thoracolumbar differential roll and yaw ROM when ridden at walk, while a higher ratio in the thoracic epaxial musculature dimensions, indicating a more convex back shape (Greve and Dyson, 2013b), related to more pronounced increases in the lumbar differential roll ROM. These findings indicate that horses with a more optimal thoracic epaxial muscle function, in terms of less muscle asymmetry and more muscle development, allow more pronounced increases in the differential roll and yaw ROM in the thoracolumbar region when ridden at walk. This observation invalidates the perception that the increased roll and yaw ROM at walk indicate a destabilising effect of being ridden on the horse's back movement given that spinal instability is related to dysfunctions in the stabilising trunk musculature, represented by poor muscle development, i.e. atrophy, and muscle volume asymmetries (Clayton, 2012; McGowan and Hyytiäinen, 2017). However, it must be appreciated that measuring the horse's epaxial musculature dimensions with a Flexicurve Ruler is an indirect assessment of muscle development and cannot dissociate between the dimensions of the deeper and more superficial trunk musculature, nor between the muscular and the skeletal and adipose structures.

Finally, the horse's rounding reflex score demonstrated a significant interaction with the horse's back movement when ridden at trot. It was found that horses demonstrating more back flexibility and coordination during the rounding reflex also demonstrated a more pronounced increase in the lumbar pitch ROM when ridden, which coincided with a less pronounced increase in the lumbosacral roll ROM when ridden. This observation invalidates the perception that the increased pitch ROM indicate a destabilising effect of being ridden on the horse's back movement, but rather that the horse has the flexibility and coordination to facilitate this movement. Furthermore, decreased dorsoventral flexibility at the trot has been observed previously in horses with back problems (Jeffcott, 1980; Wennerstrand *et al.*, 2004, 2009) and the dorsoventral movement is a favoured performance characteristic in the ridden horse at trot (Hobbs *et al.*, 2020), all supporting the idea that increased pitch ROM in the lumbar region is a favoured movement adaptation associated with more optimal spinal functioning in the ridden horse at trot. The association between the horse's croup reflex score and the less pronounced increase in lumbosacral roll ROM when ridden might then coincide with the horse requiring less lateral movement compensations when facilitating more movement in the pitch direction.

The rider-horse body mass ratio interacted with the horse's back movement at walk only. Considering previous literature reporting positive correlations between the pressures underneath the saddle and the rider's body mass at halt (Jeffcott, Holmes and Townsend, 1999; de Cocq, van Weeren and Back, 2006; de Cocq *et al.*, 2009b) and between the horse's movement asymmetries and the rider-horse body mass ratio (Dyson *et al.*, 2019), a significant interaction between the rider-horse body mass ratio and the horse's back posture at halt and back movement when at trot was expected as well. However, no heavy riders were included in this study, with the rider-horse body mass ratio ranging from 7-14%, which would be classified as a light-to-moderate rider body mass according to Dyson *et al.* (2019). Therefore, it could be that the riders included in this study were not heavy enough to confirm this speculation. More research recruiting a more heterogeneous rider population with riders of different sizes is warranted to confirm the interaction between the rider-horse body mass ratio and the horse's back posture at halt and movement at trot. It could furthermore be hypothesised that the rider-horse body mass ratio interacted with the horse's back movement at walk and not at trot due to the increased activity of the trunk musculature at the trot (Zsoldos *et al.*, 2010; Kienapfel *et al.*, 2018), supporting the horse in accommodating the saddle and rider's load.

5.9.3 Limitations

For this study, no postural or kinematic measurements were taken of the horse's mid-caudal thoracic region. As established in Chapter 4, novel research methods enabling the evaluation of the posture of the horse's mid-caudal thoracic region when covered by the saddle are still warranted. Given the high prevalence of pathological changes in the mid-caudal thoracic region (Townsend *et al.*, 1986; Zimmerman, Dyson and Murray, 2011; Clayton and Stubbs, 2016), postural measures of this region would, however, be of particular interest to advance current understanding of the loading mechanisms in this back region. In the interest of facilitating the recruitment process of the study population, it was decided not to place a skin-mounted IMU in the saddle region for the collection of kinematic measurements. That way, horses with a saddle that had a smaller clearance between the panels did not have to be excluded due to the potential risk of the saddle's movement directly interfering with the movement of the IMUs attached to the anatomical landmarks of mid-caudal thoracic spinous processes. Consequently, no comparison could be made with previous research reporting decreased roll and yaw ROM in the more cranial back region (T5-T13) when ridden in sitting trot (MacKechnie-Guire and Pfau, 2021a, 2021b) or loaded with a saddle at walk and trot (Deckers *et al.*, 2022), compared to when unloaded. However, this study reported a significant decrease in the roll ROM at T6-L1 when ridden at walk and trot, providing further quantitative evidence for a saddle and rider's load to have a constraining effect on roll ROM of the skin/ spinal segments in this region, alongside a potential stabilising effect, as was suggested by Fruehwirth *et al.* (2004).

It must be appreciated that the comparative analysis between the study conditions represents the combined effect of a saddle and rider and being ridden in a working posture on the horse's back. The horse's posture is known to alter its biomechanics when ridden at walk (Rhodin *et al.*, 2018) and trot (Rhodin *et al.*, 2009), and might therefore present a confounding factor for the results reported in this study for the effect of saddle and rider on the horse's back. It must also be acknowledged that the reported results of how being ridden influences the horse's back kinematics at trot include the effect of being ridden in rising trot as opposed to in other seating styles, such as in the sitting or two-point seating styles, which are known to influence the horse's back biomechanics differently (Peham *et al.*, 2009; Persson-Sjodin *et al.*, 2018). Therefore, further research repeating this study with the horse in different postures and the rider in different seating styles is required to confirm the results reported in this study for the effect of the saddle and rider on the horse's back.

It must also be noted that some of the significant results reported in this study were small and within the range of biological variance (Faber *et al.*, 2000; Faber *et al.*, 2001a; Hardeman *et al.*, 2020). Furthermore, these measures were collected from skin-mounted IMUs, with the skin displacement being another potential source of error when representing the horse's spinal kinematics. How saddle and rider influence the skin movement of the horse's back has not yet been studied, again suggesting that relatively small changes in the reported measures of the horse's back kinematics in particular should be interpreted with caution. Therefore, it is recommended to evaluate the reported kinematic findings in light of related literature, and more research is warranted to complement these findings as well as to advance further our understanding of the ridden dynamics of the horse's back.

Caution should be taken in generalising these study findings to the overall equine population, considering the study population represents a rather uniform population of competition horses that were deemed fit for ridden purpose and without a recent musculoskeletal injury at the time of data collection. Regardless, this study provided quantitative evidence for subclinical back dysfunctions to be common in this population, as acknowledged previously (Haussler, 1999b; Wennerstrand, 2008), and to impact the horse-saddle-rider interaction. Considering the previously reported high prevalence of back pain (Kraft *et al.*, 2007) and altered neuromotor control (Deckers *et al.*, 2020) as well as riding asymmetries (Gunst *et al.*, 2019) in the rider, subclinical musculoskeletal dysfunctions will likely have been present in the riders of this study population as well. It was considered outside the scope of this study to control for alike dysfunctions in the rider, which might present another confounding factor in the study results. Future research as well as clinical practice are recommended to take into consideration the impact of subclinical (back) dysfunctions in both the horse and the rider into the horse-saddle-rider interaction.

5.10 Conclusion

The study evaluated the association between functional measures of the horse's back and the postural and movement adaptations in the horse's back when being ridden in a sample of actively competing horses that are deemed fit for ridden purpose. It was found that the horse's back posture extends more when loaded with a saddle and rider at halt, which was more pronounced in horses with a higher epaxial muscle tone and reactivity in the thoracic region and horses with an S-backed postural type compared to sway- and straight-backed horses. Being ridden at walk and trot was found to significantly decrease the thoracolumbar roll ROM (T6-L1), while the most prominent increased ROM occurred in the lumbosacral roll and thoracolumbar yaw ROM at walk and in the thoracolumbar pitch ROM at trot. Different movement adaptations to being ridden at walk and trot were seen in the horses with different postural types, which are in line with the muscle and movement (dys)functions typical to the postural types. Furthermore, significant interactions were found between the horse's back movement when ridden and the thoracic epaxial musculature dimensions and the rider-horse body mass ratio at walk and with the horse's thoracolumbar epaxial muscle tone and reactivity and rounding reflex scores at trot. These interactions suggest that (1) horses with less asymmetric and more convex thoracic epaxial musculature dimensions allow bigger increases in the differential roll and yaw ROM in the thoracolumbar region when ridden at walk, (2) heavier riders increase the pitch and yaw ROM in the horse's lumbar region when ridden at walk, (3) horses with higher epaxial muscle tone and reactivity will demonstrate more pronounced yaw ROM in all back regions when ridden at trot, and (4) that horses with more back flexibility and coordination facilitate increased pitch ROM in the lumbar region, requiring less compensatory roll ROM in the lumbosacral region.

These study findings confirm the importance of the functioning of the horse's back in the horse's back biomechanics when loaded with a saddle and rider, revealing altered postural and movement adaptations when subclinical back dysfunctions are present. Furthermore, this study supports the use of the reported functional measures of the horse's back to evaluate back functioning in the ridden horse, i.e. the horse's capacity to meet the biomechanical demands when loaded with a saddle and rider. Early detection of back dysfunctions in the horse using those functional measures could steer the prevention management of back problems in ridden horses.

CHAPTER SIX

6 General discussion and implications

The overarching purpose of this thesis was to advance our understanding of the biomechanical interaction between saddle, rider, and the horse's back, and how this relates to the horse's back functioning. Six studies were conducted to meet the study aims, including: (1) a literature study about how the horse's back functions and how we can evaluate this, (2) a systematic review study about the effect of saddle and rider on the horse's back biomechanics, (3) an exploratory study about the development of an experimental saddle enabling optical motion capture of the horse's mid-caudal thoracic region, (4) a pilot study evaluating the use of a preliminary hybrid optical-inertial motion capture approach to measure a horse's back movement, (5) an observational study investigating the effect of a saddle on the horse's back kinematics at walk and trot, and (6) a final observational study investigating the effect of saddle and rider on the horse's back posture at halt and movement at walk and in rising trot in relation to functional measures of the horse's back. This Chapter summarises how each study contributed to the overarching purpose of this thesis and discusses the general limitations and implications of the thesis.

6.1 A summary of the individual studies

The literature review of the thesis (Chapter 2) evaluated current knowledge of the anatomy, functional assessments, biomechanics, and movement analysis of the horse's back. It was established that optimal spinal function in the ridden horse can be defined as the capacity to provide sufficient stability and mobility to match the biomechanical demands of the horse's back when loaded with a saddle and rider while performing sport-specific motor tasks. Recent advances in the equine literature established valid and reliable functional assessments to evaluate a horse's back functioning, of which the most accessible ones were applied in the observational study of the association between the effect saddle and rider have on the horse's back biomechanics and the horse's back functioning (Chapter 5B). Continuing with the study of the horse's back movement, i.e. the biomechanics, this literature review alludes to the coupling between the movement of the horse's back and this of the cervical and appendicular skeleton and confounding factors to consider in the biomechanics of the horse's back, including the head-neck position, speed and degree of collection of the horse's gait, and the presence of lameness or back dysfunctions. These confounding factors were evaluated in the identified studies in the systematic review (Chapter 3) and standardised or controlled for in the observational studies of this thesis (Chapter 5). The literature review concludes with an overview of the research methods used for the movement analysis of the horse's back, evaluating their validity and reliability as well as their limitations in equine movement analysis, which are targeted in Chapter 4 of this thesis.

Appreciating the complexity of the horse-saddle-rider interaction (Greve and Dyson, 2013a) as well as the growing evidence related to this research field (van Weeren, McGowan and Haussler, 2010), a second review study concentrating on the literature related to the effect of a saddle and rider on horse's back biomechanics was conducted, which is presented in Chapter 3. Synthesis of the evidence collected in this systematic review demonstrated an association between saddle pressures and back ROM, with increased pressures in a particular saddle region coinciding with reduced ROM in this region while adjacent, less constrained back regions will simultaneously increase in ROM. Being ridden was also found to increase the degree of extension and induce a particular movement adaptation in the horse's back, referring to decreased roll and yaw ROM in the more cranial back region underneath the saddle, being the region exposed to the highest shearing forces and focal pressures, and increasing the ROM between the more caudal back segments. Furthermore, this systematic review collected consistent evidence for correctly fitting saddles to reduce peak pressures on the horse's back, and more efficiently so than treeless saddles, and demonstrated that alterations in saddle design and the use of saddle pads considered in function of saddle fit aid further reduction of peak pressures and optimisation of pressure distribution, therefore facilitating the horse's back movement. Rider-related characteristics that could be considered to manage the effect of saddle and rider on the horse's back biomechanics, or the biomechanical demands of the horse's back, include the rider's body mass, seating style, riding skills, and asymmetries. The systematic review study also served to identify research areas related to the overarching thesis aims still warranting more quantitative evidence as well as saddle- and rider-related characteristics that can be considered as confounding factors when studying the biomechanical interaction between saddle, rider, and horse. Thereby, this systematic review facilitated the development of the research methods and methodologies for the sequential thesis studies (Chapter 4 and 5).

One of the areas identified in the systematic review (Chapter 3) to warrant more quantitative evidence to advance our understanding of the biomechanical interaction of saddle, rider, and the horse's back in relation to the horse's back functioning was the study of the horse's posture, or alignment, in the mid-caudal thoracic region and in field when loaded with a saddle and rider. With previously established research methods relying on the line-of-sight of optical motion cameras to quantify the alignment between back segments, as discussed in the literature review (Chapter 2), novel research methods were investigated to facilitate postural measurements of the horse's entire back region and in field, which is presented in Chapter 4. Chapter 4A presents the development of a (loaded) experimental saddle with an open seat and a pilot study evaluating its suitability for optical motion capture of the horse's back while on the treadmill, including this of the mid-caudal thoracic region. It was found that the experimental saddle enables optical motion capture of the horse's mid-caudal thoracic region, meeting the study objectives, though the experimental saddle demonstrated dynamic instability at the trot when loads (10-53 kg) were attached to the saddle. These study findings support that the effect of a rider's load on the horse's back cannot be simplified to a mere passive mass, lacking dampening capacities to accommodate the horse's locomotory forces – at trot in particular. Chapter 4B presents a pilot study evaluating the level of error of a preliminary hybrid optical-inertial motion capture approach against optical motion capture in measuring a horse's back movement and posture at walk and trot on a treadmill. The findings from this pilot study demonstrated encouraging results for the use of hybrid optical-inertial motion capture to measure a horse's back movement and posture. However, further development and evaluation of hybrid optical-inertial motion capture approaches encountering some of the addressed limitations of the proposed approach are recommended prior to their use in empirical research. While the outcomes from the studies presented in Chapter 4 do not directly meet the overarching aims of this thesis, these investigations were considered a substantial investigation in pursuing these aims.

The first observational study (Chapter 5A) aimed to investigate the effect a saddle, without a rider, has on the horse's back kinematics, including the kinematics of the mid-caudal thoracic region, which was another area identified in the systematic review (Chapter 3) to warrant more quantitative evidence. Evidentially, the role of the saddle includes this of the girth, which secures the saddle on the horse's back and reduces thoracic excursions (Murray *et al.*, 2013). This study provides quantitative evidence for a saddle to limit the roll and yaw ROM in the horse's cranial back region underneath the saddle and induce compensatory increased ROM in the more caudal back regions. However, it was observed that the thoracolumbosacral roll ROM reported in this study were notably higher than previously reported vertebral ROM (Faber *et al.*, 2000, 2001a), inferring that these outcomes appear to be affected by skin movement inducing rotational movement errors. Still, the movement adaptations observed in the horse's back when being loaded with a saddle were comparative to those previously reported in the literature when being ridden (Fruehwirth *et al.*, 2004; de Cocq *et al.*, 2009a; MacKechnie-Guire and Pfau, 2021a, 2021b). Therefore, this study also alludes that the saddle plays an important role in the movement adaptations in the horse's back when ridden.

The second observational study (Chapter 5B) aimed to investigate the effect of a saddle and rider on the horse's back posture at halt and movement when being ridden at walk and in rising trot and how these effects relate to functional measures of the back in veterinary-approved sound competition horses without recent injury. The functional measures of the horse's back assessed in this study included these of the horse's postural type, thoracolumbar epaxial muscle tone and reactivity, thoracic epaxial musculature dimensions, and back flexibility and coordination. The study findings demonstrated significant associations between the functional measures of the horse's back and the postural and movement adaptations in the horse's back when being ridden. Horses with a higher thoracolumbar epaxial muscle tone and reactivity demonstrated a more pronounced extending effect of saddle and rider on the horse's back posture at halt, as well as more pronounced increased yaw ROM in the different back regions when ridden at trot. Horses with less asymmetric and more convex thoracic epaxial musculature dimensions allowed bigger increases in the differential roll and yaw ROM in the thoracolumbar region when ridden at walk, and horses with more back flexibility and coordination facilitated increased pitch ROM in the lumbar region when ridden at trot. Different alignment and movement adaptations to being ridden were seen in the horses with different postural types, which are in line with the muscle and movement (dys)functions typical to the postural types. Additionally, heavier riders increase the pitch and yaw ROM in the horse's lumbar region when ridden at walk. These study findings indicate that back functioning plays an important role in the back biomechanics of the ridden horse, even in sound competition horses without a recent injury. Furthermore, this study supports the use of the reported functional measures of the horse's back to evaluate back functioning in the ridden horse, i.e. the horse's capacity to meet the biomechanical demands when loaded with a saddle and rider.

6.2 General thesis limitations

The main limitation of the thesis was that the developed experimental saddle and the proposed hybrid optical-inertial motion capture approach were not used in empirical research, regardless of this originally being intended. The shortcomings in the transferability of the loaded experimental saddle in representing a rider's load due to its dynamic instability in the trotting horse meant that no follow-up studies using the experimental saddle were conducted. The limitations of the preliminary hybrid optical-inertial motion capture approach proposed in this thesis implied that its reliability and validity to measure a horse's back movement and posture in overground study conditions were questioned, and further developing and evaluating hybrid motion capture for such purpose were considered outside the scope of this thesis. Regardless, the investigations into the development of the experimental saddle and the use of hybrid optical-inertial motion capture were presented in this thesis to share the challenges faced and reflections made within the journey of this thesis. The purpose of investigating these novel research methods was to overcome some of the limitations in movement analysis of the horse's back using current research methods, advancing research methods in measuring the horse's back movement and posture in industry-specific settings, i.e. when loaded with saddle and rider and in study conditions in the field, as urged elsewhere (Egan, Brama and McGrath, 2019). While the development of the experimental saddle and hybrid optical-inertial motion capture approach can be considered unsuccessful for their use in empirical research, these investigations can support future researchers in exploring how we can further advance motion capture tools to measure a horse's back movement and posture in loaded study conditions in the field.

A general limitation of this thesis is that the biomechanical interaction between the saddle, rider, and the horse's back was narrowed down to the interaction during straight-line walk and trot locomotion, limiting the extrapolation of the study findings to other types of ridden movement, such as circular and canter ridden movement. Previous literature demonstrated that circular movement alters the biomechanics of the horse's back movement at walk (Egenvall, Engström and Byström, 2020) and trot (Starke *et al.*, 2012; Greve, Pfau and Dyson, 2017; Byström *et al.*, 2021). The biomechanics of the horse's back movement during canter differs from the back movement during walk and trot, with the canter representing an asymmetrical gait with a rocking motion of the upper body (Clayton and Hobbs, 2017). While it must be appreciated that the study findings reported in this thesis about the biomechanical interaction between saddle, rider, and the horse's back cannot be extrapolated to the interaction during other types of movement, it can serve as a useful baseline for comparison with other types of movement. Furthermore, gait analysis in clinical practice is traditionally performed most frequently during walk and trot straight-line locomotion (Greve and Dyson, 2020), supporting why these types of movement were concentrated on in this thesis. This thesis also only reported study findings from horses that were deemed fit for ridden purpose, limiting the extrapolation of the study findings to rehabilitation practices. However, the findings reported in this thesis can support the equine practitioner in his/ her clinical reasoning when managing back health in the ridden horse, which is the basis of developing a safe and effective rehabilitation program (Haussler *et al.*, 2021a).

This thesis demonstrates that the effect of a saddle and rider on the horse's back is directly influenced by confounding factors related to horse, saddle, and rider, stressing that their interaction should be evaluated in the context of the individual horse-saddle-rider combination. The confounding element of saddle fit in the biomechanical interaction between saddle, rider and the horse's back was repeatedly emphasised in this thesis. In theory, an optimally fitting saddle transmits the constantly changing interplay of forces between the horse's back and the rider in the most efficient and comfortable way. When evaluating saddle fit, it must first be appreciated that saddle fit is not a binary evaluation indicating whether the saddle fits or not but rather a scale variable with different grades of saddle fit. Correct saddle fitting remains an art and comes with a high degree of subjectivity (Guire *et al.*, 2017) with a wide variety in saddle fitting practice as a consequence, as was observed within the literature identified in the systematic review (Chapter 3). While more supporting evidence is still warranted to standardise saddle fitting practices, including a dynamic saddle fit evaluation, a contemporary and evidence-based saddle fitting protocol was applied to minimise saddle fit confounding the results from this thesis. More specifically, saddle fit was evaluated by two SMS QSFs adhering to the saddle fitting protocol described by Guire *et al.* (2017) and the SMS, and horses with an unacceptable saddle fit were excluded from the studies (Chapters 5A and 5B).

6.3 Implications for future research

Evidence-based directions are urged to support clinical and sport practice in optimising the welfare management of ridden sport horses (van Weeren and Back, 2014; Egan, Brama and McGrath, 2019; Federation Equestrian International, 2022). The welfare concern targeted in this thesis was the prevalence of back problems in the ridden horse by striving to advance our understanding of the biomechanical demands of the horse's back when loaded with a saddle and rider in relation to the horse's back functioning. Based on the insights gained from this thesis, several implications for future research were identified.

Firstly, an ongoing need for quantitative research advancing our understanding of the loading mechanisms of the mid-caudal thoracic region when loaded with a saddle and rider was identified. The mid-caudal thoracic region is the spinal region with the highest prevalence of pathological changes in the horse (Townsend *et al.*, 1986; Zimmerman, Dyson and Murray, 2011; Clayton and Stubbs, 2016), justifying why measurements of the movement and posture in this region when loaded with a saddle and rider are of particular interest. While the use of skin-mounted IMUs allows measurements of the movement amplitudes in the horse's mid-caudal thoracic region in saddled conditions (Martin *et al.*, 2017b), motion capture tools quantifying the posture, i.e. alignment between different segments, when loaded are still missing. However, the alignment between segments is a relevant indicator of the mechanical stresses on the surrounding musculoskeletal structures (Schlacher *et al.*, 2004; Clayton, 2016a), and a more extended posture when loaded with a saddle and rider has previously been suggested to be a predisposing factor to the development of back problems in the ridden horse (de Cocq, van Weeren and Back, 2004). This thesis investigated if optical motion capture, which can quantify the alignment between body segments visible to the optical motion cameras, of the horse's mid-caudal thoracic region when loaded with a saddle and rider could be enabled and if optical motion capture of the horse's back could be facilitated in ridden study conditions in the field. The development of an experimental saddle with an open seat and the use of hybrid motion capture were investigated, demonstrating promising results to meet these study objectives. Future research is encouraged to explore this field further, establishing tools that can be used in empirical research for these purposes. Suggested directions to make such advances are: (1) the development of more valid simulations of a rider's load, which can be combined with the experimental saddle outlined in this thesis to enable optical motion capture of the horse's mid-caudal thoracic region when loaded with a mass equivalent to that of a saddle and rider, and (2) the establishment of more valid and reliable hybrid motion capture approaches that enable pose estimation and tracking of the horse's back segments, ideally including the mid-caudal thoracic region in saddled conditions.

Secondly, a constant outcome across the different studies in this thesis is that the effect of a saddle and rider on the horse's back cannot be generalised and should be evaluated in the context of the individual horse-saddle-rider combination. Reviewing related literature (Chapter 3), insufficient standardisation practices controlling for the established confounding factors related to the saddle, rider, and horse were observed in some of the studies. For example, a considerable proportion (34%) of the literature concerning this interaction did not mention if saddle fit was verified in their study horses, while strong levels of evidence were found for saddle fit to confound the horse's back biomechanics. Identified confounding factors related to the rider were the rider's body mass, seating style, riding skills, and riding asymmetries. This thesis also established that the horse's (sub)clinical conditions also play a significant role in the horse's back biomechanics (Chapter 2 and 5B), though the (sub)clinical condition of the study horses is missing detail in a majority of the identified studies (see Appendix A.V). Other riding-related factors that have previously been established to influence the back biomechanics of the ridden horse significantly are the posture (Rhodin, 2008) and the speed (Bogisch *et al.*, 2014) and degree of collection (Byström, 2019) of the horse's gait. Standardising or controlling for the aforementioned factors will support future research studying the horse-saddle-rider interaction in optimising their studies' methodological quality.

6.4 Implications for practice

The findings from this study can support equine practice in the management of back health in the ridden horse. First of all, the findings from this study indicate that the effect of a saddle and rider on the horse's back should be evaluated for the individual horse-saddle-rider combination. This thesis supports that factors such as saddle fit, the rider's body mass, seating style, riding skills, and riding asymmetries, and the functional measures of the horse's back should be considered when monitoring the applied load, i.e. saddle and rider, in function of the horse's back health.

The collected evidence in Chapter 3 confirms that optimal saddle fit should be encouraged at all times in the interest of preventing saddle-related discomforts in the horse's back and facilitating the back movement underneath the saddle, thereby also facilitating optimal horse-rider performance. Saddle design and the use of saddle pads should be considered in the function of saddle fit and have the potential to reduce peak pressures underneath the saddle, with higher peak saddle pressures being associated with decreased ROM in the horse's back. The locomotory adaptations to being loaded with a saddle only identified in Chapter 5A confirmed that even correctly fitting saddles have a movement-constraining effect on the cranial back region underneath the saddle, evidentially including the girthing effect. These movement adaptations when loaded with a saddle should be taken into consideration in saddle fitting practice.

Consistent evidence was found for the rider's body mass to influence the ridden horse's back biomechanics, with heavier riders exerting higher forces on the horse's back (Chapter 3), exaggerating the locomotory adaptations to being ridden in the lumbar region at walk, potentially indicating movement instability (Chapter 5B), and inducing locomotory asymmetries at trot (Chapter 3). While it seems evident that horses with weaker core strength need to be exposed gradually to heavier weights for their strength to build up accordingly, it must be considered that heavier riders in balance may be less detrimental to the horse's back biomechanics than a lighter rider who is not in balance, as suggested elsewhere (Greve and Dyson, 2013a). Preliminary evidence is found for a more skilled rider to decrease the variability of the horse's back movement (Lagarde *et al.*, 2005), thereby having a stabilising effect on the horse's back (Peham *et al.*, 1998a). It has elsewhere been shown that the quality of the ridden work, associated with a more skilled rider, significantly influences the horse's back functioning in terms of epaxial musculature activity when ridden, with better ridden quality resulting in more pronounced epaxial musculature development both in the short (Greve, Murray and Dyson, 2015) and long term (Greve and Dyson, 2015). However, the evaluation of riding skills remains challenging and is often prone to subjectivity. Recent research provided evidence for factors such as the rider's skill to ride the horse with an independent seat, measured by the coordination variability between the horse's and the rider's movement, is more relevant to understand the horse-rider interactions than the rider's competition level (Wilkins *et al.*, 2022). More research is thus required to study the role of riding skills in the biomechanical interaction between saddle, rider, and the horse's back, applying coordination measures to quantify riding skills. A final rider-related factor that influences the effect saddle and rider have on the horse's back biomechanics and is identified in this thesis is the rider's seating style. The collected evidence in Chapter 3 supports the use of a light seat at the trot, i.e. the two-point seated trot above the rising trot and the rising trot above the seated trot, in horses that are prone to back problems or young horses that are developing the muscular strength to accommodate the rider's weight (Clayton, 2016a).

This study also provided evidence for functional measures of the horse's back, such as postural type, epaxial muscle tone and reactivity, epaxial musculature dimensions and back flexibility and coordination, to relate to the horse's postural and movement adaptations when being ridden (Chapter 5B). These findings confirm an interaction between the horse's back functioning and the biomechanical demands of the horse's back, as deducted from the human literature in Chapter 1, and that functional assessments can be used to evaluate subclinical dysfunctions in the horse's back that are relevant to the horse's ridden performance. Therefore, integration of those functional assessments in equine practice can support early detection of dysfunctions in the back which might lead to clinical back problems if not resolved, and provide equine practitioners with outcome measures of the horse's back functioning relevant for the horse's ridden performance. Adhering to the load-capacity principle (Boucher et al., 2005), such dysfunctions can then be managed by increasing the functioning and/ or decreasing the biomechanical demands of the horse's back, targeting the optimal loading zone monitored to the individual horse (see Figure 1.1). Musculoskeletal function can be improved by appropriate health management, both in preventative and rehabilitative stages, which targeted and supported by a multidisciplinary framework including a veterinarian, physiotherapist, farrier, saddle fitter, dentist, and so on (McGowan, Stubbs and Jull, 2007; McGowan and Cottriall, 2016). Decreasing the biomechanical demands of the ridden horse's back can be approached by monitoring the aforementioned saddle- and rider-related characteristics alongside the horse's training and rehabilitation programme (Clayton, 2016a; Haussler *et al.*, 2021a). Furthermore, this study provides quantitative evidence that subclinical back dysfunctions are common in ridden horses even when they are considered sound and fit for ridden purpose, as acknowledged elsewhere already (Haussler, 1999b; Wennerstrand, 2008). This observation strengthens the rationale for evaluating and managing the horse's back functioning on a regular basis in order to optimise the prevention management of back problems in the ridden horse.

CHAPTER SEVEN

7 Conclusion

This thesis provides novel insights into the biomechanical interaction between saddle, rider, and the horse's back, advancing our understanding of the biomechanical demands of the ridden horse's back in relation to the horse's back functioning. While this thesis concentrated on the horse-saddle-rider interaction during straight-line walk and trot locomotion and in horses that are in active ridden work and without clinical back problems or lameness, the study findings can serve as a useful baseline for comparison with other types of movement and the development of training and rehabilitation programs for the general equine population.

This thesis established that optimal spinal functioning in the ridden horse can be defined as the capacity to provide sufficient stability and mobility to match the biomechanical demands of the horse's back when loaded with a saddle and rider while performing sport-specific motor tasks. Valid and reliable measures to evaluate the functioning of the ridden horse's back were identified, referred to as functional measures of the horse's back, including the horse's postural type, thoracolumbar epaxial muscle tone and reactivity, back flexibility and coordination, and thoracic epaxial musculature dimensions and asymmetries.

This thesis demonstrates that the effect of a saddle and rider on the horse's back biomechanics should not be generalised but rather evaluated in the context of the individual horse-saddle-rider combination. A systematic review of the related literature identified that the saddle and rider-related characteristics confounding the effect saddle and rider have on the horse's back biomechanics include the fitting of the saddle, saddle design, saddle type, the use of saddle pads, and the rider's seating styles, riding skills, riding asymmetry, and body mass. These saddle and rider-related factors can be considered in the management of back health in the ridden horse when monitoring the biomechanical demands of the horse's back to the horse's back functioning.

This thesis provides quantitative evidence that saddle and rider induce movement adaptations in the horse's back, decreasing roll and yaw ranges of motion (ROM) in the more cranial back region underneath the saddle, while increasing the ROM between the more caudal segments at walk and trot. The decreased ROM in the horse's back are associated with the back regions exposed to higher saddle pressures, resulting from the saddle and rider which includes the effect of the girth, and coincide with compensatory movements in the more caudal back segments. At walk, the most prominent increased ROM when being ridden occurred in the lumbosacral roll and thoracolumbar yaw ROM and at trot, these occurred in the thoracolumbar pitch ROM. However, these alterations are significantly associated with the horse's back functioning, as well as to the rider-horse body mass ratio, suggesting that (1) horses with more symmetric and convex thoracic epaxial musculature dimensions allow bigger increases in the differential roll and yaw ROM in the thoracolumbar region when ridden at walk, (2) heavier riders increase the pitch and yaw ROM in the horse's lumbar region when ridden at walk, (3) horses with higher epaxial muscle tone and reactivity will demonstrate more pronounced yaw ROM in all back regions when ridden at trot, and (4) that horses with more dorsoventral back flexibility and coordination facilitate increased pitch ROM in the lumbar region, requiring less compensatory roll ROM in the lumbosacral region at trot. Moreover, different movement adaptations to being ridden at walk and trot were seen in the horses with different postural types, which are in line with the muscle and movement (dys)functions typical to the postural types. Those study findings confirm the role of the horse's back functioning in the back biomechanics of the ridden horse.

This thesis also identified a consistent postural adaptation to being ridden, providing quantitative evidence for the horse's back posture to extend more when loaded with a saddle and rider. The alterations seen in the horse's back posture at halt with a saddle and rider compared to without was also significantly related to functional measures of the horse's back, with the extending effect of saddle and rider being more pronounced in horses with a higher epaxial muscle tone and reactivity in the thoracic region and with an S-backed postural type compared to sway- and straight-backed horses.

Finally, this thesis presents novel research methods overcoming some of the limitations of current research methods used to measure a horse's back movement and posture when loaded with a saddle and rider. More specifically, this thesis found promising results for the use of an experimental saddle with an open seat to enable optical motion capture of the horse's mid-caudal thoracic region, and hybrid optical-inertial motion capture to facilitate optical motion capture of the horse's back in ridden study conditions in the field. Future research is encouraged to develop these research methods further, exploring (1) more valid simulations of a rider's load which, in combination with the proposed experimental saddle, would enable optical motion capture measurements of the horse's mid-caudal thoracic region when loaded with a saddle and rider and (2) more valid and reliable hybrid motion capture approaches that enable pose estimation and tracking of the horse's back segments for measurements in field, ideally including the mid-caudal thoracic region in saddled conditions.

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Appendix A. Supplementary materials of the thesis chapters

Appendix A.I Template of the postural type evaluation (Chapter 2 and 5)

TEMPLATE OF THE POSTURAL TYPE EVALUATION ACCORDING TO PAUL (2016) AND TABOR *ET AL.* (2023).

Zone	Structure	Observations: Highlight the rows in columns D, E and F when you have a positive observation.	Sway backed	Straight backed	S backed
1	Spine	Extension of cervical to sacral spine in a continuous curve	X		
		Straight line visible from cranial thoracic to sacrum		X	
		Extension of cranial thoracic with neutral or flexed caudal thoracic and a sharp angle over 1 or 2 spinal segments			X
	Abdominals	Visible long continuous curve from T3-S1	X		
		Straight line ascending as it goes from cranial thoracic to caudal lumbar region		X	
		Visible continuous curve from cranial thoracic to mid/caudal thoracic with a sharp angle sweeping caudally and upward in the caudal third			X
2B	Lumbosacral junction	Extended	X		
		Neutral or flexed		X	X
		Muscle bulk: Atrophied	X		
		Muscle bulk: Hypertrophied		X	X
	Pelvis	Cranially rotated	X		
		Neutral or posteriorly rotated		X	X
	Pelvic limb	Muscle balance: atrophied Biceps femoris and hypertrophied semimembranosus and semitendinosus	X	X	X
		Muscle is balanced		X	X
		Muscle bulk: Normal for the amount of work		X	
		Muscle bulk: Atrophied		X	X
2F	Scapula	(Posture: reliant on muscle adaption, so it is not a reliable observation but worth noting as the muscle balance will contribute to the movement.) Protraction	X	X	X
		Retraction	X		X
		Neutral	X	X	X
	Thoracic limb	Muscle balance: atrophied thoracic trapezius and cranial dorsal serrate with hypertrophied cervical trapezius and latissimus dorsi	X		X
		Muscle is balanced		X	
		Muscle bulk: atrophied		X	X
3B	Pelvic limb	Muscle balance: hypertrophied Gastrocnemius	X		
		Muscle balance inconsistent	X	X	X
3F	Thoracic limb	Muscle balance: Atrophied long head of triceps and hypertrophied Biceps brachii and long forearm extensors	X		X
		Muscle balance: inconsistent		X	X
3C	Cervical spine and head	Posture: Extended	X		X
		Posture: Neutral		X	X
		Muscle balance: atrophied rhomboids and hypertrophied capitates and brachiocephalic	X		
		Muscle balance: Hypertrophied splenius and rhomboids		X	X
		Muscle balance: inconsistent		X	X
		Muscle bulk: atrophied		X	X

Result on balance: **Count the total number of Highlighted X in each column**

Appendix A.II The 14 items evaluated in the QualSyst tool (Chapter 3)

CHECKLIST FOR ASSESSING THE QUALITY OF QUANTITATIVE STUDIES, USING THE QUALSYST TOOL (KMET, LEE AND COOK, 2004).

Criteria		Yes (2)	Partial (1)	No (0)	N/A
1	Question/ objective sufficiently described?				
2	Study design evident and appropriate?				
3	Method of subject/ comparison group selection *or* source of information/ input variables described and appropriate?				
4	Subject (and comparison group, if applicable) characteristics sufficiently described?				
5	If interventional and random allocation was possible, was it described?				
6	If interventional and blinding of investigators was possible, was it reported?				
7	If interventional and blinding of subjects was possible, was it reported?				
8	Outcome and (if applicable) exposure measure(s) well defined and robust to measurement/ misclassification bias? Means of assessment reported?				
9	Sample size appropriate?				
10	Analytic methods described/ justified and appropriate?				
11	Some estimate of variance is reported for the main results?				
12	Controlled for confounding?				
13	Results reported in sufficient detail?				
14	Conclusions supported by the results?				

N/A = not applicable.

Appendix A.III The QualSyst tool guidelines – definition of the 14 items (Chapter 3)

1. Question or objective sufficiently described?

Yes: Is easily identified in the introductory section (or first paragraph of methods section). Specifies (where applicable, depending on study design) all of the following: purpose, subjects/target population, and the specific intervention(s)/ association(s)/ descriptive parameter(s) under investigation. A study purpose that only becomes apparent after studying other parts of the paper is not considered sufficiently described.

Partial: Vaguely/ incompletely reported (e.g. "describe the effect of" or "examine the role of" or "assess opinion on many issues" or "explore the general attitudes"...); or some information has to be gathered from parts of the paper other than the introduction/background/objective section.

No: Question or objective is not reported, or is incomprehensible.

N/A: Should not be checked for this question.

2. *Design evident and appropriate to answer study question?*

Yes: Design is easily identified and is appropriate to address the study question/ objective.

Partial: Design and /or study question not clearly identified, but gross inappropriateness is not evident; or design is easily identified but only partially addresses the study question.

No: Design used does not answer study question (e.g., a comparison group is required to answer the study question, but none was used); or design cannot be identified.

N/A: Should not be checked for this question.

3. *Method of subject selection (and comparison group selection, if applicable) or source of information/ input variables (e.g., for decision analysis) is described and appropriate.*

Yes: Described and appropriate. Selection strategy designed (i.e., consider sampling frame and strategy) to obtain an unbiased sample of the relevant target population or the entire target population of interest (e.g., consecutive patients for clinical trials, population-based random sample for case-control studies or surveys). Where applicable, inclusion/exclusion criteria are described and defined. Studies of volunteers: methods and setting of recruitment reported. Surveys: sampling frame/ strategy clearly described and appropriate.

Partial: Selection methods (and inclusion/exclusion criteria, where applicable) are not completely described, but no obvious inappropriateness. Or selection strategy is not ideal (i.e., likely introduced bias) but did not likely seriously distort the results (e.g., telephone survey sampled from listed phone numbers only; hospital-based case-control study identified all cases admitted during the study period, but recruited controls admitted during the day/evening only). Any study describing participants only as "volunteers" or "healthy volunteers". Surveys: target population mentioned but sampling strategy unclear.

No: No information provided. Or obviously inappropriate selection procedures (e.g., inappropriate comparison group if intervention in women is compared to intervention in men). Or presence of selection bias which likely seriously distorted the results (e.g., obvious selection on "exposure" in a case-control study).

N/A: Descriptive case series/ reports.

4. *Subject (and comparison group, if applicable) characteristics or input variables/ information (e.g., for decision analyses) sufficiently described?*

Yes: Sufficient relevant baseline/ demographic information clearly characterizing the participants is provided (or reference to previously published baseline data is provided). Where applicable, reproducible criteria used to describe/categorize the participants are clearly defined (e.g., ever-smokers, depression scores, systolic blood pressure > 140). If "healthy volunteers" are used, age and sex must be reported (at minimum). Decision analyses: baseline estimates for input variables are clearly specified.

Partial: Poorly defined criteria (e.g. "hypertension", "healthy volunteers", "smoking"). Or incomplete relevant baseline / demographic information (e.g., information on likely confounders not reported). Decision analyses: incomplete reporting of baseline estimates for input variables.

No: No baseline/ demographic information provided. Decision analyses: baseline estimates of input variables not given.

N/A: Should not be checked for this question.

5. *If random allocation to treatment group was possible, is it described?*

Yes: True randomization done - requires a description of the method used (e.g., use of random numbers).

Partial: Randomization mentioned, but method is not (i.e. it may have been possible that randomization was not true).

No: Random allocation not mentioned although it would have been feasible and appropriate (and was possibly done).

N/A: Observational analytic studies. Uncontrolled experimental studies. Surveys. Descriptive case series / reports. Decision analyses.

6. *If interventional and blinding of investigators to intervention was possible, is it reported?*

Yes: Blinding reported.

Partial: Blinding reported but it is not clear who was blinded.

No: Blinding would have been possible (and was possibly done) but is not reported.

N/A: Observational analytic studies. Uncontrolled experimental studies. Surveys. Descriptive case series/ reports. Decision analyses.

7. *If interventional and blinding of subjects to intervention was possible, is it reported?*

Yes: Blinding reported.

Partial: Blinding reported but it is not clear who was blinded.

No: Blinding would have been possible (and was possibly done) but is not reported.

N/A: Observational studies. Uncontrolled experimental studies. Surveys. Descriptive case series/ reports.

8. *Outcome and (if applicable) exposure measure(s) well defined and robust to measurement/ misclassification bias? Means of assessment reported?*

Yes: Defined (or reference to complete definitions is provided) and measured according to reproducible, "objective" criteria. Little or minimal potential for measurement/ misclassification errors. Surveys: clear description of questionnaire/ interview content and response options. Decision analyses: sources of uncertainty are defined for all input variables.

Partial: Definition of measures leaves room for subjectivity, or not sure (i.e., not reported in detail, but probably acceptable). Or precise definition(s) are missing, but no evidence or problems in the paper that would lead one to assume major problems. Or instrument/ mode of assessment(s) not reported. Or misclassification errors may have occurred, but they did not likely seriously distort the results (e.g., slight difficulty with recall of long-ago events; exposure is measured only at baseline in a long cohort study). Surveys: description of questionnaire/ interview content incomplete; response options unclear. Decision analyses: sources of uncertainty are defined only for some input variables.

No: Measures not defined, or are inconsistent throughout the paper. Or measures employ only ill-defined, subjective assessments. Or obvious misclassification errors/measurement bias likely seriously distorted the results (e.g., a prospective cohort relies on self-reported outcomes among the "unexposed" but requires clinical assessment of the "exposed"). Surveys: no description of questionnaire/ interview content or response options. Decision analyses: sources of uncertainty are not defined for input variables.

N/A: Descriptive case series/ reports.

9. *Sample size appropriate?*

Yes: Seems reasonable with respect to the outcome under study and the study design. When statistically significant results are achieved for major outcomes, appropriate sample size can usually be assumed, unless large standard errors (SE > ½ effect size) and/ or problems with multiple testing are evident. Decision analyses: size of modelled cohort/ number of iterations specified and justified.

Partial: Insufficient data to assess sample size (e.g., sample seems "small" and there is no mention of power/ sample size/ effect size of interest and/ or variance estimates aren't provided). Or some statistically significant results with standard errors > ½ effect size (i.e., imprecise results). Or some statistically significant results in the absence of variance estimates. Decision analyses: incomplete description or justification of size of modelled cohort/ number of iterations.

No: Obviously inadequate (e.g., statistically non-significant results and standard errors > ½ effect size; or standard deviations > _ of effect size; or statistically non-significant results with no variance estimates and obviously inadequate sample size). Decision analyses: size of modelled cohort/ number of iterations not specified.

N/A: Most surveys (except surveys comparing responses between groups or change over time). Descriptive case series/ reports.

10. *Analysis described and appropriate?*

Yes: Analytic methods are described (e.g. “chi square”/ “t-tests”/ “Kaplan-Meier with log rank tests”, etc.) and appropriate.

Partial: Analytic methods are not reported and have to be guessed at, but are probably appropriate. Or minor flaws or some tests appropriate, some not (e.g., parametric tests used, but unsure whether appropriate; control group exists but is not used for statistical analysis). Or multiple testing problems not addressed.

No: Analysis methods not described and cannot be determined. Or obviously inappropriate analysis methods (e.g., chi-square tests for continuous data, SE given where normality is highly unlikely, etc.). Or a study with a descriptive goal/ objective is over-analysed.

N/A: Descriptive case series/ reports.

11. *Some estimate of variance (e.g., confidence intervals, standard errors) is reported for the main results/ outcomes (i.e., those directly addressing the study question/ objective upon which the conclusions are based)?*

Yes: Appropriate variances estimate(s) is/are provided (e.g., range, distribution, confidence intervals, etc.). Decision analyses: sensitivity analysis includes all variables in the model.

Partial: Undefined “+/-“ expressions. Or no specific data given, but insufficient power acknowledged as a problem. Or variance estimates not provided for all main results/outcomes. Or inappropriate variance estimates (e.g., a study examining change over time provides a variance around the parameter of interest at “time 1” or “time 2”, but does not provide an estimate of the variance around the difference). Decision analyses: sensitivity analysis is limited, including only some variables in the model.

No: No information regarding uncertainty of the estimates. Decision analyses: No sensitivity analysis.

N/A: Descriptive case series/ reports. Descriptive surveys collecting information using open-ended questions.

12. Controlled for confounding?

Yes: Randomized study, with comparability of baseline characteristics reported (or non-comparability controlled for in the analysis). Or appropriate control at the design or analysis stage (e.g., matching, subgroup analysis, multivariate models, etc). Decision analyses: dependencies between variables fully accounted for (e.g., joint variables are considered).

Partial: Incomplete control of confounding. Or control of confounding reportedly done but not completely described. Or randomized study without report of comparability of baseline characteristics. Or confounding not considered, but not likely to have seriously distorted the results. Decision analyses: incomplete consideration of dependencies between variables.

No: Confounding not considered, and may have seriously distorted the results. Decision analyses: dependencies between variables not considered.

N/A: Cross-sectional surveys of a single group (i.e., surveys examining change over time or surveys comparing different groups should address the potential for confounding). Descriptive studies. Studies explicitly stating the analysis is strictly descriptive/ exploratory in nature.

13. *Results reported in sufficient detail?*

Yes: Results include major outcomes and all mentioned secondary outcomes.

Partial: Quantitative results reported only for some outcomes. Or difficult to assess as study question/objective not fully described (and is not made clear in the methods section), but results seem appropriate.

No: Quantitative results are reported for a subsample only, or "n" changes continually across the denominator (e.g., reported proportions do not account for the entire study sample, but are reported only for those with complete data -- i.e., the category of "unknown" is not used where needed). Or results for some major or mentioned secondary outcomes are only qualitatively reported when quantitative reporting would have been possible (e.g., results include vague comments such as "more likely" without quantitative report of actual numbers).

N/A: Should not be checked for this question.

14. Do the results support the conclusions?

Yes: All the conclusions are supported by the data (even if analysis was inappropriate). Conclusions are based on all results relevant to the study question, negative as well as positive ones (e.g., they aren't based on the sole significant finding while ignoring the negative results). Part of the conclusions may expand beyond the results, if made in addition to rather than instead of those strictly supported by data, and if including indicators of their interpretative nature (e.g., "suggesting," "possibly").

Partial: Some of the major conclusions are supported by the data, some are not. Or speculative interpretations are not indicated as such. Or low (or unreported) response rates call into question the validity of generalizing the results to the target population of interest (i.e., the population defined by the sampling frame/ strategy).

No: None or a very small minority of the major conclusions are supported by the data. Or negative findings clearly due to low power are reported as definitive evidence against the alternate hypothesis. Or conclusions are missing. Or extremely low response rates invalidate generalizing the results to the target population of interest (i.e., the population defined by the sampling frame/ strategy).

N/A: Should not be checked for this question.

Appendix A.IV The template used to extract data about the study aims, sample, and methods from the studies included in the systematic review (Chapter 3)

DATA EXTRACTION TEMPLATE

Studies investigating the effect of the saddle on the horse's back biomechanics				
Study	Study aim(s)	Study sample	Outcome measure(s)	Measurement tool(s)
Author(s) and date	*As described in the study*	*Horses: n°, age, breed(s), discipline(s), training level(s); Riders: n°, body mass, riding level(s); Saddle: fit*	*Any outcome related to saddle pressure magnitudes or the horse's back kinematics and a description of the study conditions they were measured in*	*Tool(s) used to collect the saddle pressure measurements or measurements of the horse's back kinematic*
Studies investigating the effect of the rider on the horse's back biomechanics				
Study	Study aim(s)	Study sample	Outcome measure(s)	Measurement tool(s)
Author(s) and date	*As described in the study*	*Horses: n°, age, breed(s), discipline(s), training level(s); Riders: n°, body mass, riding level(s); Saddle: fit*	*Any outcome related to saddle pressure magnitudes or the horse's back kinematics and a description of the study conditions they were measured in*	*Tool(s) used to collect the saddle pressure measurements or measurements of the horse's back kinematic*

Appendix A.V The clinical conditions of the study horses from the studies included in the systematic review (Chapter 3)

THE CLINICAL CONDITIONS OF THE STUDY HORSES, AS DESCRIBED IN THE STUDIES INCLUDED IN THE SYSTEMATIC REVIEW.

Author(s)	The clinical condition of the study horses
Belock et al (2012)	Sound with lameness grade <1/5 on the American Association of Equine Practitioners lameness scale
Bogisch et al (2014)	Free from lameness or pain or dysfunction of the back based on a thorough clinical examination by an experienced clinician
Byström et al (2010)	NC
Byström et al (2020a)	Free from lameness, pain or dysfunction of the limbs and back, checked by a veterinarian
Clayton et al (2013)	<1/5 on AAEP lameness scale when evaluated by a veterinarian, no signs of pain/ sensitivity in response to back palpation
Clayton, O'Connor and Kaiser (2014)	<1/5 on AAEP lameness scale when evaluated by a veterinarian
De Cocq, van Weeren and Back (2004)	Clinically sound, had no apparent back problems
De Cocq et al (2009a)	Clinically sound, had no apparent back problems
Dittmann et al (2021)	Owner-sound
Dyson et al (2019)	Absence of lameness grade >1/8 (Dyson 2011) based on evaluation by a Veterinary Surgeons Specialist in Equine Orthopaedics
Egenvall et al (2019)	Clinically sound
Fruehwirth et al (2004)	Without clinical signs of back pain or lameness
Gunst et al (2019)	Eight sound horses, 45 horses with grade 1 and 41 horses with grade 2 gait asymmetries in one or more legs, horses with grade 3 gait asymmetries were excluded
Harman (1994)	NC
Heim et al (2016)	Free of any clinical evidence of back pain and lameness
Kotschwar, Baltacis and Peham (2010a)	Sound based on a routine orthopaedic and back examination
Kotschwar, Baltacis and Peham (2010b)	Sound and without clinical signs of back pain based on a routine orthopaedic examination

Lagarde et al (2005)	NC
Licka, Kapaun and Peham (2004)	NC
MacKechni-Guire et al (2018)	Sound based on a full lameness evaluation by two veterinary surgeons
MacKechnie-Guire et al (2019)	No lameness based on veterinary evaluation
MacKechnie-Guire et al (2020b)	No lameness based on a veterinary evaluation, good muscle definition and well-defined musculature of the thoracolumbar region
MacKechnie-Guire, Fisher and Pfau (2020)	No overt signs of lameness were observed, well-defined epaxial musculature
MacKechnie-Guire and Pfau (2021a)	No overt signs of lameness were observed, well-defined epaxial musculature
MacKechnie-Guire and Pfau (2021b)	No lameness based on a veterinary evaluation, epaxial hypertonicity and pain were assessed
MacKechnie-Guire et al (2021)	No lameness based on a veterinary evaluation
Martin et al (2015)	No overt signs of lameness or back discomfort/conditions were observed
Martin et al (2016)	No clinical signs of back problems or lameness
Martin et al (2017a)	No clinical signs of back problems or lameness
Martin et al (2017b)	Clinically sound
Meschan et al (2007)	No clinical signs of back problems or lameness
Murray et al (2017)	No clinical signs of back problems or lameness
Peham et al (2004)	No clinical signs of back problems or lameness
Peham et al (2009)	Fit and without lameness based on a regular program of veterinary management and physiotherapy
Persson-Sjodin et al (2018)	Not been treated for lameness for the six months preceding data collection and considered free from lameness according to their owner
Roepstorff et al (2009)	Free from lameness or pain or dysfunction of the back based on a thorough clinical examination by an experienced clinician
Roost et al (2019)	No forelimb lameness or hindlimb lameness > grade 1/8, assessed by a Royal College of Veterinary Surgeons Specialist in Equine Orthopaedics with the horses in-hand at walk and trot and ridden by their normal rider in walk and trot
Von Peinen et al (2010)	Sound based on a routine orthopaedic and back examination

NC = not clarified; AAEP = American association of equine practitioners.

Appendix A.VI Details of the trials collected (Chapter 4B)

DETAILS OF THE COLLECTED NUMBER OF STRIDES, SPEED, AND MEAN (±STANDARD DEVIATION) STRIDE TIME FOR EACH HORSE AT EACH GAIT.

	N° of strides	Speed (m/s)	Stride time (ms)
Walk			
Horse1	28	1.4	1192 (±35)
Horse2	17	1.4	1272 (±59)
Horse3	17	1.4	1299 (±53)
Horse4	24	1.4	1135 (±20)
Horse5	23	1.4	1228 (±23)
Horse6	17	1.4	1279 (±52)
Trot			
Horse1	21	3.0	729 (±6)
Horse2	35	3.4	792 (±7)
Horse3	28	3.4	764 (±18)
Horse4	37	3.1	735 (±11)
Horse5	29	3.4	755 (±12)
Horse6	29	3.2	828 (±13)

Appendix B. MatLab scripts used for Chapter 4B

Appendix B.1 MatLab script for the synchronisation of the time series collected with optical motion capture and inertial measurement units

```
% omc = time series collected with optical motion capture
% imu = time series collected with the inertial measurement units

function [omc, imu] = sync(omc, imu)

%% plot time series before sync
figure
plot(imu.LTCvelZ)
hold on
plot(omc.LTCvelZ)
title('Not synchronised', 'FontSize', 16)
xlabel('Time (s)', 'FontSize', 16)
ylabel('LTC vertical velocity (m/s)', 'FontSize', 16)
legend('imu', 'omc', 'FontSize', 16)

%% find lag between time series and correct length of time series for lag
[r, lag] = xcorr(imu.LTCvelZ, omc.LTCvelZ);
maximum = max(r);
r = r/maximum; % normalize the data
[~, index] = max(r);
t = lag(index);

figure
plot(lag, r, [t t], [-0.5 1], 'r:')
text(t+100, 0.5, ['Lag: ' int2str(t)])
ylabel("Cross correlation")
axis tight

if t<0
    omc(1:abs(t),:) = [];
end
if t>0
    imu(1:abs(t),:) = [];
end

if length(omc.Time)<length(imu.time)
    endindex = find(omc.Time==omc.Time(end));
    imu((endindex+1):end,:) = [];
end
if length(omc.Time)>length(imu.time)
    endindex = find(imu.time==imu.time(end));
    omc((endindex+1):end,:) = [];
end

%% Quality check - plot time series after synchronisation
figure
plot(LTC.velZ)
hold on
plot(omc.LTCvelZ)
title('Synchronised', 'FontSize', 16)
xlabel('Time (s)', 'FontSize', 16)
ylabel('LTC vertical velocity (m/s)', 'FontSize', 16)
legend('imu', 'omc', 'FontSize', 16)
```

Appendix B.2 MatLab script for splitting the time series, collected with optical motion capture and inertial measurements units, into strides

```
% This function splits the time series into strides based on the vertical position
of the left and right tuber coxae (LTC and RTC).

function [strides] = stridesplit(omc, imu)

%% Identify mid-stance phases (i.e. peaks at walk, troughs at trot)
promptMessage = sprintf('is this capture at trot?');
titleBarCaption = 'Gait?';
button = questdlg(promptMessage, titleBarCaption, 'Yes', 'No', 'Yes');
if strcmpi(button, 'Yes')
    imuLTCZ = -imu.LTCZ; %turn the troughs into peaks
    imuRTCZ = -imu.RTCZ;
end

if strcmpi(button, 'No')
    imuLTCZ = imu.LTCZ;
    imuRTCZ = imu.RTCZ;
end

[peakLTC,ind] = findpeaks(imuLTCZ, 'minpeakdistance', 25);
[peakRTC,~] = findpeaks(imuRTCZ, 'minpeakdistance', 25);

for t = 1:length(ind)-1
    if peakLTC(t) > peakRTC(t)
    ind1(t) = ind(t);
    end
end
ind1(ind1==0) = [];

% Quality control 1: evaluate if the peaks are identified correctly
figure
plot(imuLTCZ)
hold on
for k = 1:length(ind1)
    xline(ind1(k))
end
title('vertical position of LTC')

promptMessage = sprintf('Do lines align with peak vertical position?');
titleBarCaption = 'Quality Check 1?';
button = questdlg(promptMessage, titleBarCaption, 'Yes', 'No', 'Yes');
if strcmpi(button, 'Yes')
   ind = ind1;
end

if strcmpi(button, 'No')
   t = 1:length(ind);
   even = rem(t, 2) == 0;
   uneven = rem(t, 2) ~= 0;
   if peakLTC(2) > peakLTC(1)
      ind(uneven) = [];
   end
   if peakLTC(2) < peakLTC(1)
      ind(even) = [];
   end
```

```
    % Quality control 2: evaluate if the peaks are identified correctly this time
    figure
    plot(omcLTCZ)
    hold on
    for k = 1:length(ind)
        xline(ind(k))
    end
    title('vertical position of LTC')

    %% Quality control 2
    promptMessage = sprintf('Do lines align with peak vertical position?');
    titleBarCaption = 'Quality Check 2?';
    button = questdlg(promptMessage, titleBarCaption, 'Yes', 'No', 'Yes');

    if strcmpi(button, 'Yes')
    end

    while strcmpi(button, 'No')
        promptMessage = sprintf('Select peaks manually');
        figure
        plot(omcLTCZ, 'b')
        hold on
        prompt = {'Number of Peaks'};
        dlgtitle = 'Input';
        dims = [1 35];
        pks = inputdlg(prompt,dlgtitle,dims);
        pks = str2double(pks);
        y = floor(ginput(pks));
        ind = y(:,1);
    end
end

for k = 1:length(ind)
    stance(k) = ind(k);
end

% chop the parameters of interest into strides (e.g. omc.T5X)
strides = struct;

for i = 1:numel(stance)-1
    strides.omcT5X{i} = omc.T5X(stance(i):stance(i+1));
    % and same for all the other parameters of interest
end

strides.omcT5X = strides.omcT5X';
% and same for all the other parameters of interest

end
```

Appendix B.3 MatLab script for estimating the position of the inertial measurement units according to the hybrid optical-inertial motion capture approach

```
%% this function estimates the position of the inertial measurement units (IMUs)
using 1) the average XYZ coordinates of the hemispherical markers placed on the
IMUs throughout the first full stride collected with optical motion capture (omc)
and 2) the XYZ displacement time series collected with the IMUs


% in this example, the position is estimated of an IMU affixed to the anatomical
landmark of T5


hybrid.T5X = mean(strides.omcT5X{1, 1}) + imu.T5X*1000; % data from IMUs is in m
hybrid.T5Y = mean(strides.omcT5Y{1, 1}) + imu.T5Y*1000;
hybrid.T5Z = mean(strides.omcT5Z{1, 1}) + imu.T5Z*1000;
```

Appendix B.4 MatLab script for the calculation of flexion-extension and lateral bending displacements

```
%% this function calculates the flexion-extension (FlExt) and lateral bending (LB)
%displacements at T10, T13, and T18 and using the XYZ coordinates of %markers/
IMUs placed on the horse’s back, collected with optical motion capture %(omc) and
the hybrid optical-inertial motion capture approach (hybrid)

function [angdisp] = angulardisplacements(omc, hybrid)


% calculate the craniocaudal distance (cc) to quantify FlExt in the sagittal plane
ccT5L2omc = sqrt(((omc.T5X-omc.L2X).^2) + ((omc.T5Y-omc.L2Y).^2));
ccT13S3omc = sqrt(((omc.T13X-omc.S3X).^2) + ((omc.T13Y-omc.S3Y).^2));

angdisp.FlExtT13omc = rad2deg(atan((omc.L2Z-omc.T5Z) ./ abs(ccT5L2omc)));
angdisp.LBT13omc = rad2deg(atan((omc.L2Y-omc.T5Y) ./ abs(omc.L2X-omc.T5X)));
angdisp.FlExtL2omc = rad2deg(atan((omc.sacrumZ-omc.T13Z) ./ abs(ccT13sacrumomc)));
angdisp.LBL2omc = rad2deg(atan((omc.sacrumY-omc.T13Y) ./ abs(omc.sacrumX-
omc.T13X)));

ccT5L2hybrid = sqrt(((hybrid.T5X-hybrid.L2X).^2) + ((hybrid.T5Y-hybrid.L2Y).^2));
ccT13sacrumhybrid = sqrt(((hybrid.T13X-hybrid.sacrumX).^2) + ((hybrid.T13Y-
hybrid.sacrumY).^2));

angdisp.FlExtT13hybrid = rad2deg(atan((hybrid.L2Z-hybrid.T5Z) ./
abs(ccT5L2hybrid)));
angdisp.LBT13hybrid = rad2deg(atan((hybrid.L2Y-hybrid.T5Y) ./
abs(hybrid.L2X-hybrid.T5X)));
angdisp.FlExtL2hybrid = rad2deg(atan((hybrid.sacrumZ-hybrid.T13Z) ./
abs(ccT13sacrumhybrid)));
angdisp.LBL2hybrid = rad2deg(atan((hybrid.sacrumY-hybrid.T13Y) ./
abs(hybrid.sacrumX-hybrid.T13X)));
```

Appendix B.5 MatLab script for time normalizing the angular displacements

```
%% time normalizing the parameter of interest
y = 0:100;
for k = 1:length(y)
    for i = 1:length(parameter)
        t = linspace(0, 100, length(parameter{i,1}));
        normalised{i,1} = spline(t, parameter{i,1}, y);
        normalised{i,1} = normalised{i,1}';
    end
end
```

Appendix C. MatLab scripts used for Chapter 5B

Appendix C.1 MatLab script for plotting the horse's back alignment

```
%% this code plots the back alignment of the study horses when standing %without
and with saddle and rider (SR)
%this code requires a struct called 'horses' with the coordinates of all back
%markers for all horses (n=19) included and organised per study condition

for i = 1:19
    fns = fieldnames(horses);
    H = horses.(fns{i});

    cc1withoutSR(i) = sqrt(((H.withoutSR.T6X - H.withoutSR.L1X).^2) +
    ((H.withoutSR.T6Y - H.withoutSR.L1Y).^2))/1000; %/1000 to be plotted in meters
    cc2withoutSR(i) = sqrt(((H.withoutSR.L1X - H.withoutSR.L3X).^2) +
    ((H.withoutSR.L1Y - H.withoutSR.L3Y).^2))/1000;
    cc3withoutSR(i) = sqrt(((H.withoutSR.L3X - H.withoutSR.L5X).^2) +
    ((H.withoutSR.L3Y - H.withoutSR.L5Y).^2))/1000;
    cc4withoutSR(i) = sqrt(((H.withoutSR.L3X - H.withoutSR.L5X).^2) +
    ((H.withoutSR.L3Y - H.withoutSR.L5Y).^2))/1000;

    cc1withSR(i) = sqrt(((H.withSR.T6X - H.withSR.L1X).^2) + ((H.withSR.T6Y -
    H.withSR.L1Y).^2))/1000; %/1000 to be plotted in meters
    cc2withSR(i) = sqrt(((H.withSR.L1X - H.withSR.L3X).^2) + ((H.withSR.L1Y -
    H.withSR.L3Y).^2))/1000;
    cc3withSR(i) = sqrt(((H.withSR.L3X - H.withSR.L5X).^2) + ((H.withSR.L3Y -
    H.withSR.L5Y).^2))/1000;
    cc4withSR(i) = sqrt(((H.withSR.L3X - H.withSR.L5X).^2) + ((H.withSR.L3Y -
    H.withSR.L5Y).^2))/1000;

    z0withoutRS(i,:) = H.withoutSR.T6Z/1000;
    z1withoutRS(i,:) = H.withoutSR.L1Z/1000;
    z2withoutRS(i,:) = H.withoutSR.L3Z/1000;
    z3withoutRS(i,:) = H.withoutSR.L5Z/1000;
    z4withoutRS(i,:) = H.withoutSR.S3Z/1000;

    z0withRS(i,:) = H.withSR.T6Z/1000;
    z1withRS(i,:) = H.withSR.L1Z/1000;
    z2withRS(i,:) = H.withSR.L3Z/1000;
    z3withRS(i,:) = H.withSR.L5Z/1000;
    z4withRS(i,:) = H.withSR.S3Z/1000;
end

% plot
% average position of back markers in sagittal plane without and with SR
cc0 = 0; % craniocaudal position T6
cc1 = abs(mean(cc1withoutSR))/1000; % craniocaudal position L1
cc2 = abs(mean(cc2withoutSR))/1000; % craniocaudal position L3
cc3 = abs(mean(cc3withoutSR))/1000; % craniocaudal position L5
cc4 = abs(mean(cc4withoutSR))/1000; % craniocaudal position S3

z0 = abs(mean(z0withoutSR))/1000; % vertical position T6
z1 = abs(mean(z1withoutSR))/1000; % vertical position L1
z2 = abs(mean(z2withoutSR))/1000; % vertical position L3
z3 = abs(mean(z3withoutSR))/1000; % vertical position L5
z4 = abs(mean(z4withoutSR))/1000; % vertical position S3

withoutSRalignmentCC = [cc0 cc1 cc2 cc3 cc4];
```

```
withoutSRalignmentZ = [z0 z1 z2 z3 z4];

cc0 = 0;
cc1 = abs(mean(cc1withSR))/1000;
cc2 = abs(mean(cc2withSR))/1000;
cc3 = abs(mean(cc3withSR))/1000;
cc4 = abs(mean(cc4withSR))/1000;

z0 = abs(mean(z0withSR))/1000;
z1 = abs(mean(z1withSR))/1000;
z2 = abs(mean(z2withSR))/1000;
z3 = abs(mean(z3withSR))/1000;
z4 = abs(mean(z4withSR))/1000;

withSRalignmentCC = [cc0 cc1 cc2 cc3 cc4]';
withSRalignmentZ = [z0 z1 z2 z3 z4]';

zwithoutSR = [z0withoutSR, z1withoutSR, z2withoutSR, z3withoutSR, z4withoutSR];
zwithSR = [z0withSR, z1withSR, z2withSR, z3withSR, z4withSR];

figure
scatter(withoutSRalignmentCC, zwithoutSR, "filled")
hold on
scatter(withSRalignmentCC, zwithSR)

text(withSRalignmentCC(1), withoutSRalignmentZ(1)+60, 'T6Z')
text(withSRalignmentCC(2), withoutSRalignmentZ(2)+60, 'L1Z')
text(withSRalignmentCC(3), withoutSRalignmentZ(3)+60, 'L3Z')
text(withSRalignmentCC(4), withoutSRalignmentZ(4)+60, 'L5Z')
text(withSRalignmentCC(5), withoutSRalignmentZ(5)+60, 'S3Z')

axis equal
xlim([0-0.05 x4+0.05])
ylim([1.45 1.85])
xlabel('Craniocaudal position (m)', 'FontSize', 14, 'Position', [x1-0.05 1.4])
ylabel('Vertical position (m)', 'FontSize', 14)

title('Back alignment', 'FontSize', 14)
```

Appendix D. Supportive learning experiences

Appendix D.1 Postgraduate learning credits

1. Accredited learning

UWE approved my application for the accredited learning 60-credit M-module ‘Postgraduate Dissertation’ (HANVL5-60-7), which I completed at Hartpury University in 2020, against the UWE 60-credit M-module ‘Postgraduate Dissertation’ (UINVL5-60-M) as part of my 60 M-level credits requirements.

2. MSc module ‘Applied motor control and motor learning for Strengthening and Conditioning’

While the 60 M-level credits requirement was fulfilled by means of the accredited learning, I chose to attend the 15-credit M-module ‘Applied motor control and motor learning for Strengthening and Conditioning’ at Hartpury University. I attended this module between February ’21 and May ’21. The module provided me with a more thorough understanding of motor control and motor learning in athletic settings.

Appendix D.2 CPD hours

The CPD hours I gathered throughout my time as a PhD-student facilitated remaining on top of current knowledge and advances in research fields relevant to those discussed in this thesis and implementing up-to-date research methodologies in this thesis. The events also provided me with the opportunity to connect with experts within those field and to build my profile as a researcher within the industry.

1. AdvanceHE course 'New to digital teaching' (October 2020)
2. CentaurBiomechanics 'International Equine Sports Science Virtual Summit' (October 3, 2020)
3. Hartpury's Equine Research Seminar (November 25th, 2020)
4. CentaurBiomechanics Webinar 'Clinical Biomechanics of the Thoracolumbar Region', by Dr Kevin Haussler (February 7, 2021)
5. ISBS Symposium (February, 2021)
6. CentaurBiomechanics Webinar 'Motor-Control Based Rehabilitation for Equine Spinal Dysfunction', by Dr Nicole Rombach (February 20, 2021)
7. TMLS workshop 'human and animal movement: where do stereotype end and variability start?' (March 18, 2021)
8. CentaurBiomechanics Webinar 'A Strong, Healthy Back: The Foundation of a Successful Sport Horse', by Dr Hilary Clayton (March 21, 2021)
9. NEWC workshop 'welfare of the equine athlete' (March 30, 2021)
10. Horses inside out workshop 'myofascial chains in horses', by Vibeke Elbrond (April 12, 2021)
11. CentaurBiomechanics Webinar 'Biomechanics of the Equine Back with and without a Rider', by Dr Russell MacKechnie-Guire (April 29, 2021)
12. UWE Thesis Bootcamp (May 28-30, 2021)
13. Hartpury Research Conference (July 2021)
14. CentaurBiomechanics Webinar 'Evidence-Based Saddle Fit: Linking Evidence-Based Saddle Fit to Practical Saddle Fit', by Dr Russell MacKechnie-Guire (July 18, 2021)
15. ISBS Mid-Year Symposium (February, 2022)
16. ICEEP Conference at Uppsala (June 2022)
17. Hartpury Research Conference (July 2022)
18. Multidisciplinar discussion night 'Sporthorse Management', at SMDC (March 15, 2023)
19. Health, Science and Society Postgraduate Research Conference at Bristol (June 2023)
20. Laterality workshop, by the International Task Force on Laterality in Sport Horses (August, 2023)
21. ICEL Conference at Utrecht (August, 2023)
22. Workshop 'How to publish your manuscript with Wiley', by Mary Helen Yount (November 7, 2023)
23. Multidisciplinar discussion night 'Neck problems in the horse', at SMDC (November 15, 2023)

Appendix D.3 Additional learning experiences

There have been a number of other learning experiences throughout my time as a PhD-student at Hartpury University which have helped me developing as a researcher and academic, including:

1. Presenting the progress of my thesis at the Hartpury Research Conferences (2020-2022)
2. Presenting the publication of my MSc thesis “Assessing the sport-specific and functional characteristics of back pain in horse riders” at Hartpury’s Equine Research seminar (2021)
3. Invited talk at the ISBS Mid-Year Symposium about “Horses for courses: the challenges and future directions of measuring horses and riders in motion”, together with Dr Celeste Wilkins (2022)
4. Presenting my thesis study “The effect of a saddle on the kinematics of the thoracolumbosacral spine at walk and trot in-hand” at the ICEL Conference (Uppsala, 2022)
5. Presenting the progress/ summary of my thesis at the Health, Science and Society PGR Conference (Bristol, 2023)
6. Teaching UGR and PGR students at Hartpury University (2020-2023). The modules I taught on and supported workshops for included:
    - Research club (UGR + PGR)
    - Equine Therapy in Practice (UGR)
    - Equine Functional Anatomy (UGR)
    - Horse and Rider Performance (UGR)
    - Undergraduate Research Process (UGR)
    - Equine Therapy and Rehabilitation (UGR)
    - The Principles of Assessing Animal Performance (UGR)
    - Understanding Veterinary Diagnostics and Physiotherapeutic Assessments (PGR)
7. Supervising Undergraduate Dissertation students at Hartpury University (2022-2023)
    - ‘Functional Asymmetry in the Performance Horse: Wither and Pelvic movement In-Hand, Free- Ridden and Working Posture at trot’
    - ‘Functional impact of dynamic mobilization exercises on the equine thoracic static profile’
    - ’A comparison between the effects of ‘A framed’ and ‘n framed’ saddles on equine thoracolumbosacral kinematics’
8. Supporting veterinary gait analyses with the Three Counties Equine Hospital at Hartpury University with the EquiGait© system, including writing up EquiGait reports (2022-2023)
9. Supporting a filming day with the Operation Ouch-Team at Hartpury University, including the set-up of the optical motion cameras for a full-body capture of a jockey on the racing simulator (2021)
10. Participating and winning the XSens Biomechanics Challenge, together with my supervisor Dr Celeste Wilkins and colleague Amelia Dingley (2021)

Appendix E. Published abstracts

Appendix E.1 Mediolateral hock motion: relationship with pelvic symmetry and hindlimb muscle development

Maddock, C.[1], Tabor, G.[1], Deckers, I.[1], Murray, R.[2], Walker, V.[1]

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Excessive mediolateral (ML) hock range of motion (ROM) has been linked to pathology or hindlimb muscle weakness. The study aimed to investigate the relationship between ML hock ROM, muscle development (MD) and pelvic symmetry (PS) at walk and trot in competition horses. Twelve horses (13±4 years) with no known history of hock pathology walked (1.5±0.1 m/s) and trotted (3.2±0.1 m/s) on a high-speed treadmill. Optical motion capture (240 Hz) determined ML hock ROM in walk and trot via a caudal calcaneus marker. PS was calculated via min diff/max diff of tubera sacrale. An ACPAT physiotherapist assigned MD scores for *gluteus medius* (GM)/*biceps femoris* (BF)/*semitendinosus* (ST)/*semimembranosus* (SM) and *gracilis* (GR) (muscle scores obtained for eleven horses). A paired t-test compared ML hock ROM between walk and trot. Pearson's/Spearman's tested for associations between ML hock ROM, PS and MD scores ($p<0.05$). A lower BF MD score was associated with greater ML ROM of the contralateral hock in walk (left: $p=0.037$/right: $p=0.038$). For right hock, lower MD scores for left ST ($p=0.020$) and SM ($p=0.033$) were associated with increased ML hock ROM but no differences were seen for left hock ($p>0.05$). No relationships were significant in trot ($p>0.05$). Hock ML ROM was not associated with PS but may indicate less contralateral hamstring MD. ML hock ROM is greater in walk than trot, therefore walk appears to be preferable for assessing ML hock ROM, when using calcaneus as a reference point.

Appendix E.2 Quantifying back movement during sternal and croup reflexes using mounted inertial measurements unit

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Sternal and croup reflexes are used in practice as a therapeutic intervention and assessment tool. Quantification of these reflexes to evaluate movement patterns between back regions and support their application within rehabilitation programmes. The aim was to quantify pitch range of motion (ROM) and direction (positive/nose-up or negative/nose down) of the thoracolumbosacral (TLS) region during a sternal/croup reflex (SR/CR). Twelve horses (11±5.6 years) were recruited with no known clinical history of back injury/dysfunction. Skin mounted inertial measurement units (100 Hz) were placed at thoracic(T)6, T13, Lumbar(L)2, Sacral(S)3 vertebrae. Horses halted square on a flat surface with a neutral head and neck position. A chartered physiotherapist carried out all SR and CR with three repeats. One complete reflex per horse were included in the analysis. TLS pitch ROM for SR and CR were analysed using paired t-tests (significance set at $p<0.05$). At T6, pitch ROM was greater during SR (6.53±2.8°) compared to CR (4.01±2.7°; $p=0.022$). CR induced greater pitch ROM at T13 (SR: 2.63±1.3°; CR: 4.98±1.9°; $p=0.004$) and S3 (SR:1.91±0.8°; CR:7.89±2.3°; $p<0.001$) compared to SR. No differences at L2 (SR:3.87±2.1°; CR: 4.36±2.9°; $p\geq0.05$) were observed. SR induced positive pitch at T6 and negative pitch at T13, L2 and S3, but CR induced negative pitch at T6 and T13 and positive pitch at L2 and S3. TLS pitch is influenced differently by a SR and CR, with the SR having a greater influence on the cranial/mid-thoracic and CR on the caudal thoracic/lumbosacral spine. The findings have implications on exercise selection within rehabilitation programmes.

Appendix E.3 Assessing static postural types in sport horses

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Postural assessment, within equine physiotherapeutic assessment, provides information about clinical condition, however, evidence-based methods to identify horses' postural type are scarce. Horses' postural type (sway-backed, straight-backed, or S-backed) is associated with features such as spinal alignment, muscle balance and movement (dys)functions. This study aimed to develop an Equine Postural Assessment Tool (EPAT) and to evaluate its inter-rater agreement. An EPAT template, guidance document and video were developed to support evaluation of horses' static postural type based on 25 possible observations in six body zones. The EPAT was used to evaluate 21 sport horses' postural type based on sideview standing photographs. The inter-rater agreement for EPAT scores was evaluated between seven ACPAT Veterinary Physiotherapists (P1-P7) using Kappa-agreement coefficients. P2 and P3 received verbal training from P1 about how to score horses' postural type using the EPAT, after which the EPAT was updated with the complementary guidelines. P4-P7 received these guidelines only to score horses' postural type using the EPAT. Excellent agreement (average κ=0.893, p<0.001) were obtained between P1, P2, P3 scoring horses' postural types using the EPAT, whilst fair-to-good levels of agreement were found between all evaluators (P1-P7) (average κ=0.519, p<0.05). The EPAT was found reliable to evaluate horses' postural type from side-view standing photographs. The tool is a simple and promising tool to assess horses' static postural type, which could support practitioners in their clinical reasoning and decision making. Further research is warranted to establish the EPAT intra-rater reliability, reliability in live horses, and its association with horses' movement (dys)functions.

Appendix E.4 The effect of a saddle on the kinematics of the thoracolumbosacral spine at walk and trot in-hand

Deckers, I.[1], MacKechnie-Guire, R.[2], Fisher, M.[3], Fisher, D.[3], and Nankervis, K.[1]

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There have been significant advances in research investigating horse-saddle-rider interactions. However, evidence on the effect of a saddle without rider on the horses' spinal kinematics is limited. This study aimed to quantify the thoracolumbosacral kinematics with and without a saddle at walk and trot in-hand. Thoracolumbosacral kinematics of eight horses (10±4 years, 1.68±0.05 m) were quantified using eight inertial sensors (4.7×3.0×1.1 cm) placed on the head, T5, T13, T18, L3, TS, left/ right tuber coxae. Data were collected walking and trotting in-hand on a hard surface with/ without saddle. Saddle and girth fit were checked subjectively by qualified saddle fitters. Translational, rotational, and differential rotational ranges of motion (ROM) for each condition were analysed using paired t-tests. Stride time did not differ between conditions (P>0.05). At walk, T13 and T18-L3 yaw increased by 21% and 21% respectively and sacrum pitch by 4% in the saddle trials compared to the trials without, whilst T5 roll decreased by 18% and T5-T13 yaw by 22% (all P≤0.05). At trot, T13 pitch, T13-T18 and T18-L3 yaw increased by 20, 77, and 27% respectively in the saddle trials compared to the trials without, whilst T5 dorsoventral flexion, laterolateral flexion, and roll decreased by 5, 17, and 21% respectively (all P≤0.05). These findings suggest that a saddle without rider alters the horse's spinal kinematics at walk and trot in-hand, with an increased ROM in caudal thoracolumbosacral segments and decreased ROM in cranial thoracic segments. It is emphasised that the saddle plays a significant role in the horse-saddle interaction.

Appendix E.5 The effect of walking speed during water treadmill exercise on pelvic kinematics in racehorses

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There is little knowledge about the biomechanical responses of horses to speed at different water depths on the water treadmill (WT). This study aimed to determine whether belt speed was associated with alterations in equine pelvic kinematics at walk in four water depths. Six Thoroughbreds (5.8±0.4 yrs; 166.8±1.8 cm) non-lame and in regular WT exercise walked on the WT at 2.8/4.3/5.5/6.0 kph at dry, fetlock and carpal water depths. Inertial-motion-sensors on the left/right tuber coxae were used to measure left/ right pelvic vertical displacement (mm). Bivariable mixed effects linear regression analyses were used to determine the relationship between pelvic dorsoventral displacement and belt speed/ water depth. Tests at 6.0 kph in carpal depth water and for two horses in fetlock depth water were abandoned at onset in response to veterinary monitoring of the horses' behavioural and gait alterations at this speed. At speeds 2.8, 4.3, 5.5 and 6.0 km/h, LTC/RTC dorsoventral displacements for all water depths pooled increased significantly (p<0.0001/p<0.0001) and carpal depth water compared to dry (p<0.0001/p<0.0001) when all speeds were pooled. For all water depths pooled, pelvic dorsoventral displacements plateaued between 5.5 and 6 km/h, suggesting that at speeds ≥5.5 km/h, horses could be limited in their ability to lift the distal limb above the water, even in low water. In practice, this could be avoided by either limiting belt speed within a WT session, or decreasing belt speed in response to water depth increases.

Appendix E.6 Change in muscle development of horses undergoing 20 weeks of water treadmill exercise compared with control horses

Murray, R. C.[1], Hopkins, E.[2], Tacey, J. B.[2], Nankervis, K. J.[3], Deckers, I.[3], MacKechnie-Guire, R.[4], and Tranquille, C. A.[2]

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Background: Water treadmill (WT) exercise has recently become a popular tool for rehabilitation/training of horses. However, no studies describing long-term effects of WT exercise on muscle development (MD) exist.

Objectives: To describe changes in MD over a 20-week period in sports horses that use WT in their regular training regime and in control horses.

Study design: Observational study.

Methods: Forty-four horses (age: 11 ± 4 years) that use the WT weekly/fortnightly and 23 horses (age: 11 ± 4 years) that do not use WT were recruited, paired by breed and stage of training. All horses were deemed clinically sound. Subjective MD assessment of specific regions was undertaken using a previously published grading scale at weeks 0 and 20, including neck, cervical trapezius, thoracic trapezius, thoracic, lumbosacral, gluteal, hamstring, hindlimb adductor/abductor, abdominal musculature. MD assessments were carried out by an experienced veterinarian and a trained research assistant; inter and intra-observer repeatability was confirmed. Data from weeks 0 and 20 were compared using a Wilcoxon-Signed Ranks test, with a significance level $p<0.05$.

Results: After 20 weeks of WT, MD significantly increased at all locations ($p\leq0.046$) except the cervical trapezius and the abdominal region, with the most significant increase in the gluteal and hindlimb musculature ($p<0.0001$). In the control horses, after 20 weeks MD only significantly increased in the hamstring musculature ($p=0.007$).

Main limitations: Slightly higher proportion of dressage horses in the control group (75% vs 60%).

Conclusions: It appears regular WT exercise increases MD, particularly for musculature used to create movement patterns seen on the WT, increasing tarsal flexion. Less increased cervical trapezius/abdominal MD indicates WT exercise may be more beneficial for development hindlimb/lumbosacral musculature than elevation of the thorax, supporting clinical impression. WTs may be appropriate to be used under veterinary guidance as part of a directed rehabilitation/training programme to increase core and hindlimb muscle development.