BIOMECHANICS IN EQUINE REHABILITATION: A WEIGHT-REDUCTION SYSTEM AND MOVEMENT TRACKING DEVICE

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By

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ABSTRACT

Equine musculoskeletal conditions can be challenging to treat and career-ending or result in euthanasia in severe cases. Often it is the secondary complications (weight and immobility related) that develop while treating the initial injury that carries the poor prognosis. For this reason, many attempts have been made to reduce the horse's weight during recovery. This study aimed to design and test a chest support (breastplate) for use with a rehabilitation lift and test a movement tracking device for monitoring rehabilitation progress. By focusing on the horse's biomechanics, support can be directed to load-bearing structures, minimizing the risk of compromised breathing or restricted blood flow. Tracking movement could assist in early detection of changes in movement patterns that may be indicative of the onset of complications, such as supporting limb laminitis, in horses with ambulatory difficulties.

A breastplate was developed to facilitate front limb support, attempting to minimize the risk of complications, such as pressure ulcers. Design testing included strength tests (to 227 kg) for safety, fit tests to minimize discomfort, and weight compensation trials using a computer-controlled rehabilitation lift to reduce load. The goal was to reach a 50% weight reduction of the forelimbs. Weight reduction was incrementally increased, observing the horse's behaviour and respiratory rate, indicating discomfort and directing design modifications. A 50% weight reduction was achieved after a series of design iterations.

To aid in the objective assessment of movement of horses during stall confinement, a readily available motion sensor (inertial measurement unit = IMU) was tested. The IMU was placed at three different locations (withers, right forelimb, and hindlimb) to determine the best location to quantify step count when compared to a video-based step count criterion. Data was recorded in five-minute intervals for three movements (free movement, circles, and figure-eight). An intra-class correlation (ICC) analysis determined that the IMU placement on the limbs was the most accurate using the vertical axis to determine step count with the current algorithm, while the withers location was the least accurate. The movement analysis demonstrated the potential of a limb-mounted IMU to quantify movement during stall confinement.

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There are several contributions to the field of equine rehabilitation made in this dissertation. These are: (1) Initial development of a support system (one phase (breastplate) in a multi-phase research program – a computerized lift and harness) for the rehabilitation of horses with musculoskeletal injuries; (2) a system aimed at reducing pressure ulcer risk; and (3) suggested monitoring device for horses during stall confinement to reduce the risk of complications when horses have to be on stall rest.

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DEDICATION

This dissertation is dedicated to the memory of an extraordinary horse, Cash. The complications from a limb injury that resulted in him being taken too soon were my inspiration to pursue research in the field of equine rehabilitation and musculoskeletal injuries.

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LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AAEP	American Association of Equine Practitioners
AP	Anteroposterior
ARTS	Animal Rescue and Transportation Sling
ASAT	Aspartate Aminotransferase
ASPCA	American Society for the Prevention of Cruelty to Animals
BCS	Body Condition Score
bpm	Breathes Per Minute
C	Circles
CK	Creatine Kinase
COF	Coefficient of Friction
CPS	Composite Pain Scale
EARL	Equine Assisted Rehabilitation Lift
F8	Figure-eight
FM	Free Movement
HGS	Horse Grimace Scale
IMU	Inertial Measurement Unit
LAL	Large Animal Lift
ML	Mediolateral
MT	Movement Type
RF	Right Forelimb
RH	Right Hindlimb
ROM	Range of Motion
RR	Respiratory Rate
SADP	Suspensory Apparatus of the Distal Phalanx
SLL	Supporting Limb Laminitis
VL	Vertical
W	Withers
WCVM	Western College of Veterinary Medicine

CHAPTER 1 INTRODUCTION

This dissertation presents a study contributing to the development of a weight reduction system for use in equine rehabilitation. Contributions were made through the initial design and testing of an air-pressurized computer-controlled breastplate for front limb support in combination with a rehabilitation lift and harness previously developed. This dissertation further includes gait analysis (step count determination) during stall confinement to aid in objective monitoring of mobility in horses during stall rest. This chapter introduces the background and motivation of the dissertation research and describes the specific objectives. The organization of the dissertation will follow the background and objectives.

1.1. Background and motivation

In horses, severe limb injuries and other conditions resulting in ambulatory difficulties are challenging to manage. Complications such as supporting limb laminitis (SLL) can be career-ending or even lead to euthanasia. Effective and safe weight reduction through the provision of support around the horses' limbs could minimize the risk of SLL and other load and immobility associated complications. SLL is believed to be caused by increased load and decreased blood flow in the healthy limbs. The decreased blood flow has been suggested to be related to reduced mobility (Medina-Torres et al., 2016; Orsini, 2012; West, 2007) and overloading (van Eps et al., 2010; van Eps and Burns, 2019). Many researchers have tried to find a solution to supporting horses with impaired ambulation and painful limb injuries. However, no standard protocol currently exists, and none of the tested approaches are consistently successful (Steinke et al., 2019a). The biomechanics of the horse should be considered in the development of a support system that enables load reduction. Previously developed support devices, such as rescue slings, place significant pressure on the thorax and abdomen, which can result in compromised breathing, inhibition of blood flow, or tissue trauma (Montgomery et al., 2019; Steinke et al., 2019a). Many are also static devices that limit the horses' movement and can thereby lead to further complications, such as muscle atrophy, osteopenia and SLL (Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981). By focusing on the typical load-bearing structures of the horse, the weight can be applied to solid structures minimizing such risks. The ability to maintain normal movement while reducing load could help reduce the risk of SLL and other complications even further. Tracking of movement during rehabilitation could assist veterinarians in early detection of complications, such as laminitis. Therefore, a device that effectively and safely reduces the weight of the horse while allowing for controlled mobility, along with a movement tracking device, could have a significant impact on veterinary medicine, reducing complications and increasing success in treating challenging injuries.

In response to the pressing need for a device that can reduce the load while maintaining mobility for equine rehabilitation, a dynamic weight compensation lift has been developed and tested (Montgomery et al., 2019). A rehabilitation harness prototype has also been designed, but further design modifications and testing were needed. A need to objectively assess movement during stall confinement was also required. Quantitative tracking of movement during stall confinement could assist in the monitoring of mobility and rehabilitation progress. Such a device would allow for early detection of changes in movement, which can indicate complications, such as the development of SLL and provide vital information to direct rehabilitation protocols. An inertial measurement unit (IMU) can easily be attached to a limb or surcingle for equine gait analysis. An Apple Watch contains an IMU and can be synchronized with other devices allowing for a quick transfer of data and immediate analysis. Consequently, the ability of an IMU (mounted and compared in several different locations) to determine a valid step count was assessed by comparing it to a video-based criterion measure.

Both tools that will be described in this thesis could prove valuable for equine rehabilitation when the prognosis of the limb injury is very poor. Obtaining a successful 50% weight reduction through breastplate design and testing would provide a significant improvement over previous harness designs (tested in Steinke et al., 2019a) and weight reduction methods (e.g., rescue slings and forced recumbency). Prior studies by our research group (Montgomery et al., 2019) using the Anderson sling demonstrated the need to develop a new harness. Significant discomfort was displayed through aversion behaviours in these trials. The Anderson sling further affected the horses' breathing. Furthermore, horses learned to 'sit' in the sling, which affected their balance and the weight compensation ability of the lift. When the horses were able to ‘sit’ in the sling, they also transferred a significant amount of weight to the hindlimbs, which creates a potential risk of overloading. Other complications include spreading of the legs and resisting movement. The removal of the hindlimb harness component of the Anderson sling (to avoid ‘sitting’ in the sling) resulted in significant pressure being transferred to the chest. As increasing tension was applied during weight compensations, the chest piece of the Anderson sling rose, placing pressure on the neck, which could result in a restricted airway and blood flow in the neck. A new harness was needed to increase comfort for long-term use (up to six weeks).

1.2. Objectives and Scope

To achieve the overall objective of developing and testing tools to aid in the rehabilitation of horses with ambulatory difficulties, the following specific objectives were identified.

Objective 1: To test and modify the design of an air-pressurized computer-controlled breastplate for front limb support of the horse, to be used in combination with a dynamic weight compensation lift to reduce the weight supported by the horses’ legs by up to 50%. Design considerations included: (1) the horses' biomechanics related to solid support structures that normally bear weight, (2) blood vessels and nerves that could be damaged or inhibited by pressure, (3) tissue trauma that could develop with significant pressure applied to the skin and underlying tissue for a prolonged period of time (hours, days, weeks), (4) safety of the horse and handler in an emergency, (5) ease of application to the horse with limited personnel, (6) flexible and soft materials that permit movement with the horse and (7) the application of load over the largest surface area possible while avoiding the need for complete customization to each horse. This design project hypothesized that a front limb support device could be designed for use with the weight compensation lift, allowing for the removal of up to 50% of the front-end weight comfortably. Comfort was determined by observing behavioural changes and respiratory rate.

Objective 2: To test the use of an inertial measurement unit (IMU) for mobility assessment in horses during stall confinement. Testing included assessing the IMUs ability to reliably record the step count of horses during stall-confined movement by comparing it to a visually-based criterion measure (video). This objective included two sub-objectives: (2a) to determine IMU and video-based step counts for three different types of movements in a stall environment, and (2b) to determine the ideal IMU location by comparing three different locations with respect to accuracy, usability, and safety. The hypothesis was that an IMU could reliably (intraclass correlation >0.75) quantify equine step counts (lifting of the foot) during stall confinement.

The scope of this dissertation was to test and modify a harness design component (i.e., breastplate), with a focus on front limb support, that can be used for rehabilitation of horses with ambulatory difficulties. It also assessed the ability of a body-fixed sensor to monitor the rehabilitation progress effectively.

1.3. Organization of dissertation

This dissertation is composed of five chapters.

Chapter 1 introduces the research completed in this thesis, including the background and motivation for each study, followed by the objectives and scope.

Chapter 2 presents a literature review on why weight reduction is important and the background on weight reduction methods and devices used previously, as well as the difficulties in rehabilitating horses with a compromised musculoskeletal system. This chapter also discusses physiological measures and behavioural monitoring for observing behaviours that may indicate discomfort. The discomfort of the musculoskeletal system is frequently shown through reduced movement. Therefore, biomechanical tools that have been used in research with horses to analyze movement are discussed, as well as the applicability to the assessment of movement in a small space. Then important considerations for the rehabilitation of horses while they are confined to a stall are reviewed.

Chapter 3 presents the design process and testing of an air-pressurized computer-controlled breastplate to be used in combination with a dynamic weight compensation lift for equine rehabilitation. Testing included safety testing to ensure the strength of the material to support the horse's weight, in addition to comfort and fit testing. The weight compensation trials involved design modifications to ensure comfort and safety of the horse and its handlers for up to 50% weight reduction in the front limbs (150 kg in a 500 kg horse) in preparation for long-term testing. This stepwise process is described in detail.

Chapter 4 presents step count quantification for monitoring movement during stall confinement. Three IMUs were used to test accuracy in healthy horses and determine the optimal

IMU location for the most accurate step count when compared to a visually-based step count criterion obtained through video recordings.

Chapter 5 presents a discussion and interpretation of the results and conclusions drawn from those results, summarizing the contributions of the dissertation, and recommendations for future research work.

The weight reduction methods and initial lift and harness development content in Chapter 2 has also been presented in the following peer-reviewed publications:

Steinke, S.L., Carmalt, J.L., Montgomery, J.B., 2019b. Weight reduction and possible implications for the rehabilitation of horses with ambulatory difficulties. Equine Vet. Educ. 1-7 (Published as early view). https://doi.org/10.1111/eve.13210

Montgomery, J.B., Steinke, S.L., Williams, A.C., Belgrave, L.J., 2019. Initial testing of a computer-integrated weight compensation system for rehabilitation of horses. Comp. Exerc. Physiol. 15, 379–384. https://doi.org/10.3920/CEP180060

Steinke, S.L., Belgrave, L.J., Montgomery, J.B., 2019a. Development of a novel harness system to aid in rehabilitation of horses. Comp. Exerc. Physiol. 15, 385–391. https://doi.org/https://doi.org/10.3920/CEP180062

CHAPTER 2 LITERATURE REVIEW

2.1. Introduction

In horses, severe limb injuries resulting in ambulatory difficulties are challenging to manage. They can result in complications, such as supporting limb laminitis (SLL), which may lead to euthanasia. Effective weight reduction on the horses' limbs while maintaining mobility could minimize the risk of developing SLL. SLL is believed to be caused by excessive load and decreased blood flow in the healthy limbs. The decreased blood flow has been suggested to be related to mobility (cyclic loading and unloading of the limbs (Medina-Torres et al., 2016; Orsini, 2012; West, 2007)), as well as overloading (van Eps et al., 2010; van Eps and Burns, 2019). Due to the high mortality rate of SLL (reported to be 50-75% (Gardner et al., 2017)) and the challenging treatment of fractures with SLL development, this thesis will focus on the secondary complications during recovery from fractures. The author was involved with the project prior to this Master's thesis as a research assistant and completed an honours project designing the initial testable full-body harness with a significant weight reduction (46%), improvements in materials, and usability (Steinke et al., 2019a). Previously published papers describe the initial testing of the rehabilitation lift with the Anderson sling (Montgomery et al., 2019) and the initial development of the harness (Steinke et al., 2019a). Both were completed before this Master's thesis began.

Many equine veterinarians and researchers have tried to find a solution to the complicated nature of treating injuries and other diseases affecting ambulation in horses. However, no standard protocol has been developed, and none of the reported load-reduction techniques are consistently successful (Steinke et al., 2019a). Frequently, other complications develop and further exacerbate the problem (e.g., muscle atrophy or wasting, osteopenia, tissue trauma, respiratory compromise, aversion behaviour) (Gimenez et al., 2008; Hutchins et al., 1987; Ishihara et al., 2006a, 2006b; McClintock et al., 1987; Montgomery et al., 2019; Smith, 1981). To improve the development of load-reduction systems for horses, the biomechanics of the horse should be considered. The focus should be directed to load-bearing structures (e.g., bones) and away from moving structures (i.e., the abdomen during breathing) and tissues that are more prone to damage (e.g., blood vessels, nerves, muscles). Previously developed support devices, such as rescue slings, support the horse under its mid-section and place significant pressure on the thorax and abdomen, which can result in compromised breathing, inhibition of blood flow or tissue trauma (Montgomery et al., 2019; Steinke et al., 2019a). Many are also static devices that limit the horse's movement and can thereby further lead to immobility induced complications, such as SLL, muscle wasting and osteopenia. Flotation tanks using buoyancy to achieve load reduction and reduce complications associated with overloading limbs have been used with some success (Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981). Furthermore, laminitis was not observed in the flotation tank recoveries. Horses recovered successfully, but other complications were observed (e.g., muscle wasting, osteopenia, hair loss). They were believed to be the result of too much weight being removed from the limbs and constant submersion in water (Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981).

There is a pressing need for a device to reduce the load on the limbs while maintaining mobility for the rehabilitation of horses. Such a device has the potential to significantly decrease the risk of complications and increase the chance of successful recovery from limb injuries. It would provide horses that are currently euthanized immediately at the site of a tragic event a second chance and would also help horses that need extra support. A dynamic weight compensation lift (Equine Assisted Rehabilitation Lift, EARL) has been developed to support the horse's weight and was successfully tested with live horses (Montgomery et al., 2019). A rehabilitation harness prototype has also been developed and tested short-term (i.e., 30 minutes to 2 hours), but further studies were needed to improve its design (Steinke et al., 2019a).

Unlike humans, it is not possible to simply ask a horse where they are experiencing discomfort. This limitation in communication adds to the complexity of treating animals in comparison to humans. In addition, horses have evolved to hide pain to avoid predation (de Grauw and van Loon, 2016; West, 2007). Researchers and clinicians often have to depend on slight changes in behaviour to indicate pain or stress (de Grauw and van Loon, 2016). Pain or stress can surface in many forms, through aggression, aversion, or withdrawal, and often depend on the horse's specific personality. Pain-related parameters include physiological parameters (e.g., heart rate and respiratory rate), endocrine (e.g., hormone and mediator concentrations), or behavioural aspects (e.g., aversion behaviour, avoidance or aggression) (de Grauw and van Loon, 2016). Therefore, pain indicators are essential in all aspects of handling horses and are important in determining if a horse is experiencing discomfort and needs treatment or removal from the environment causing the pain or stress.

The ability to maintain normal movement while reducing load during equine rehabilitation could help to further reduce the occurrence of SLL through the facilitation of healthy blood flow to the foot (Medina-Torres et al., 2016). Tracking of movement during stall confinement could assist veterinarians in early detection of reduced movement, thereby aiding in rehabilitation monitoring and designing a proper rehabilitation protocol increasing or decreasing movement with or without weight support, based on the individual needs of each horse. If a horse’s movement is declining daily, it could indicate increasing pain, with the potential for overloading of the healthy limbs and the risk of SLL. Each horse's risk seems to be related to the ability to bear weight on the injured limb (Orsini, 2012). Quantitative tracking of movement during stall confinement could assist in monitoring mobility needed to maintain the circulation of blood in the limbs and possibly aid to identify horses at risk of SLL (Medina-Torres et al., 2016; Orsini, 2012). Early detection of changes in movement could provide vital information to direct rehabilitation protocols.

It is crucial to understand tissue healing properties in recommending rehabilitation protocols in horses, based on an understanding of the nature and severity of the injury. The wrong treatment at the wrong time can be detrimental. Because of the lack of scientific evidence on horses, indications, contraindications and precautions are often borrowed from human research, which is potentially problematic (Haussler et al., 2020). Nevertheless, all bodies generally adapt to movement and loading (Paulekas and Haussler, 2009), resulting in beneficial or detrimental adaptations. For this thesis, the focus of current rehabilitation strategies is directed to the rehabilitation of the skeletal system and fractures (given that fractures are one of the most common and catastrophic injuries in racehorses (Geor, 2002; Hayton and Sneddon, 2004)), including secondary complications (such as SLL), deconditioning, healing and re-conditioning of the skeletal system.

2.2. Indications for controlled weight reduction and mobility: consequences of weight re-distribution and immobility

Horses with severe limb injuries may have to be humanely euthanized due to complications that develop during treatment of fractures, tendon and ligament injuries, septic joints and laminitis (Baxter and Morrison, 2009; Gaschen and Burba, 2012; Hill et al., 2015; Hutchins et al., 1987; Singer et al., 2008). Euthanasia of injured horses in sporting events is a huge welfare concern, especially in racehorses (Baxter and Morrison, 2009; Gardner et al., 2017; van Eps et al., 2010). The horses' large size and heavy weight (combined with fine-boned energy-efficient support limbs) can make it challenging to manage such injuries and the resulting impairment of ambulation (Baxter and Morrison, 2009; Belloli and Zizzadoro, 2010; Clayton, 2016; Goodship and Smith, 2008; Smith, 1981). Injuries may also result in the development of secondary complications such as SLL, muscle atrophy or wasting, osteopenia, and ventilatory or perfusion problems associated with prolonged recumbency.

2.2.1. Supporting limb laminitis (SLL)

The horse's natural compensatory response to a painful limb is to increase weight bearing on the healthy limbs in an attempt to off-load the injured limb (Gardner et al., 2017; Orsini, 2012; West, 2007). SLL is a condition that is believed to develop with decreased movement and excessive loading of supporting limb(s). These conditions lead to decreased blood flow to the foot (load-induced ischemia) and mechanical failure of the connection between the hoof bone and hoof capsule (suspensory apparatus of the distal phalanx (SADP), which normally keeps the hoof bone in suspension) (Belknap and Durham, 2017; Gardner et al., 2017; Orsini, 2012; Sloet van Oldruitenborgh-Oosterbaan, 1999; van Eps, 2012). This chronic overloading likely results in arterial occlusion due to reduced frequency of cyclic weight distribution between limbs, which is relieved through regular unloading (such as walking or lifting of the hooves), restoring blood flow (Hood et al., 2001; Medina-Torres et al., 2016; Orsini, 2012; van Eps et al., 2010; van Eps and Burns, 2019). The mortality rate after the development of SLL is reported to be between 50% to 75% (Gardner et al., 2017). This high mortality rate reinforces the importance of preventing SLL from developing in the first place. The risk of SLL increases with increased time spent in recovery, usually confined to a stall, and with increasing body weight of the horse (Baxter, 2017; Ishihara et al., 2006b; Smith, 1981). One study suggests that the risk of SLL increases by 20% with each additional week of recovery (Virgin et al., 2011). Preventative techniques include increasing movement resulting in cyclic loading and unloading of limbs aiding in blood flow (Belknap and Durham, 2017) and reducing the load borne by the horse. Redden (2004) observed a decreased risk of SLL in horses bearing even a small amount of weight on the injured limb or moving around the stall compared to horses who stand with the supporting limb fully loaded. Even a slight flexion of the supporting limb can restore vascular filling (Orsini, 2012; Redden, 2004). This finding explains why healthy horses shift their weight between feet 70-180 times per hour (or approximately 1-5 times/minute) (Baxter and Morrison, 2009; Orsini, 2012; van Eps et al., 2010). Therefore, movement is a requirement for healthy circulation in the limbs (Orsini, 2012; West, 2007).

SLL usually develops weeks or months after the initial injury (17-134 days). This delayed development is believed to be due to the injured limb's pain masking the pain in the supporting limb. SLL is often noticed when the pain in the supporting limb exceeds the injured limb (Orsini, 2012). If SLL becomes even more painful than the initial injury, it can cause a transfer of weight back to the injured limb. This weight transfer can lead to re-injury or SLL in additional limbs (van Eps et al., 2010; Virgin et al., 2011). Another theory is that microdamage accumulates until the SADP fails (Orsini, 2012). Early detection of reduced movement during recovery and rehabilitation during stall confinement could significantly influence the treatment outcome (Hurkmans et al., 2003), allowing for early preventative measures.

2.2.2. *Muscle atrophy*

Muscle atrophy can occur with reduced movement and loading of structures. Movement is essential in order for muscles to function normally (Valberg, 2018). Smith (1981) reported muscle atrophy as a complication of flotation. Flotation was used in an attempt to reduce the risk of complications while healing from limb injuries, reducing weight by approximately 75%. Other noted severe complications with flotation tanks include muscle weakness and osteopenia (Bowman, 1995; Hutchins et al., 1987), which Hutchins et al. (1987) also observed in their study. Weakened musculature is reported to occur within a few weeks of the initial injury. With reduced muscle activity after an injury, there will also be an associated reduction in muscle size (i.e., atrophy) (Tabor and Williams, 2018). This reduction in size can have a negative effect on strength and muscle activation, impacting the return to a performance career (Tabor and

Williams, 2018; Valberg, 2018). Muscle adapts in response to loading (Rivero and Hill, 2016), and therefore, with reduced loading, muscles atrophy (Tabor and Williams, 2018).

2.2.3. Osteopenia

Osteopenia (low bone mineral density) can occur with decreased loading of bone structures, which in turn can be associated with painful injuries. Bone adapts to its environment, and structural changes occur depending on the mechanical forces applied (Dittmer and Firth, 2017; Firth et al., 2012; Goodship and Smith, 2008; Jann and Fackelman, 2010). It has been found that low-magnitude, high-frequency loading was the most effective for increasing bone formation and that osteocytes are key in controlling the formation and resorption process (Dittmer and Firth, 2017; Goodship and Smith, 2008). Repetitive strains can lead to the formation of microcracks, which, if not repaired, can lead to catastrophic failure, fracturing the bone (Dittmer and Firth, 2017; Hayton and Sneddon, 2004; Hitchens et al., 2018; J. Holmes et al., 2014). With immobility when recovering from fractures, bone resorption increases, resulting in decreased bone structure and strength (Dittmer and Firth, 2017; Hutchins et al., 1987). With prolonged immobility and insufficient weight, muscle wasting and osteopenia can occur. However, care has to be taken to avoid re-injury if too much weight is applied (Baxter and Morrison, 2009; Bowman, 1995; Clark-Price, 2013; McClintock et al., 1987; Smith, 1981; van Eps et al., 2010). There is a minimum effective strain required to strengthen the bone, and below this threshold, remodelling reduces bone strength. The exact amount of strain is still debated (Dittmer and Firth, 2017). However, cyclic loading (with time for recovery) is believed to elicit the most effective bone response, improving bone formation (Dittmer and Firth, 2017), strengthening or maintaining bone and avoiding bone loss.

In athletic horses (such as racehorses who may already have reduced bone strength due to high intensity of training and removal of osteoid (bone material) before remodelling can occur), the bone resorption or formation processes may already be hindered, leading to weakened bones and eventually micro and then macro crack formation when the rate of training does not allow for proper bone remodelling (removal is greater than the deposit of new material) through recovery periods (rest). Another important consideration is the asymmetrical loading that occurs during racing in one direction around the track, for example, North American Thoroughbreds who run counterclockwise. This asymmetrical loading can lead to increased density on the right side compared to the left side and imbalances in bone strength and remodelling behaviour (Dittmer and Firth, 2017). This asymmetry is an important consideration in rehabilitating horses after an injury that may have imbalances in bone mineral density due to their training or recovery time and immobilization. Care must be taken to avoid injury and overloading of structures.

Age is an important consideration in building or maintaining bone strength, as bone readily adapts when young but is substantially diminished in the elderly (Dittmer and Firth, 2017). Therefore, avoiding any bone loss during an injury or immobility in an older horse may be crucial in preventing future injuries and maintaining strength, as once lost, it may be difficult to build back. Simply walking, which creates cyclic hydrostatic pressure, has been shown to increase bone development and may be crucial to minimizing bone loss (Dittmer and Firth, 2017).

2.3. Current methods of weight reduction in horses

Immobilization and weight reduction have been considered treatment methods for equine lameness or limb injuries (Bowman, 1995; McClintock et al., 1987). Stall rest is most commonly the first line of defence. In more severe cases, cross-tying or slinging (Bowman, 1995). Many different load supporting and immobilization techniques have been developed and tested to assist horses with ambulatory difficulties such as limb injuries. However, due to complications observed with such devices, there is no standard practice for their use.

In many cases, during limb injury recovery, the horse must support its full weight with no relief and a high risk of re-injury. When weight is immediately applied after surgical repair or during treatment, there is a risk of failed repair in the injured limb or the development of secondary complications, such as SLL in supporting limbs (Baxter and Morrison, 2009; Bowman, 1995; Clark-Price, 2013; Smith, 1981). Load reduction has been suggested as a possible solution to the current challenge of preventing SLL and failure of repair, improving the chance of successful recovery from limb injuries (Steinke et al., 2019b). The main goal in treatment is to effectively reduce the weight supported by the limbs to decrease stress on both the injured limb and the supporting limbs to prevent complications (McClintock et al., 1987). Some of the rehabilitative methods used in the past include rescue slings, forced recumbency, flotation tanks, water treadmills and aquatic therapy (e.g., Hutchins et al., 1987; King et al., 2013; McClintock et al., 1987; Smith, 1981; Wattle et al., 1995). However, van Eps (2012) suggested that further development of sling technology for redistributing or relieving body weight to aid in recovery from injuries should be investigated.

2.3.1. Slings

Slings are the traditional choice for weight reduction in skeletal injuries (Hutchins et al., 1987; Schatzmann, 1998; Smith, 1981). Slings have been under development since 300-360 Common Era (Schatzmann, 1998). However, current slings are intended for short-term use in rescues or to temporarily lift recumbent horses (Ishihara et al., 2006b). Slings are only recommended for short-term use because of their static nature, inability to change load reduction (or measure load) and because they place significant pressure on the thorax and abdomen, possibly causing respiratory compromise (François et al., 2014; Gimenez et al., 2008; Montgomery et al., 2019; Steinke et al., 2019b, 2019a). Standard sling components include a wide belly band, a breast collar, a breeching (i.e., a strap around the haunches preventing the horse from sliding out the back of the sling), a crupper (i.e., a strap that wraps underneath the head of the horses tail), and a hoist mechanism (Bowman, 1995). Many slings only have one attachment point to a fixed hoist. Only having one pick-up point limits the ability to remove the load from the front or hind legs separately or redistribute the load (Hutchins et al., 1987; Puhl, n.d.; Schatzmann, 1998; Steinke et al., 2019a). Slings can be tedious to use and generally require constant supervision to avoid sliding or twisting out of the sling (Hutchins et al., 1987). Even with the known limitations and risks, slings have proven their importance in the veterinary field and are still used today (Hunt, 2008; Ishihara et al., 2006a; Jurga, 2016; Schatzmann, 1998). Painful conditions that can especially benefit from sling use include laminitis, fractures and tendon or ligament injuries (Jurga, 2016; Steinke et al., 2019b). Attempts have been made with available technology and homemade devices to reduce weight supported during recovery (Jurga, 2016). While studies suggest that slings have been used for long-term rehabilitation (Schatzmann, 1998), studies confirming or reporting results of sling use long-term (i.e., weeks or months) are few. Other information sources include articles written about famous horses who sustained limb injuries requiring a load-supporting device for recovery.

The two studies using slings to recover horses with injuries were completed by Sprick and Koch (2020) and Fürst et al. (2008). Sprick and Koch (2020) reported using a full-body animal rescue and transportation sling (ARTS) to successfully recover a Shetland pony from coxofemoral luxation over eight weeks. The pony returned to regular use with no residual lameness (Sprick and Koch, 2020). Fürst et al. (2008) evaluated the use of a modified version of the ARTS in 181 horses. Only 56 horses were supported long-term (averaging 17 days; a range of 1-117 days). Horses with fractures were supported with the ARTS for four to 10 weeks, with the only adverse effect of mild pressure sores on the trunk and SLL in two horses. The tolerance of 85% of the horses was excellent, 10% good, 3% poor, and 2% did not allow application. The ARTS was successfully used in a variety of situations to lift and support horses (Fürst et al., 2008).

Weight reduction and sling rehabilitation for limb injuries were used in the following racehorses. The horses were suspended during their recovery, and most had a successful outcome, with the exception of Barbaro. Swaps, also known as the “California Comet,” was training for a race with an already troublesome right front foot when he broke his left hind leg in two spots. He was known as one of the greatest and fastest thoroughbreds to race turf, often racing with only three sound legs and winning the Kentucky Derby in 1955. A week after obtaining a fracture during training, Swaps broke his cast, worsening the fracture (Fox, 2019, 2017; Nolte, 2015; Tower, 1956). A sling was determined to be his only chance for complete recovery (Tower, 1956). Swaps was successfully recovered in a sling (U.S. Army sling pictured in the article) for seven weeks and retired to a career as a breeding stallion (Fox, 2019; Nolte, 2015). He was sold for $2 million in 1957 (Fox, 2017).

Nureyev, a champion racehorse with a yearling price of $1.3 million in 1978 and son of Northern Dancer, sustained a severe injury to his right hock joint with a projected 10% survival rate (Brown, 2006; Schmitz, 2001). After 59 days in a sling, Nureyev was alternated between sling and recumbency, spending one to 3.5 hours recumbent before returning to standing with a sling (Brown, 2006). His recovery after surgery was filled with complications, broken screws, severe discomfort, respiratory infection, fears of colitis, but he recovered and stood at stud for the following breeding season (Brown, 2006; Schmitz, 2001).

Barbaro, a racehorse who won the 2006 Kentucky Derby, shattered his right hind leg two weeks later in the Preakness Stakes. Following months of recovery and support in a sling (Anderson sling), the fracture healed. The cast was removed, but SLL was present in the left hind foot (Press Release, 2006), eventually leading to euthanasia eight months after the injury

(Walker, 2016). van Eps attributes Barbaro's complication (i.e., SLL) to "disturbances to blood flow that occurred when the horse's ability to cycle weight bearing among its limbs is impaired" (Baillie, 2018). The key is to prevent the overloading of a sound limb due to painful loading in the injured limb (Oakford, 2013), which is a difficult task with currently available weight-supporting technology. This example reinforces the importance of the balance between too much load or not enough load. It is likely the combination of reduced mobility and overloading that led to Barbaro's poor prognosis, even after healing from the fracture.

Paynter, a three-year-old racehorse with a promising season, developed colitis-related laminitis that was prevented from becoming chronic through cryotherapy and leg supporting casts, unloading the wall and laminae of the hoof. In Paynter's case, his successful outcome and return to racing were attributed to the early preventative measures taken to avoid laminitis development before any damage had occurred (Oakford, 2013). Although Paynter was not supported in a sling, weight was removed through weight supporting casts and early preventative measures.

These stories show the need for a proven and tested device to support a horse comfortably and safely during recovery, as slings that have not been properly tested and evaluated, lacking evidence for safe long-term use, are being used in recovery from injuries when extra support is needed. The added ability to allow full control of weight reduction and movement would further benefit horses recovering from such injuries. Slings are important because (unlike humans) horses cannot handle, physically or mentally (as prey animals), being laid down to reduce the load on their feet until healed (West, 2007), making recumbency challenging to maintain for longer than a few days.

With suggestions that aggressive mechanical support and maintaining blood flow can be lifesaving (West, 2007), the race to develop such a device has continued over many decades. With the lack of evidence and reporting of successfully used devices, people have made home-made slings to recover horses in their personal barn and have saved lives this way (Jurga, 2016). In conversations with horse owners, it is not uncommon to find someone who knows of a successful recovery of a horse in a sling that would have otherwise been euthanized. Even animal cruelty organizations have recognized the need for a sling to support horses, developing their own sling for this purpose.

“The American Society for the Prevention of Cruelty to Animals (ASPCA) developed a horse rescue sling for supporting a debilitated animal in a stall” in 1875 (Gimenez et al., 2008). Henry Bergh, the founder of ASPCA, invented a canvas sling to rescue horses stuck in deep ravines or mud. This sling was later used to support injured horses in WWI (ASPCA, n.d.; “Horsepower Helping Horses and People,” n.d.). Although this sling is mentioned in multiple places online and in textbooks with different uses, the sling's actual design and components are not described. Many slings used over the years have little information or go unreported, making further developments difficult.

Most studies that have used slings report short-term lifts in recovery from anesthesia. These studies have shown a 95% success rate (Ishihara et al., 2006b) in cases where there might have been an increased risk for further injury, allowing the horse to stand with support sooner (Clark-Price, 2013; Hubbell, 1999; Taylor et al., 2005) and preventing large forces from being applied to a healing injury. If a horse stands too soon after anesthesia, they are often uncoordinated, stressing the skeletal structure, potentially causing injury or re-injury (Hubbell, 1999; Taylor et al., 2005), especially when standing after a surgical repair of a fracture. Slings can help reduce damage to muscles, promote the use of limbs to aid in circulation, and decrease the occurrence of pressure sores due to recumbency and immobility. However, horses placed in a sling should still be able to lie down, especially if fatigued or intolerant of the sling (Bowman, 1995). Two studies have discussed the long-term (i.e., over several weeks) use of slings. Other studies only describe short-term lifts (i.e., minutes) for anesthesia or development testing.

François et al. (2014) evaluated the arterial oxygen tension and pulmonary ventilation in six recumbent horses and horses placed in the Anderson sling. The horses spent 50 minutes recumbent and then were either maintained in recumbency or placed in the Anderson sling for another 60 minutes to recover. Horses in the Anderson sling group had a better recovery with higher arterial oxygen tension, lower alveolar-arterial oxygen tension gradient, lower respiratory rate and lower minute volumes. They concluded that the Anderson sling resulted in improved cardiopulmonary function and recovery quality compared to recumbent horses recovering from anesthesia. Recovery in the standing position also decreases fracture risk when awakening from anesthesia (François et al., 2014).

Madigan (1993) described a sling developed to support injured, ill or compromised horses. According to Madigan (1993), the sling was tested on various subjects in both rescue and clinical situations with success, but these tests were not described. The Anderson Sling Support Device (referred to in this thesis as the Anderson sling due to variations in the literature, e.g., Anderson Sling Support Device and U.C. Davis-Anderson sling) was determined to be valuable for equine practice providing support through head control and skeletal system support in debilitating problems and helicopter rescues (Madigan, 1993).

Madigan et al. (2019a) described and evaluated a simple new sling system for short-term vertical lifts of trapped or recumbent horses. The Loop Vertical Lift System uses four-round slings (i.e., loops) placed on a horse to utilize the skeletal system for support. The initial pilot trial involved the horse kicking out its hind feet and bucking. Foam cushions were added between the hind legs to provide additional comfort and prevent the straps from wedging up between the hind legs. The sling was used to lift six sedated horses for three minutes, resulting in no adverse effects. One horse had mild sheath edema after the lifting procedure. They recommend using the UC Davis Large Animal Lift, Anderson sling or ARTS for long-term lifting and support (Madigan et al., 2019a).

Disadvantages of slings include intolerance to the sling, possible injury to the surgical site and the need for trained personnel in the proper application (Clark-Price, 2013; Madigan, 1993; Madigan et al., 2019a, 2019b). They are also believed to result in respiratory compromise due to pressure on the thorax and abdominal organs. This pressure is believed to affect heart and lung function and inhibit blood flow from the head, neck and legs due to tight support straps, primarily when used in long-term situations (François et al., 2014; Gimenez et al., 2008), although no studies documenting this have been found except for the study completed by Montgomery et al. (2019). Bowman (1995) recommends caution when using slings in horses that cannot support their weight, when personnel are inexperienced, when facilities or equipment are inadequate, or constant supervision is impossible (Gimenez et al., 2008). One major obstacle is that large animals are often uncooperative and may resist slings, struggling violently against the device (Gimenez et al., 2008; Madigan et al., 2019a, 2019b).

The most commonly used sling is the Anderson sling, which is considered the safest for vertical lifts (Gimenez et al., 2008; Jurga, 2016). This sling is complex and challenging to apply

(Madigan et al., 2019a; Rush et al., 2004) due to the numerous straps and separate components. The full sling system involves a large metal frame, in which the harness is attached after application to the horse. Components consist of mesh panels first applied around the abdomen, followed by panels across the chest and around the hind end, all of which are separate components. Additionally, leg components can be applied for further support to relieve pressure from the abdomen, consisting of four more components, one around each leg. None of the attachment points (18) are quick-release, making this sling potentially dangerous for both the horse and its handlers in the event of an emergency or if a horse reacts badly to use of the sling (Taylor et al., 2005). A new device with the above complication risk and safety features taken into consideration could be a valuable tool for veterinary medicine. A summary of the slings used on horses that have been described in the literature is included in Table 2.1.

Table 2.1. Summary of slings, uses, and components. Table created from information available in various articles, studies and patents (Alexander and Heppner, 1980; Fathauer, 2013; Fürst et al., 2008; Gimenez et al., 2008; Jurga, 2016; Madigan, 1993; Madigan et al., 2019a, 2019b; McFadden, 1914; Montana, n.d.; "Munks Cow Sling," n.d., "Munks Livestock Sling," 2015; Musselman, 1913; Publication and Graphics Department NASA Center for Aerospace Information (CASI), 2008; Sprick and Koch, 2020; Strickland, 2001; Taylor et al., 2005).

Common Name	Used for	Design/Components/Materials	Pick-up points/ attachments
U.S. Army Sling	Not stated	A belly strap passing under the abdomen, with leather straps and metal loops to attach the breechings and breast collar (4-inch canvas belting) reinforced with leather	1 – directly above the horse and abdomen strap
EquiSling	Support during farrier work	A thick band of material that wraps around the girth attached to a breast collar made of the same material	1-2 – only front limb support
Horse Sling	Slinging or suspending animals, especially for therapeutic purposes	Neck-band (12 inches wide in triangle or T-shape) extending in front of and between the front legs, breast-band connected to the neckband and located at the rear of forelimbs extending over the animal's breast but not the abdominal region, breech-band connected to breast-band and a rump strap connected to the breech-band, all made of heavy canvas attached to metal rings via leather for attachment between pieces and connected to a suspension tree	1 – directly over mid-region of horse
Animal Sling	Supporting large animals for short or extended periods of time while stationary or travelling	T-shaped member conforming to the sternum and shoulders, belly band or sternum abdominal band attached to T-member, tailpiece attached to the abdominal band via six adjustable straps, additional head support can be attached to the abdominal band	1 – Directly over the mid-region of the horse
Self-Adjusting Equine Sling	Support to injured animals for a considerable period of time or lifting	Surcingle, breech-band, breastband, and surcingle bar, sheave wheel on either end of surcingle bar, supporting crossbar with more sheave wheels, attachment straps are secured to breast-band and breech-band over crossbar wheels and surcingle wheels, so all strains are equalized	1 – directly above the horse
Munks Livestock Sling (Equine)	Support over extended periods, repair of torn or strained muscles or nerves, trimming feet, lifting animals to feet, regaining proper circulation, eating and drinking habits and restoring normal bodily functions sooner	Lightweight, strong-zinc-plated pipe and polypropylene webbing for straps. Straps supporting abdomen attached to a metal pipe on either side of horse, breast and hindquarter straps attached to abdomen piece	2- chest and pelvis

Liftex Sling	Support severe musculoskeletal trauma or neurological injury, induction of anesthesia, transport between stall to surgery or recovery pool, lifting recumbent animals and lift animals out of ravine or entrapment	3-piece sling design (a continuous sheet of material wrapped underneath abdomen, with separate straps around the chest and hindquarter, all of which attach to the belly piece), adjustable in size and support (sternal or abdominal support) (no longer manufactured)	1 – withers
Becker Sling	Recumbent, geriatric, and mud-entrapped animals	Minimum 15 cm (6 inches) heavy-duty webbing with sewn loops on each end, Prusik loop connectors, steel attachment points, quick-release snap buckles, front and rear abdomen straps with breast piece attached to front abdomen piece	2 – chest and pelvis
Large Animal Lift (LAL)	Clinical and rescue use can be placed on recumbent animals supporting the musculoskeletal system or used in anesthetic recovery	A modification of the figure-eight sling around the front and hind legs attached to a metal bar	5 – 3 front limbs, 2 hindlimbs
Fire Hose Slings	Rescue, lifting recumbent horses	Retired fire hoses with loops sewn/tied on the ends, 4-6 cm (1.5-2.5 inch) hose, to support front and hindlimbs	2 – chest and pelvis
Enduro NEST	Post-surgical support and long-term rehabilitation of neurological conditions	Two pieces – back blanket (horse blanket-like design) and abdominal wrap. No pressure on sternum or abdomen. Quick connect seatbelt buckles with built-in cam-locks. Standing frame with walker/gait trainer	4 point lift from shoulders and pelvis/femurs (legs)
Sling-Shell System	Recovery from anesthesia (not used in rescue)	Two customized glass-fibre-enhanced plastic shells fit adult horses (280-685 kg or 616-1,500 lb) connected via short girth. One shell contours to the chest, one around the ventral thorax caudal to (behind) the elbows. Girths pass in front of and behind the hindlimbs for support of the hindquarters	Not mentioned
Animal Rescue and Transportation Sling (ARTS)	Rescue with a crane or helicopter, transport in an emergency vehicle, stabilization, lifting of the horse to standing position, anesthesia	abdominal piece of the sling made of netting material, front and hind straps running under the tail and hindquarters and chest strap similar to a breast collar (weight maximum of 1,100 kg)	1 – directly over the horse
Loop Vertical Lift System	Rescue of stranded or recumbent horses, a brief vertical lift	Four round slings applied to the horse, with foam cushions, to support the skeletal structure, two at the front limbs and two at the hindlimbs	1 – directly above the horse
UC Davis-Anderson sling (Anderson sling)	Initially intended for long-term surgical recovery and management of recumbent horses, but is industry standard for helicopter operations (emergencies and military)	Many accessories and pieces (head and leg support) and expensive. The soft part of the sling encircles the barrel, and skeletal support is provided by mesh panels and cross straps intended to prevent respiratory compromise, pressure points, or excessive abdominal pressure. An overhead steel frame with 18 attachment points for weight distribution, head and neck support, uniform stability, and animal support.	18 – to a steel frame connected to a hoist

2.3.2. Flotation tanks

Flotation tanks have been used to assist in the recovery of horses from fractures, laminitis, tendon sprains or other limb injuries requiring weight-reduction. Smith (1981) indicated that body weight is a significant obstacle in recovery from orthopedic surgery. Humans can follow instructions given by the doctor, and small animals are often confined to small areas. Owners can more easily dictate their behaviours. However, horses have substantial weight (i.e., approximately 450 kg) and can move 1.6 meters in a fraction of a second after rising. Together, these two factors can result in drastic forces being applied to the limbs (and across a fracture) that present a high risk of re-injury. The most common technique to avoid injury after the orthopedic repair is to sling the horse (Smith, 1981). However, Smith (1981) cautions that slings are usually not tolerated well and can result in pressure ulcers, although no evidence was reported. Smith (1981) also cautions against the use of forced recumbency (reviewed below), due to the need to stand at periodic intervals, which can cause misalignment of repaired bones or further injury due to substantial forces applied during rising to a standing position.

Smith (1981) suggested that relieving horses “of their great weight, can be managed in a manner which will enhance repair of any part of an injured limb” and by utilizing the buoyancy of water, a horses weight can be reduced from 450 kg to 100 kg (approximately a 78% weight reduction) (Smith, 1981). Based on the water level, 10-75% weight-reduction can be achieved (Bowman, 1995). Flotation allows weight to be applied to the entire body surface submerged in the water, spreading the weight across the entire surface, minimizing effects on peripheral blood flow. This weight distribution across the entire surface is challenging to achieve with a sling, where straps are usually used as the weight supporting material.

Smith (1981) described the tank as being 1.7 meters high, 2.5 meters long and 1 meter wide, which would be just large enough for a horse to stand in, highly limiting mobility. Tanks require a heater and thermostat to regulate water temperature (35°C to 36°C), a water reservoir of approximately 5,000 litres (which has to be disposed of after use and changed every 48 hours) with 0.95% sodium chloride, and a pump to move water to the flotation tank. Care has to be taken to avoid contamination of the injury or surgical site, and extra equipment may be required to prevent contact with the water. Recoveries ranged from two weeks to eight weeks of flotation. Cases that did not survive resulted from equipment malfunction and the development of pneumonia (Smith, 1981). The main complications observed by Smith (1981) were muscle atrophy and stiffening of the neck muscles, as well as a few cases of alopecia (i.e., hair loss) on areas submerged in the water. Other noted complications with flotation tanks include respiratory dysfunction from the build-up of pulmonary secretions, re-acclimatization difficulties (e.g., pyrexia, tachycardia, tachypnea, lack of sweating) associated with water temperatures, muscle weakness and osteopenia (muscle weakness preventable with decreasing water levels the last 10-14 days), neck stiffness and potential infertility (Bowman, 1995).

McClintock et al. (1987) set out to confirm the actual weight reduction achieved by Smith (1981). The displaced volume of liquid by the horse in the tank was assumed to equal the reduction in weight of the horse (i.e., 1 L of saline = 1 kg). The calculation of weight reduction was then based on Archimedes' principle, which states that a body immersed in a fluid displaces a volume of that liquid. The displaced liquid provides a buoyancy equal to the weight of the displaced fluid. McClintock et al. (1987) determined anatomical locations that resulted in approximately 10% (elbow/stifle), 30% (scapulohumeral joint), 50% and 75% (tubera coxae) weight reduction (McClintock et al., 1987; Nankervis et al., 2017; Smith, 1981; Steinke et al., 2019b) and they do not recommend flotation over 75% (water at the height of the tubera coxae). A higher water level can cause discomfort due to the door's high placement (which can cause pressure and friction injuries) and difficulty in obtaining food and water. McClintock et al. (1987) also suggested a 75% weight reduction was unnecessary and recommended only a load reduction equal to the weight normally supported by the injured limb before the injury. Therefore, the load supported through weight reduction should ensure that the normal load (30% on each forelimb and 20% on each hindlimb before the injury) on the remaining limbs is not exceeded (McClintock et al., 1987) through redistribution of the load from the injured limb.

Hutchins et al. (1987) used flotation tanks to assist in the recovery of seven horses with limb fractures, in which four were successful. The length of time spent in the flotation tank ranged from two weeks to 13 weeks. Of the successful cases, one horse was removed due to respiratory distress but did heal. The remaining three remained in the tank for 10 to 13 weeks. Of the unsuccessful cases, one horse fell when leaving the tank sustaining another fracture (the first fracture was healing) and was euthanized, one horse was removed early for economic reasons and succumbed to SLL, and the third horse tried to jump out of the tank repeatedly, therefore, was removed from the tank and euthanized. These results indicate flotation can be dangerous, not well-tolerated, and can result in severe complications (e.g., respiratory distress due to the build-up of nasal secretions, muscle weakness, osteopenia), all of which were observed in this study. Most horses had stiffness in their neck, and all horses had alopecia to the height of the saline (Hutchins et al., 1987). These complications suggest that flotation should only be used when there is a high risk of complications and should be used cautiously. Complications with any weight reduction method are inevitable. However, the severity, ability to make changes to prevent or reduce risk and the cost of the method are important considerations (Hutchins et al., 1987).

2.3.3. Forced Recumbency

Normal recumbency periods in horses have been observed to occur in several periods throughout the day. Time spent in recumbency can last anywhere from 10 minutes to over five hours in one day (longest period uninterrupted was 3 hours and 30 minutes) (Hansson, 2011). One study observed 12 hours of continuous recumbency after sleep deprivation (Hansson, 2011). Raabymagle and Ladewig (2005) observed lying behaviour of eight horses in box stalls with varying size (2 sets; each set including 1 large stall and 1 small stall) for large and small horses – large horses defined as approximately 155 cm high at the withers and small horses 145 cm at the withers. Horses in a larger box stall (approximately $[2.5 \text{ x height of the horse}]^2 m^2$) spent more time recumbent, and when moved from a large box to a small box (approximately $[1.5 \text{ x the height of the horse}]^2 m^2$), they exhibited rolling behaviour three times more often before standing up. When horses are given an insufficient area to lie down, resting time is reduced (Raabymagle and Ladewig, 2005). With greater amounts of time spent in recumbency in the larger sized stalls, the horses were likely more comfortable and able to lie down easier, with more space to stand back up (Raabymagle and Ladewig, 2005). Prolonged periods of recumbency have been used in an attempt to prevent the progression of laminitis. A significant concern in horses is that they fear losing their footing and can expend a lot of energy struggling to rise. Although a fatigued horse is easier to handle, it may cause the animal to give up any effort to survive (Strickland, 2001). Other concerns include the development of myopathy (muscle damage), poor gut motility, gas distension, urine retention, head trauma, nerve paralysis, poor perfusion (blood circulation) of the kidneys, ventilatory/perfusion problems including congestion in the down lung or impaired gas exchange, or ocular (eye) trauma (Corp-Minamiji, 2017; François et al., 2014; Madigan et al., 2019a; Schatzmann, 1998). These complications in recumbent horses raise concerns in forcing a horse to remain recumbent for days or weeks to heal from musculoskeletal injuries.

Forced recumbency has been used in an attempt to treat acute laminitis and avoid failure of the suspensory apparatus and possibly dislocation of the third phalanx (Hansson, 2011; Wattle et al., 1995). These studies were completed over two days, which is important in considering this as a treatment option for injuries requiring more time to stabilize before supporting full body weight. Studies have been completed in both Shetland ponies (Wattle et al., 1995) and Standardbred trotters (Hansson, 2011). Both studies used a specialized box (i.e., quadrangle shaped (Wattle et al., 1995) and octagonal shaped (Hansson, 2011)) to lower the ceiling to maintain recumbency. The octagonal box resulted in fewer attempts to rise, indicating better tolerance. Hansson (2011) lowered the ceiling to 125-140% of the horse's thoracic height. They observed behaviour, bodily functions and measured creatine kinase (CK) and aspartate aminotransferase (ASAT) for any complications (i.e., muscle tissue damage) for up to two days during the study. Horses were immediately checked for lameness at a walk and a trot upon removal from the forced recumbency box and monitored for four days following the study. There were no adverse effects (e.g., neuropathy or gastrointestinal problems), except mild myopathies and elevated CK up to 24 hours after the study, and horses responded well to the treatment. The increased body weight in Standardbreds did not have a negative effect in comparison to the Shetland ponies.

Wattle et al. (1995) proposed forced recumbency to counteract the disabling effects of laminitis by avoiding weight-bearing and thereby secondary tissue damage by allowing the tissue to heal and regain the strength to support weight before reloading the tissues. Wattle et al. (1995) successfully prevented the adverse effects of laminitis through forced recumbency. The main concerns in these studies were when discomfort was shown due to attempting to rise, or when stuck in an uncomfortable position or in the corner of the stall. They did note that the horses were able to move unassisted into a more comfortable position. The horses did shift between lateral and sternal recumbency frequently (i.e., average 15 times per hour), spending no more than 20 minutes in one position (Hansson, 2011). Shifting body positions is essential to allow blood flow and is crucial in avoiding pressure sores (Hansson, 2011). Muscle tremors were observed in all horses throughout the study, and the increased CK levels in four out of the six horses indicated some acute muscle damage. Horses were able to eat and drink. One horse did have an impaction (i.e., a hard, dry mass of stool becomes stuck in the colon or rectum), but it was treated while remaining recumbent. Some horses were able to urinate during recumbency, while others urinated immediately after being removed from the stall. Horses were able to pass feces but also did so shortly after being removed from recumbency. Respiratory rate (RR) ranged from 12 to 16 breathes per minute (bpm) with times where the RR rose to 32 bpm before changing positions (and therefore, was regarded as a sign of discomfort). Heart rate (HR) was within normal ranges of 24-48 beats per minute, except two horses rose to 60 beats per minute in the last few hours of recumbency, which returned to normal after rising. After rising horses did appear stiff and had a shortened stride length, which returned to normal within 24 hours (Hansson, 2011). Hansson (2011) suggested that forced recumbency "seems less cruel" than "state of the art" treatments to prevent severe dislocation of the distal phalanx and months to years of rehabilitation or euthanasia. However, these "state of the art" treatments were not listed or described.

One significant concern with recumbency is the difficulty in making a definitive diagnosis if complications occur during recumbency. If complications occur, they may not be observable until the horse can rise again (Hansson, 2011; Nollet et al., 2005). Hansson (2011) observed stiffening of the gait when evaluating lameness after the horse was removed from recumbency. In addition, the horses also had reduced urination and defecation, which would be problematic in extended periods, such as six weeks to heal a fracture. The ability of the horse to change positions when in recumbency and healing from a fracture with a cast would be limited due to the inability to bend the leg in the cast, which could cause trauma or re-injury when rolling. Nollet et al. (2005) stated that a horse's gait and posture could not be examined when a horse is recumbent. Many are uncooperative, limiting evaluation and treatment ability. These complications further highlight that great caution should be taken in recommending forced recumbency as a treatment option.

Although forced recumbency does show some promise in reducing weight supported by the limbs and reducing laminitis risk, serious complications (e.g., gastrointestinal, pulmonary, and tissue damage) can occur when maintained longer-term (i.e., up to six weeks). Horses typically spend short periods in recumbency throughout the day, indicating that recumbency is vital in normal daily functioning. However, due to their adaptations for a high level of athletic performance and as prey animals, recumbency for extended periods is generally not tolerated well.

2.4. Tools for assessment of harness design and rehabilitation monitoring: pain assessment (including behaviour & posture), assessment of physiological measures (respiratory rate)

Pain assessment is vital in determining if a horse needs intervention, such as increased pain medication or removal from the environment causing pain. Unlike humans, it is not possible to simply ask a horse where they are experiencing discomfort. This inability to communicate adds to the complexity of treating animals in comparison to humans. In addition, horses have evolved to hide pain to avoid predation (de Grauw and van Loon, 2016). Researchers and clinicians often have to depend on slight changes in physiological measures or behaviour to indicate pain or stress (de Grauw and van Loon, 2016; van Loon et al., 2010). Pain can surface in many forms through aggression, aversion or withdrawal and often depend on the specific individual's personality (Bussières et al., 2008). Pain-related parameters include physiological parameters (e.g., heart rate and respiratory rate), endocrine measures (e.g., hormone and mediator concentrations) and emotional or behavioural aspects (e.g., aversion behaviour, avoidance or aggression) (Bussières et al., 2008; de Grauw and van Loon, 2016; van Loon et al., 2010). These parameters will be discussed in more detail below.

2.4.1. Physiological parameters

Physiological parameters alone are generally not accepted as pain measures due to the influence of confounding factors, such as ambient temperature, dehydration, excitement and cardiovascular or respiratory disease (de Grauw and van Loon, 2016). Therefore, they are best used in combination with other pain assessment parameters or scales (de Grauw and van Loon, 2016).

Normal respiratory rate ranges from 10 to 24 breaths per minute. The Composite Pain Scale (CPS) validated in the study by Bussières et al. (2008) indicated increases of less than 10% from baseline respiratory rate (RR) were considered to be healthy and not indicative of pain. The scale ranged from zero to three (3 being severe pain), in which zero was an increase of less than

10% from baseline, one was an increase of 11 to 30%, two was 31 to 50% and three was greater than 50%. This scale was used to determine whether the respiratory rate was affected by harness use and the application of weight compensation by a rehabilitation lift. This thesis chose respiratory rate as a potential indicator of pain because respiratory compromise was observed in earlier trials described in Montgomery et al. (2019), due to the Anderson sling components placing significant pressure on the thorax and abdomen. Veterinarians have also expressed concern with respiratory compromise when slings are used clinically (Gimenez et al., 2008; Steffey et al., 2009; Taylor et al., 2005), but the studies using the Anderson sling for short-term lifts (2-15 minutes) did not report any respiratory complications. Therefore, it was important to monitor changes in respiratory rate during the assessment of harness design modifications, as the trials were longer than 15 minutes.

2.4.2. Endocrine measures

Endocrine measures such as hormone and mediator concentrations are indirect indicators of pain (de Grauw and van Loon, 2016). Circulating compounds that can be measured include endogenous cortisol, β-endorphins and catecholamines (de Grauw and van Loon, 2016; van Loon et al., 2010). These measures can indicate pain or stress but may not accurately reflect the severity (de Grauw and van Loon, 2016). Pro-inflammatory mediators (e.g., prostaglandin E_2, substance P and bradykinin) could indicate inflammation, which can be associated with pain but are not a direct measure of pain (de Grauw and van Loon, 2016). Therefore, they cannot be relied upon to independently indicate pain. Another drawback is the delay in results, as blood has to be sent to a lab to analyze these compounds (van Loon et al., 2010). Therefore, measuring these compounds would not be beneficial in short-term design trials.

2.4.3. Behavioural observations and scoring for pain assessment

Pain is defined as an '*unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage*' (de Grauw and van Loon, 2016; van Loon et al., 2010). Pain is subjective and cannot be communicated from animals to humans verbally in a meaningful manner (Bussières et al., 2008; Dalla Costa et al., 2014; de Grauw and van Loon, 2016; van Loon et al., 2010). However, pain changes the horse's physiology and behaviour in order to prevent or reduce damage and avoid re-injury during healing (Hopster and van Eps, 2018; van Loon et al., 2010). Furthermore, although changes in physiology and behaviour occur, horses are prey animals. Therefore, they have evolved to hide pain to avoid predation (Dalla Costa et al., 2014; de Grauw and van Loon, 2016), which can make detection of pain through behaviour difficult, requiring close observation for subtle changes in behaviour that can be an indication of pain and its severity (de Grauw and van Loon, 2016; van Loon et al., 2010).

Common behavioural aspects that indicate pain include changes in demeanour, posture, gait and interactive behaviour (Dalla Costa et al., 2016; de Grauw and van Loon, 2016). Bussières et al. (2008) found behavioural parameters of the Composite Pain Scale (CPS) to be repeatable and indicative of pain among observers and when compared to blood cortisol levels and mean non-invasive systemic arterial blood pressure. The most sensitive parameters in their study were pawing, head movement and posture, with posture being the most highly recommended for orthopedic pain. Altered weight distribution and limb loading have also been noted to be a good indicator of pain (Bussières et al., 2008; Hopster and van Eps, 2018), which are within the recommended categories of pawing and posture (Bussières et al., 2008). Heart rate, respiratory rate, appearance, appetite and interactive behaviour were less indicative of pain and had a lower sensitivity (Bussières et al., 2008). Therefore, behavioural observation would likely be the most accurate parameter for assessing pain.

van Loon et al. (2010) also evaluated the reliability and clinical applicability of the CPS used in Bussières et al. (2008). van Loon et al. (2010) indicated that it was a promising tool for direct day-to-day assessment of pain in various painful equine conditions. Horses admitted for nonpainful conditions and nonpainful diagnostic procedures under general anesthesia were compared to horses with painful acute or chronic surgical and nonsurgical conditions of internal and external origin. They also compared observers for inter-observer reliability. Many researchers have evaluated different pain indicators for various clinical applications in which CPSs have been built upon and later evaluated as a whole (e.g., Bussières et al., 2008; de Grauw and van Loon, 2016; van Loon et al., 2010). Each behaviour, source and application is described in a review by Ashley et al. (2005).

CPSs are valuable because they provide a direct and immediate analysis of pain (van Loon et al., 2010). However, behaviour can also be influenced by breed, temperament, sex, age and environment (Bussières et al., 2008; de Grauw and van Loon, 2016). The ‘Flight’ response is an instinctive behaviour in horses to escape a stressful or painful environment (Bussières et al., 2008). In circumstances where the horse cannot flee the environment, they can turn to aggression directed at the source of pain (Ashley et al., 2005; Bussières et al., 2008). Therefore, it is critical to know a horse's 'normal' behaviour in the absence of pain to accurately evaluate behaviour that could be influenced by pain and become potentially dangerous. In evaluating behaviour concerning pain, it is also vital to note familiarity with the environment (de Grauw and van Loon, 2016). If the horse is in a new environment, changes in behaviour could be attributed to the new environment and not necessarily pain.

Pain scoring systems can be valuable in recognizing and treating pain (de Grauw and van Loon, 2016; van Loon et al., 2010). They can raise awareness of pain states and increase agreement between personnel on the degree of pain (de Grauw and van Loon, 2016). Standard scales classify pain in four categories, absent, mild, moderate, or severe, indicated as 0, 1, 2 and 3, respectively (van Loon et al., 2010). In order to reliably record pain, the scale must be easy to use and reliable. The scale must also contain relevant and well-defined parameters that allow quick and repeated observation and consistent results in detecting mild, moderate and severe pain (Bussières et al., 2008; de Grauw and van Loon, 2016; van Loon et al., 2010). There are many scales currently used in research and clinical situations, such as numerical rating scales, visual analogue scales, simple descriptive scales, and composite multifactorial scales (Ashley et al., 2005; de Grauw and van Loon, 2016; van Loon et al., 2010). However, the focus will be directed towards composite pain scales and facial expression/grimace scales because of their ease of use and reliability in all observers.

CPSs include multiple variables (behavioural and/or physiological) in distinct classes, which are added to get an overall pain score (de Grauw and van Loon, 2016). Because pain is a multi-dimensional experience, emotional, behavioural and physiological responses should be used in combination to get the best evaluation of pain and its severity (de Grauw and van Loon, 2016; van Loon et al., 2010). Many studies state that CPSs can be time-consuming and require experienced and trained personnel (Dalla Costa et al., 2014; de Grauw and van Loon, 2016). In contrast, the study by van Loon et al. (2010) found the scale to take less than 10 minutes and provide a concrete pain score immediately and was easy to use. Time can be reduced by eliminating non-relevant variables for a particular situation (de Grauw and van Loon, 2016). This reduction in variables also makes the scales easier to use.

Facial expression/Horse Grimace Scales (HGS) are intended to provide more sensitive scales to detect mild pain but also can detect severe pain (Dalla Costa et al., 2014; de Grauw and van Loon, 2016). These scales are based on several facial features that are consistently associated with pain and its severity (Dalla Costa et al., 2016, 2014; de Grauw and van Loon, 2016). The advantages of these scales are that they are not time-consuming, have high validity within and between personnel, and lack the requirement of training to use them (Dalla Costa et al., 2014; de Grauw and van Loon, 2016). They also have an added safety feature of being able to assess pain from a distance. The HGS does not require walking or moving of the horse, which is ideal when a horse is on stall rest, movement is not possible, or movement causes unnecessary pain (Dalla Costa et al., 2016). The downside to HGS is that scoring in real-time is not as straightforward and reliable as scoring from still images (Dalla Costa et al., 2016). This is problematic if real-time analysis of pain is required, such as in trials during rehabilitation lift testing that require immediate analysis to know when to stop increasing weight compensation to avoid causing pain to the horse. Although HGSs are not as reliable and straight forward in live analysis, they still can be used as a measure in combination with other scales.

Many clinicians and researchers modify existing scales to meet their needs, eliminating or combining parameters from multiple scales (Bussières et al., 2008; Dalla Costa et al., 2014; de Grauw and van Loon, 2016). The CPS validated in Bussières et al. (2008) was modified from existing scales and evaluated each indicator separately on its repeatability and ability to indicate pain. Some scales are directed towards specific conditions, such as laminitis. Examples include the American Association of Equine Practitioners (AAEP) lameness score or the Obel score for laminitis (de Grauw and van Loon, 2016). These lameness scales involve walking or trotting the horse in a straight line on different surfaces, which could cause pain affecting the horse's welfare (Dalla Costa et al., 2016). They also require expertise to be reliable (Dalla Costa et al., 2016).

A scale that combines other previously used scales was used to evaluate the horse's behaviour in this thesis, using pain indicators determined to be repeatable, sensitive and good indicators of pain in Bussières et al. (2008). It was crucial to establish a baseline, as behaviours that indicate pain in some horses may be normal for others. The table used in preliminary trials can be found in Montgomery et al. (2019) Supplementary material, Table S1. A modified version was used in combination with other scales for this thesis (Table 2.2). These scales were used to establish a more evidence-based, objective analysis (van Loon et al., 2010) of the horse-harness interaction, where other measures, such as blood tests were not possible or relevant for short-term testing of design, comfort and fit, due to the delay in the analysis. The focus for behavioural scoring and physiological data (Table 2.2) was on respiratory rate, kicking at abdomen, posture and avoidance of the sling, as these behaviours were observed in preliminary trials with the Anderson sling.

Table 2.2. Behavioural scoring to assess pain and comfort with the harness and weight compensation. Adapted from Bussières et al. (2008) and Montgomery et al. (2019).

Physiological data	**Criteria**	**Score**
Respiratory rate	Normal (<10% increase from baseline)	0
	11-30% increase	1
	31-50% increase	2
	>50% increase	3
Behaviour		
Appearance (reluctance to move, restlessness, agitation, and anxiety)	Bright, lowered head and ears, willingly moves	0
	Bright, alert, occasional head movements, willingly moves	1
	Restlessness, raised ears, abnormal facial expressions, dilated pupils	2
	Excited, continuous body movements, abnormal facial expression	3
Sweating	No apparent signs of sweat	0
	Damp to the touch	1
	Wet to the touch, beads of sweat over the horse's body	2
	Excessive sweating, beads of water running off the animal	3
Kicking at abdomen	Quietly standing, no kicking	0
	Occasional kicking at the abdomen (1–2 times/5 min)	1
	Frequent kicking at the abdomen (3–4 times/5 min)	2
	Excessive kicking at the abdomen (>5 times/5 min), intermittent attempts to lie down and roll	3
Pawing at floor	Standing quietly, no pawing	0
	Occasional pawing (1–2 times/5 min)	1
	Frequent pawing (3–4 times/5 min)	2
	Excessive pawing (>5 times/5 min)	3
Posture (weight distribution, comfort)	Stands quietly, normal walk	0
	Occasional shifting of weight, slight muscle tremors	1
	Not bearing weight, abnormal weight distribution	2
	Analgesic posture (attempts to urinate), prostration, muscle tremors)	3
Head Movement	No evidence of discomfort, head mostly straight ahead	0
	Intermittent head movements laterally or vertically, occasional looking at flanks (1–2 times/5 min), lip curling (1–2 times/5 min)	1
	Intermittent and rapid head movements laterally or vertically, frequent looking at flank (3–4 times/5 min), lip curling (3–4 times/5 min)	2
	Continuous head movements, excessively looking at flank (>5 times/5 min), lip curling (>5 times/5 min)	3
Appetite	Eats food readily	0
	Hesitates to eat	1
	Little interest in food, eats very little or takes food in the mouth but does not chew or swallow	2
	No interest in food	3
Interest in surroundings	High interest in activities around stall (looking outside stall; ears forward, head up; following movement outside the stall)	0
	Interest (head up, ears up; watching activities through head movement)	1
	Mild interest (head up, ears may be up or resting)	2
	No interest (head and ears down)	3
Human interaction	Seeks human interaction (i.e. comes to person)	0
	Acknowledges human, but not an immediate movement for attention	1
	Acknowledges human, but no movement for attention	2
	Ignores all human interaction	3
Avoidance to the sling	No avoidance behaviours***	0
	Showing 1 or 2 avoidance behaviours intermittently (>5 min between)	1
	Showing >2 of the avoidance behaviours frequently (<5 min between)	2
	Obvious and frequent avoidance behaviours, showing all signs of avoidance	3

****Avoidance behaviours included tail swishing, kicking at the abdomen, bowing of the back, sharp raising of the head, the wide spreading of the legs, reluctance to move when asked to move, and struggling against the sling when asked to stand still.*

2.5. Tools for rehabilitation monitoring: current biomechanical tools for movement analysis

Musculoskeletal injuries are common in horses, with lameness being arguably the most important clinical problem (Clayton, 2016; Poore and Licka, 2011). Because it can be challenging to treat severe limb injuries in horses, there is a need for further research on protocols and devices that can help veterinarians monitor horses during rehabilitation, especially when the horse is on stall rest. A device to monitor movement during stall confinement could allow for early identification of horses at risk of immobility-associated complications and monitor the horses' response to treatment.

Clinical lameness exams typically are completed through subjective assessment of a horse's gait while trotting in a straight line or in a circle, which may not be possible when the animal is severely injured and on stall rest (Davidson, 2018; Dyson, 2014; Keegan et al., 2013, 2011; Lopes et al., 2018). The accuracy of lameness detection is limited by the visual acuity of the human eye, the experience of the veterinarian, the severity of lameness and the speed of the horse (i.e., accuracy decreases with increasing speed) (Clayton, 2016). Therefore, there is often a lack of agreement between clinicians scoring lameness (Poore and Licka, 2011).

Multiple biomechanical tools (e.g., force plates, videographic systems, force-sensing horseshoes, inertial sensors, pressure plates and treadmills) are used in research to objectively assess musculoskeletal conditions involving lameness (i.e., musculoskeletal pain altering gait characteristics) and movement patterns in horses (Keegan, 2007). However, most are focused on gait-based assessment, and many are not practical in confined spaces (Chateau et al., 2009; Ratzlaff et al., 1990; Robin et al., 2009). Practical biomechanical tools for assessing and tracking injury severity in a horse during recovery in stall confinement would allow for earlier detection of complications (e.g., off-loading the injured limb and increasing weight-bearing on other limbs, and decreased step count and shifting of weight), as well as the implementation of early preventative measures (Gardner et al., 2017; Keegan, 2007; Medina-Torres et al., 2013; van Eps et al., 2010). For this thesis, inertial measurement units (IMUs) were selected to track motion due to their ease of use, small size, ease of attachment and ability to monitor the horse during movement around the stall.

IMUs consist of multiple sensors, including accelerometers, which measure acceleration (Clayton, 1996). In equine studies, these sensors have been placed at the midline (poll, withers, mid-croup) and on the limbs (hoof, cannon bone, or tuber coxae) to detect asymmetries and determine which limb is lame (Clayton, 2016; Fries et al., 2017; Maisonpierre et al., 2019). They can be used to monitor lameness progress, responses to local diagnostic anesthesia or therapy (Clayton, 2016).

Keegan (2009) and a team of researchers at the University of Missouri developed an objective body-mounted inertial sensor system with wireless transmission to aid veterinarians in lameness evaluations. The system is known as the *Lameness Locator™* and consists of three sensors with one located at the head (accelerometer), pelvis (accelerometer) and right forelimb (gyroscope), respectively. This system is used for clinical evaluation of lameness but has limitations in collecting data (e.g., uniaxial accelerometers) (Pfau et al., 2016) and is very expensive. Furthermore, it has been validated for examining the horse at a trot in a straight line. An earlier system, the Equimetrix, described in Keegan (2007), involved two 50-Hz accelerometers attached to a girth strap or saddle of a horse. A third system uses two accelerometers at the head and pelvis, two gyroscopes on the right forelimb and hindlimb, and a sampling rate of 200 Hz.

Locomotion studies (e.g., Fries et al., 2017; Keegan et al., 2013, 2011; Maisonpierre et al., 2019; Moorman et al., 2017; Olsen et al., 2013) have evaluated the accuracy of accelerometers and IMUs placed on the horse's limbs, withers, head and pelvis to analyze gait. Fries et al. (2017) analyzed locomotor activity, step frequency, and activity counts at four locations (e.g., head, withers, forelimb and hindlimb) to quantify behavioural activity in six horses. The horses were observed moving freely in a paddock, grazing at pasture, walking in hand, trotting, and cantering on a lunge line, and walking in a horse walker. This study found that the accelerometers used (Animal ActiCal) were able to differentiate between levels of activity and different gaits accurately and that the hindlimb location was the most accurate. However, the step count was doubled at the walk, and the withers were problematic (Fries et al., 2017).

Maisonpierre et al. (2019) studied the effects that pasture size had on the amount of movement and whether the accelerometer (ActiGraph) at the poll (i.e., on top of the head between the ears) could differentiate between movement types (e.g., standing, walking and ambulating). Six horses were observed during five minutes of standing, grazing and ambulating (i.e., walking in hand) for ten days for each environment. They found that pasture size affected the horses' amount of movement and that the accelerometer could differentiate between movement types (Maisonpierre et al., 2019).

Keegan et al. (2011) evaluated an IMU-based lameness evaluation system's repeatability in 236 horses. Sensors were placed at the head (accelerometer), pelvis (accelerometer) and right forelimb (gyroscope). Signal-processing algorithms were used to evaluate trial asymmetry patterns for vertical movements and maximum and minimum positions of the head and pelvis between the left and right sides of each stride when trotting in a straight line. Asymmetry (i.e., lameness) in the hindlimbs was more repeatable than in the forelimbs. They determined that inertial sensors could be used to measure asymmetry of the head and pelvic movements to detect lameness when trotting in a straight line (Keegan et al., 2011).

Keegan et al. (2013) compared an inertial sensor system to subjective lameness exams from three experienced veterinarians in 106 horses. The IMUs and veterinarians analyzed horses trotting in a straight line. Additionally, the veterinarians also evaluated horses when performing lunging in a circle and limb flexion tests (i.e., a complete lameness exam). Horses were separated into three categories, right limb lameness greater than left limb, left limb greater than right limb or equal right and left limb lameness severity in either front or hindlimbs. Subjective lameness exams and inertial sensors were significantly correlated but were not in strong agreement, especially in mild lameness (Keegan et al., 2013). In another study, Moorman et al. (2017) evaluated the effects of velocity on inertial sensor systems (Lameness Locator) and their ability to detect lameness. Twelve horses were assessed at a trot at varying speeds (3.0-4.0 m/s) on a treadmill. They determined that there was not a significant effect on forelimb lameness detection at varying speeds. However, hindlimb lameness detection was affected by velocity, decreasing detection abilities with increasing velocity. A horse may appear to be more sound as velocity increases (Moorman et al., 2017).

Olsen et al. (2013) used IMUs to quantify displacement of the distal limb of seven horses through placement over the fetlock joint. They found IMUs to have good accuracy and precision for the vertical and craniocaudal displacement and gait event detection (Olsen et al., 2013). In another study, Olsen et al. (2012) mounted IMUs on the trunk (5 IMUs) and distal limbs (4 IMUs) of seven horses to measure temporal gait events. They found the IMUs to have good accuracy and precision in detecting gait events (i.e., front and hind hoof-on/off and stance) at a walk (Olsen et al., 2012).

While many studies have been completed with IMUs due to their affordability, portability, small size and ease of use, the locations and parameters measured from the data significantly vary between studies. Inertial-body sensors that have the ability to transmit data wirelessly offer a relatively inexpensive, easy to use, objective method for gait analysis (Keegan, 2007). They also allow the subject to move with fewer constraints compared to testing on a treadmill or in a gait assessment laboratory (Olsen et al., 2013, 2012). However, placement and sampling frequency vary between studies, indicating that a standard frequency and placement have not yet been determined. Furthermore, these systems have not been tested in small spaces, such as during stall confinement.

Algorithms and software available for analysis are limited (Keegan, 2007). This lack of software could make the analysis of the data complicated if the software is not available, easily accessible, or the evaluator does not have access to an algorithm to extract the appropriate data. Therefore, it would be beneficial to have an algorithm or software available for general use and a standard variable for movement analysis with IMUs. IMUs could be useful in tracking rehabilitation progress, allowing for the constant recording of the horse's movement during confinement and all stages of its rehabilitation. Changes in movement could indicate the development of life-threatening complications and could be detected through step count. Step count is a simple, easily understood parameter that can be compared over days or weeks to track changes during the rehabilitation of a horse. The use of IMUs for step count determination during stall confinement as a possible tool to monitor rehabilitation progress in horses has been studied as part of this thesis and is described in Chapter 4.

For rehabilitation, the use of such a device could help to tailor the rehabilitation protocol to each horse and thereby give the best possible chance of successful recovery. The development of an appropriate protocol involves understanding the physiology behind the injury and healing of that injury, as well as rehabilitation modalities and exercises used to aid in healing and a gradual return to full function. To develop effective protocols, it is important to understand possible complications that could occur following an injury and how to prevent them. Many methods have been attempted to reduce weight to prevent weight-associated complications from developing, such as slings, forced recumbency and flotation tanks. Tools to assess movement (IMUs) could also be beneficial in rehabilitation protocols by indicating when interventions are necessary in order to increase movement and blood flow. Behavioural scoring can be used to assess pain and determine the need to administer pain medication or other interventions. Therefore, rehabilitation protocol development in the context of tissue healing is discussed in the next section.

2.6. Rehabilitation protocol development

In the past, evidence for rehabilitation protocols in horses has been scarce. They are often developed or implemented without considering fundamental physical therapy principles, consideration of tissue healing properties, or proof of the mechanisms of action for the treatments being used (Haussler et al., 2020; Paulekas and Haussler, 2009). For example, bandages and support wraps, stall rest, or cold hosing after exercise are frequently used without a diagnosis or evidence for their efficacy; in some cases, they may even be contraindicated (Paulekas and Haussler, 2009). Rehabilitation programs frequently lack clear outcome measures or goals (Haussler et al., 2020; Paulekas and Haussler, 2009). Although there is a growing body of evidence for specific applications, more knowledge is needed to develop safe and effective programs. These programs should consider the type, location, severity, and chronicity of the injury to prevent further damage. Clearly defined issues or goals, with objective measures, need to be outlined so that programs can be modified or terminated if problems develop during rehabilitation. Treatment can be challenging as the wrong therapy at the wrong time can be detrimental. Given the lack of evidence in equine practice, the ability to recognize problems early in the program can be challenging (Haussler et al., 2020). Often indications, contraindications and precautions are borrowed from human research, which can also be problematic due to noticeable differences in horses' size, conformation and athletic requirements or adaptations (Haussler et al., 2020).

While many tissues adapt to changing strains, this review will focus on the skeletal system specifically and will discuss the components of bone, fractures, the healing process, complications during healing, as well as reconditioning. Fractures are the most common catastrophic and fatal injury in racehorses (Hayton and Sneddon, 2004). Fractures are likely to be an indication for rehabilitation lift use due to the associated complications, such as SLL, and welfare concerns surrounding fractures in horses, especially racehorses. While this review focuses on the skeletal system, it is important to remember that a whole-body approach to rehabilitation is required to be most effective and prevent further injury.

2.6.1. The skeletal system

In combination with the muscles, tendons and ligaments, the skeleton offers structural support and a means of locomotion. It has evolved to provide maximal strength with minimal mass to minimize the risk of failure and energy expenditure. Since horses have evolved for high-speed locomotion, this is especially important. Bone mass is minimized in the distal limbs for efficiency, which could be related to higher injury occurrence in distal bones, particularly in racehorses. The majority of the muscle mass in horses' limbs are concentrated near the centre of the body (proximally). Reduced muscle mass distally decreases the energy required to move the limb, with long tendons and ligaments acting like energy-storing springs in locomotion (Goodship and Smith, 2008).

Bone develops together with the mechanical loading to optimize characteristics specifically for each bone and its function in the body. If loading conditions change, the bone will remodel to optimize for the new loading conditions, allowing material and structure to change throughout life, optimizing mass and distribution. During bone growth and adaptation, shape and architecture change through cellular activity, removing old bone and forming new bone. This removal and addition of bone is the only way bone can grow or change shape, referred to as modelling, activated through growth and mechanical loading (Goodship and Smith, 2008).

As activities and loads change throughout life, the bones functionally adapt to remain efficient for new requirements. It has been suggested that there is a threshold to the loading and deformation. When exceeded, new bone is synthesized to increase bone mass and overall cross-sectional area (Goodship and Smith, 2008; Holmes et al., 2014). Adaptation appears to require cyclic loading, as a constant load does not result in bone adaptation (Goodship and Smith, 2008). Therefore, diverse training regimes are most beneficial throughout life. This adaptation also requires a rest period. Constant cyclic loading inhibits remodelling and leads to fatigue damage and, eventually if allowed to accumulate, fracture (Hitchens et al., 2018; Holmes et al., 2014).

2.6.2. Injury (fracture)

Injuries are common in racehorses, and fractures of the distal limb are often catastrophic, leading to substantial financial losses, long recovery times or, in severe cases, euthanasia (Hayton and Sneddon, 2004; Hitchens et al., 2018; Lewiecki, 2006; Ramzan and Palmer, 2011). Equine bones can be similar in strength to steel when appropriately loaded (e.g., tensile stress); i.e., loading aligned with the bone axes. However, any material will fail if exposed to conditions beyond its capabilities (Jann and Fackelman, 2010); i.e., bones are considerably weaker when subjected to transverse or bending type forces, which are not normal forces during locomotion. As described above, the skeletal structure develops to counteract applied stresses. With repeated stress, remodelling occurs to reinforce the structure for those conditions (Dittmer and Firth, 2017; Firth et al., 2012; Jann and Fackelman, 2010). When supporting structures such as tendons become fatigued, protective forces are lost, and there is a higher risk of injury or damage (Jann and Fackelman, 2010). All structures (e.g., muscle, tendon, ligaments, and bone) work together to remain healthy and distribute forces. Injured tissues may respond differently than healthy tissues in loading and unloading during exercise (Dittmer and Firth, 2017; te Moller and van Weeren, 2017). Cracks or tears may develop in cartilage or bone, which accumulate over time, resulting in repaired ('scar') tissue from overloading (Dittmer and Firth, 2017; Hayton and Sneddon, 2004; te Moller and van Weeren, 2017). Furthermore, microdamage, which is first observed in cartilage in many cases, can result in calcified cartilage (Dittmer and Firth, 2017). This damage leads to changes in the balance of catabolic (i.e., break down) and anabolic (i.e., build up) processes that repair or regenerate tissues (Dittmer and Firth, 2017; te Moller and van Weeren, 2017). Repeated overtraining, improper training and excessive exercise or loading conditions can lead to failure of these structures without proper recovery or healing time (Hitchens et al., 2018; Holmes et al., 2014; Lewiecki, 2006).

With repeated cyclic loading, which often happens during exercise, microdamage can occur. When training continues with insufficient recovery time, microdamage and fatigue damage accumulate and eventually can result in a fracture (Dittmer and Firth, 2017; Goodship and Smith, 2008; Hayton and Sneddon, 2004; Hitchens et al., 2018). Injuries can also occur when the load applied exceeds the strength of the structure (Lewiecki, 2006). It is estimated that 53% to 70% of Thoroughbred and National Hunt racehorses suffer from stress fractures or bucked shins (Hayton and Sneddon, 2004). Stress fractures occur from chronic fatiguing processes, and the risk is reduced through increases in bone strength and recovery time (Firth et al., 2012, 2011; Hayton and Sneddon, 2004; Lewiecki, 2006). The repair process (remodelling) occurs in response to healthy daily life and functional loading of the skeletal structure with appropriate recovery time (Dittmer and Firth, 2017; Goodship and Smith, 2008).

Often recommendations for post-surgical or injured horses include stall confinement and rest until they have healed (Matthews et al., 2002; Paulekas and Haussler, 2009). This immobilization can cause detrimental effects on muscle function, joint cartilage degeneration, impairment of joint stability and flexibility, and the production of excess fibrosis (Haussler et al., 2020). Other effects of immobilization include reduced blood flow, muscle wasting or osteopenia (loss of bone mass or density) (Hutchins et al., 1987). With horses, stall confinement needs to be evaluated in terms of bone remodelling and soft tissue deconditioning that could lead to further injury if proper care is not taken to re-condition before exercise is undertaken (Haussler et al., 2020). Controlled loading helps to minimize detrimental effects that can be caused by immobilization and stimulates soft tissue and joint cartilage healing (Hutchins et al., 1987; Paulekas and Haussler, 2009). Tissues are readily adaptable to change, with one of the most effective methods being controlled mechanical loading or stress. Without loading, bone, muscle, joint, and ligamentous tissues are not stimulated to adapt positively (Paulekas and Haussler, 2009) and instead can degenerate. Care needs to be taken when reloading the structures after a repair, as too much weight can lead to re-injury, while insufficient weight can lead to muscle wasting or osteopenia (Baxter and Morrison, 2009; Bowman, 1995; Clark-Price, 2013; McClintock et al., 1987; Smith, 1981; van Eps et al., 2010). The use of a rehabilitation device that enables gradual reloading of the skeletal structures while allowing controlled mobility early on could have significant effects on the healing of fractures in horses (Montgomery et al., 2019a; Steinke et al., 2019b, 2019a). The rehabilitation lift that will be discussed in Chapter 3 can control loading and slowly add load during the healing process.

2.6.3. Tissue healing

Tissue healing is a critical component of successful rehabilitation. Movement is required to circulate blood and nutrients to aid in healing, which can slowly be increased as the healing of tissues progresses. Fracture healing occurs after a period of immobilization or surgical repair (Sanghani-Kerai et al., 2018). Many factors affect the healing process in fractures. Bone healing is controlled through cytokines and hormones, as well as other regulatory factors, which is highly dependent on blood supply and recruitment of repair cells (Sanghani-Kerai et al., 2018). In areas with less blood supply, such as the tendons and ligaments in limbs surrounding bone, healing can take longer (Dittmer and Firth, 2017). Mechanical loading can help adapt bone and stimulate strengthening.

It is suggested that compression of the fracture site can improve fracture healing if applied at the correct time. Loads applied immediately after the injury hinder healing, possibly due to damage to new blood cells. However, small cyclic loads applied four days after the fracture increase strength of the fracture callus. Therefore, it has been suggested to apply load once hard callus formation has begun (Dittmer and Firth, 2017). The amount of load is also significant, as the absence of strain can lead to disuse atrophy and removal of the callus, while too much load or compression inhibits healing (Dittmer and Firth, 2017; Rauch, 2005). Cyclic low-magnitude, high-frequency loading is recommended as it is associated with faster fracture repair (Dittmer and Firth, 2017), whereas static loads are thought to be detrimental to bone growth (Rauch, 2005). Suggested exercises to stimulate strengthening, mobility, and healing include standing the horse on foam balance pads and progressing to aquatic therapy with variable water levels and speed. Once proper adaptation and strength have been developed, work over ground poles (i.e., poles laid out on the ground at specified distances) can begin, followed by cavalleti (i.e., a small jump, usually set to one of three pre-set heights) work on a lunge line (i.e., a long, single rein for communication between the horse and handler, usually on a circle), and eventually, riding exercises over different ground surfaces (e.g., inclines or hill work) (Haussler et al., 2020).

2.6.4. Deconditioning timeline

To maintain the physiological adaptations that occur as a result of conditioning, the initial activities that stimulated the adaptation need to be maintained. With sufficient time at rest, tissues will return to their previous unconditioned state, such that tissues that adapt the most readily will also decondition the most readily (Jann and Fackelman, 2010). Disuse will result in a decline back to the genetic bone mass (Goodship and Smith, 2008). After fracture repair, there is a period of decreased weight-bearing, which can result in bone loss. This decreased weight-bearing can be due to pain of the fracture or methods applied (i.e., rescue slings, water flotation) to avoid overloading the repair or re-injury. Therefore, early mobilization is key in minimizing deconditioning (Blokhuis et al., 2000).

2.6.5. Complications in fracture recovery

Many complications can occur in fracture healing affecting the ability to heal, including mechanical stabilization and reestablishing the blood supply, inflammation or edema, infection or abscess, nutrition deficiencies, metabolic bone disease, bone tumours, endocrine disease, etc. (Dittmer and Firth, 2017; Matthews et al., 2002). An acute inflammatory response is essential for the successful healing of fractures. However, if this inflammation becomes excessive or infection occurs, it can be detrimental (Dittmer and Firth, 2017). One main component in determining the prognosis and possible success in surgery is vascular supply. Blood flow is crucial in any healing tissue – damaged skin, broken bones or other damaged tissue (Dittmer and Firth, 2017; West, 2007).

Loading is not only crucial in fracture healing but also in minimizing complications that can occur in addition to fracture healing, such as maintaining or stimulating blood supply (Dittmer and Firth, 2017; Redden, 2004). Redden (2004) suggests that the forces present in the hoof are important in maintaining blood flow. Once the forces are out of balance, such as when the laminae are stretched, a loss of structural properties and nutrients can occur and eventually result in structural failure and laminitis. Blood flow is restricted due to the tension caused by the deep digital flexor tendon forcing blood out of the laminae during the stretching (Redden, 2004; West, 2007). van Kraayenburg et al. (1982) observed the termination of blood supply in the foot when vertical force was applied in 14 horses. This lack of blood during standing further reinforces that movement is required to stimulate blood flow in the hoof. When structures are relaxed venograms indicate blood flow, which disappears when the structures are loaded (causing tension) (Redden, 2004). In the case of an injury when one foot is continuously loaded, to off-load the injured limb, the laminae are always under load and do not receive any blood resulting in a lack of oxygen and nutrient delivery and eventually cell death (Redden, 2004; West, 2007). This balance of loading and unloading, controlling pain and preventing re-injury or further injury can be challenging in treating horses with limb injuries. Often after surgical repair, movement is limited by caregivers. Horses that are active after repair are assumed not to be "taking good care of himself." However, the horse may be doing the opposite and stimulating blood flow, as horses standing for hours and not moving may have poor perfusion to aid in healing tissues (West, 2007). In the case reports by Matthews et al. (2002), horses were able to care for themselves, walking and resting when needed, carefully rising from recumbency while healing from radial fractures, with only conservative treatment of the fracture from veterinarians and minimal complications. Although early signs of laminitis were present in two out of the three horses, it did not progress (Matthews et al., 2002).

In the case of SLL, the foot is usually treated after signs of laminitis are present, which is often too late (Redden, 2004; West, 2007) as the complication of SLL has been unknowingly progressing for weeks. When the horse is switching weight back to the injured limb, significant damage has already occurred. If the injured limb is not sufficiently healed and able to support the additional weight in order for the supporting limb to heal, the prognosis is often poor (Redden, 2004; West, 2007).

2.6.6. Re-conditioning (exercise & adaptation)

With repeated exercise, systems are remodelled, and conditioning occurs, resulting in physiological adaptation, increasing exercise capacity for that activity (Jann and Fackelman, 2010). Some stress (physical or metabolic) is required for conditioning to occur, but too much stress can cause injury or damage to tissues (Haussler et al., 2020; Jann and Fackelman, 2010).

The diagnosis upon which the rehabilitation program development is based needs to be accurate, with precise subjective and objective analysis of the current state of the condition to be treated with the program. The protocol should involve regular assessments of pain, range of motion (ROM), proprioception, motor control, strength and endurance (Haussler et al., 2020). Subjective and objective measures should be used in combination to assess rehabilitation progress. The successful development of rehabilitation programs requires individual customization to needs, thought and planning of cost, availability of resources and practicality, as well as individuals with the proper training to monitor tissue healing and functional capabilities throughout the stages of rehabilitation and make recommendations on regressions or progressions to avoid injury or further damage (Haussler et al., 2020).

2.7. Conclusion

In conclusion, many factors need to be considered in the decision-making process of diagnosing, treating, recovering and rehabilitating horses with limb injuries. The tools to support such a recovery are limited and often have their own complications. Therefore, additional tools to support this injury recovery process with minimal complications are needed. This thesis will present research on two different tools that have the potential to benefit equine rehabilitation. They include: 1) a weight compensation lift and harness system and 2) a movement monitoring device to track mobility during stall confinement. When incorporating different tools into a rehabilitation program, it is essential to consider the tissue healing process and how bone adapts to loading. These are essential considerations to give the horse the best chance at a successful recovery and return to work.

CHAPTER 3 DESIGN AND TESTING OF A REHABILITATION CHEST SUPPORT TO FACILITATE WEIGHT REDUCTION IN HORSES WITH AMBULATORY DIFFICULTIES

3.1. Introduction

Musculoskeletal injuries are common in horses. In severe cases, these injuries may lead to immediate euthanasia. In cases where treatment of the primary injury could be successful, euthanasia may still become necessary for humane reasons due to secondary complications that develop during treatment or rehabilitation (Baxter and Morrison, 2009; Gardner et al., 2017; Hutchins et al., 1987; van Eps et al., 2010). One of the most feared complications is SLL (Orsini, 2012), for which Gardner et al. (2017) have reported a mortality rate between 50% to 75%. According to Hunt and Belknap (2017), the complications in horses with laminitis ultimately dictate the outcome. Laminitis itself is not a life-threatening condition, but the complications (e.g., hoof abscesses, inflammation, reduced blood supply, failure of structures) that develop during its treatment can result in humane euthanasia based on considerations for the welfare of the animal and future potential for complications (Hunt and Belknap, 2017). The situation can be similar in the treatment of fractures, where complications following fracture repair (e.g., SLL, inflammation, reduced blood supply, infection) can lead to euthanasia and not the fracture itself (Dittmer and Firth, 2017; Sloet van Oldruitenborgh-Oosterbaan, 1999). This further reinforces the idea that complications need to be prevented for the best success in treating limb injuries, as once they develop, the prognosis often worsens.

Unlike humans, horses cannot remain in recumbency for extended periods due to adverse physiological consequences, such as the accumulation of secretions in their nasal passage, hindered blood flow to their muscles and possible nerve damage (Schatzmann, 1998). For these reasons, many researchers (e.g., Bowman, 1995; Schatzmann, 1998; Smith, 1981; Wattle et al., 1995) have tried to develop a device to reduce or avoid weight being supported by the limbs during recovery (recently reviewed by Steinke et al. (2019b)). One of the concerns of using a device to support weight in the long term is the development of tissue trauma, such as pressure ulcers, myopathy, or neuropathy (Schatzmann, 1998). In response to these complications, a new harness is under development aiming to reduce the risk of complications when supporting weight long term. This thesis focuses on developing the breastplate component of the harness, which contains air pockets that cycle through programmed inflation and deflation patterns to relieve pressure intermittently and reduce the risk of tissue trauma with constant pressure. The harness aimed to remove 50% of the weight to aid in healing and support the load normally applied to the injured limb.

A 50% weight compensation was chosen because this would equate to restoring the original weight borne by a limb in the case of non-weight-bearing in the opposite limb. Removal of too much weight may be detrimental because previous studies using flotation tanks showed that a 75% weight compensation could lead to muscle atrophy (Smith, 1981; Hutchins, 1987). Therefore, McClintock et al. (1987) suggested that a sufficient weight reduction would be to maintain the load that had been supported before the injury occurred.

Standing horses support approximately 60% of their weight in the forelimbs and 40% in the hindlimbs (Clayton, 2016). This weight distribution would result in a 500 kg horse supporting 300 kg in the forelimbs. Therefore, one forelimb would support approximately 150 kg (or 50% of the forelimb weight). The incidence of SLL has been shown to increase with increasing body weight of the horse, along with an increasing length of recovery (Baxter, 2017; Ishihara et al., 2006b; Smith, 1981). Each additional week of recovery resulted in a 20% increase in SLL risk (Virgin et al., 2011). Therefore, it is crucial to find a balance in maximizing weight supported by the horse (i.e., minimize weight reduction) to aid in minimizing muscle atrophy or wasting, while also not applying too much weight to the supporting limb to prevent the development of SLL. Other precautions, such as cyclic loading and unloading, to assist in blood flow, are also beneficial (West, 2007).

Further studies are needed to determine the exact weight reduction that best minimizes complications. However, due to the static nature of commonly used support devices and the inability to readily control weight reduction, previous devices were not adequately equipped to perform such a study. A 50% weight reduction is our assumed best prediction of required weight compensation to avoid SLL, based on previous studies and their observations (e.g., Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981).

Along with a weight compensation lift to successfully reduce weight while maintaining mobility, a support harness is needed. A recent study attempted to use the Anderson sling with a weight compensation lift (Montgomery et al., 2019). However, the study was believed to be limited by the complications imposed by the Anderson sling. The study by Montgomery et al. (2019) observed respiratory compromise and significant aversion behaviour at 18% weight reduction in the forelimbs and 4% weight reduction in the hindlimbs, respectively. Taylor et al. (2005) stated this could occur if straps are applied incorrectly or too tightly and due to pressure from the horse hanging in the sling (i.e., the total weight of the horse supported by the sling) for a prolonged period of time. Veterinarians have also voiced concern with decreased venous return from the head, neck and legs if straps are applied incorrectly (Gimenez et al., 2008). François et al. (2014) noted that some of their study results could suggest less efficient pulmonary ventilation in the sling. However, further testing is required. There also appears to be controversy over whether the Anderson sling causes respiratory compromise, as vets have expressed concern but studies documenting complications have only supported the horse for two to 15 minutes, and the horse is generally under anesthesia (François et al., 2014; Gimenez et al., 2008; Taylor et al., 2005). Therefore, the indeterminate findings and potential for physiological complications demonstrate the need to develop and test a new support harness for the rehabilitation of horses long-term to avoid respiratory compromise and restricted blood flow.

Pressure ulcers can be a primary concern when a high mechanical load or prolonged pressure is applied to the soft tissues, especially over a bony prominence (Coleman et al., 2014; Nakagami et al., 2015), such as in the use of a support harness. Pressure injuries can occur with sustained pressure, shear forces, friction and high humidity/moisture (Coleman et al., 2014; Schwartz et al., 2018). Schwartz et al. (2018) found that the coefficient of friction (COF) increased in all cases with increasing moisture, regardless of the type of liquid present. Recognizing a reduction in moisture may be vital in reducing frictional and shear forces and, therefore, reducing the risk of pressure injuries (Schwartz et al., 2018; Shi et al., 2018).

In human patients particularly susceptible to pressure ulcers, ulcers can occur in as little as one to two hours if ischemia persists and necrosis occurs (Gebhardt, 2002; Kosiak et al., 1958;

Reswick and Rogers, 1976). The development of pressure ulcers also depends on blood supply and the vessels' ability to withstand pressures. Different areas of the body are designed to withstand different pressures (Gebhardt, 2002; Sangeorzan et al., 1989). For example, although there is a thin, soft tissue covering and bony prominences in the soles of human feet, the vasculature is well-adapted to withstand large distorting forces. The most substantial damage occurs when there is deformation in deep tissues near a bony prominence because larger vessels are likely to be affected. This can result in a large area being affected by necrosis before the skin surface begins to breakdown and reveals a large cavity of necrotic tissue (Gebhardt, 2002). Most studies are performed in humans, but studies have began evaluating pressure sores in horses under saddle (e.g., von Peinen et al., 2010).

von Peinen et al. (2010) performed a study to assess saddle pressure and sore development over the withers of horses with well-fitting and ill-fitting saddles. They found that mean pressures greater than 15 kPa and maximal pressures of 35 kPa during sitting trot resulted in back pain. The mean pressure in healthy horses was 7.8 ± 1.7 kPa at the walk and 9.8 kPa at the trot. In contrast, humans with prolonged exposure to pressures greater than 4.26 kPa (just above the capillary closure pressure) were at risk of pressure ulcers. The study by von Peinen et al. (2010) stated the critical pressure was 15.3 kPa in horses at a walk, which indicates horses can tolerate much higher pressures than humans. As stated by von Peinen et al. (2010), the main difference is that the human pressures are prolonged, constant pressure in bedridden or wheelchair-bound patients, whereas the horses in these studies were ridden for one to two hours a day. This difference is an important consideration in interpreting pressure values, as horses supported by a rehabilitation lift for up to six weeks would have constant, prolonged pressure 24 hours, seven days a week, similar to the human patients in these studies.

Recognizing the normal application of load or pressure to the area is key in applying support or load to the skin surface; skin in most areas of the body is not adapted to withstand high pressure or long-duration pressure (Gebhardt, 2002). Once pressure ulcers develop, there is a high cost associated with their treatment (Coleman et al., 2014; Nakagami et al., 2015; Pagnamenta, 2017; Shi et al., 2018). Levet et al. (2009) studied the presence and risk factors associated with distal limb cast sores in horses with limb injuries. They found severity to be associated with increasing age, increasing weight, increasing number of casts and total cast period. They also performed thermographic analysis and found the severity of sores to increase with increasing temperatures (Levet et al., 2009).

Bony prominences, poor medical health, and contact with rigid medical devices can also increase the risk of an ulcer (Coleman et al., 2014; Nakagami et al., 2015; Schwartz et al., 2018). One way to prevent pressure ulcers is to reduce the pressure by increasing the contact area that provides support (Nakagami et al., 2015; Shi et al., 2018), spreading the load over a greater area. Another preventative measure involves alternating the pressure applied to the body, reducing the duration of the pressure (Shi et al., 2018). For example, pressure redistribution mattresses are now used in hospitals to decrease the risk of pressure ulcer development when patients are bedridden. Nakagami et al. (2015) evaluated the effect of an alternating pressure system on tissue oxygenation in 19 healthy human participants. This system did not increase interface pressure with reduced contact surface area during deflation and significantly reduced reactive hyperemia during 30-minute testing compared to a static device.

The purpose of this part of the thesis was to test and modify a newly designed front limb support device that can be used to support 50% of the horse's front limb weight. The final device is intended to support the horse (24 hours a day, seven days a week) for up to six weeks during the rehabilitation of a musculoskeletal injury, with the possibility of increasing or decreasing load based on individual needs. The final device will be tested long-term (i.e., for six weeks, 24 hours a day, seven days a week) but was not completed in this thesis due to the multiple phases involved in the development of such a system. This study's objective was to comfortably support 50% of the horse's front limb weight with a newly designed breastplate while attached to a dynamic rehabilitation lift. The breastplate was attached via seatbelt webbing to the H-frame used to test previous harness prototypes. The H-frame was then attached to the lift via a quick-release buckle for safety. The breastplate was tested independently from the rest of the harness at this stage of testing, as the hindlimb component requires further development to support 50% weight compensation comfortably. The hypothesis was that a breastplate design could be created for use with the weight compensation lift, which allows for the removal of 50% of the front-end weight comfortably. Comfort was determined through recording behaviour score and respiratory rate. Specific aims were: 1) to apply the study of equine biomechanics, physiology and behaviour to the design and development of the rehabilitation harness components, 2) to design and implement a front limb support device that could reach a 50% weight reduction in the front limbs while maintaining reasonable comfort short-term (i.e., 30 minutes to 1 hour), and 3) test the equine rehabilitation harness design component (i.e., breastplate) when used with the weight compensation lift.

3.2. Background on Lift, Harness, and Breastplate Design

The study was approved by the University of Saskatchewan's Animal Research Ethics Board and adhered to the Canadian Council on Animal Care guidelines for humane animal use.

In order to understand the nature and progress of the study and specific attributes of the breastplate, as well as the tools used to test it, the lift will be explained along with the previous harness prototype that led to the development of the breastplate.

3.2.1. Dynamic rehabilitation lift

A novel computer-controlled dynamic lift system (Figure 3.1) was designed and built by Saskatoon-based RMD Engineering, Inc., to assist severely injured or neurologic horses, providing ambulatory support with adjustable weight compensation (i.e. load reduction). Our research group, led by Dr. Julia Montgomery, was involved with the initial testing of this lift system for horses beginning in 2015. Through controlled mobility and independent control of the front and hindlimbs, this system's overall purpose is to reduce complications when treating musculoskeletal conditions through partial weight reduction. The percent weight reduction is calculated manually based on the horse's body weight (i.e., a 500 kg horse carrying 60% on the forelimbs and 40% on the hindlimbs would result in approximately 300 kg supported by the forelimbs and 200 kg by the hindlimbs). To reduce the load by 50% on the forelimbs and hindlimbs, 150 kg and 100 kg would need to be supported by the lift, respectively, to achieve a 50% reduction. A 50% weight reduction was the aim of this research because if a horse completely transfers the weight usually borne by two limbs onto one limb, a 50% weight reduction would restore the load normally borne by each limb (i.e., in this case, 150 kg on one forelimb). Furthermore, other studies have shown that a 75% weight reduction can result in muscle atrophy (e.g., Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981). It is essential to remove enough weight that blood flow to the feet can be maintained, but also not to remove too much weight so as to mitigate the chance of muscle atrophy or, in severe cases, wasting or osteopenia (bone loss).

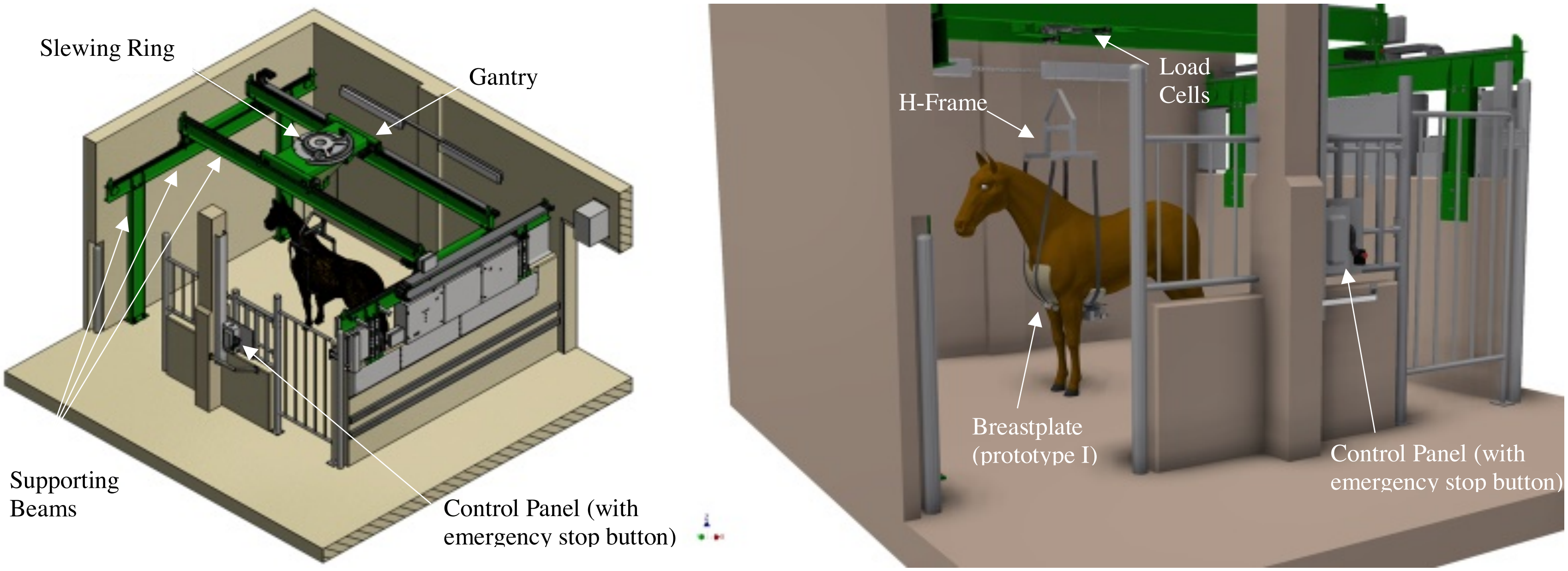


Figure 3.1. Design of the equine-assisted rehabilitation lift installed at the Western College of Veterinary Medicine. The Lift was used to develop and test the new harness design (Prototype I breastplate pictured).

3.2.2. Rehabilitation stall where lift is installed

The equine rehabilitation lift (Figure 3.1) was installed for research use at the Western College of Veterinary Medicine (WCVM) at the University of Saskatchewan in Saskatoon, Saskatchewan, in 2015. The lift was built over a period of six months. This lift is the only computerized large animal lift for rehabilitation that we are aware of to assist severely injured or neurologic horses, providing ambulatory support with adjustable weight compensation (i.e. load reduction). The lift is still in development, and therefore, has not been sold or built elsewhere. The gantry containing load cells is supported by beams running vertically, supporting horizontal beams in which the gantry is attached. The gantry is attached to a slewing ring, which allows the hoist to turn 359 degrees. The lift can move north, south, east, west and rotate (359°) (See Appendix A, Figure S1, A). Two pick up cables can be raised and lowered, together or separately, for ease of attachment to the horse. The load cells within the hoist allow the weight compensation to be measured and adjusted via remote control.

3.2.3. Lift operation principle

The lift operation principle was tested in a recent study by Montgomery et al. (2019) with the Anderson sling. The lift consists of large beams supporting a computer-controlled hoist system. The testing of the lift was completed previously before this thesis began. The lift was initially tested with the Anderson rescue sling and programmed to respond to the weight and movement of adult horses (Montgomery et al., 2019). Testing involved increasing percent body weight compensation through the lift. Heart rate, respiratory rate and behavioural scoring were measured throughout the initial trials with the Anderson sling (Montgomery et al., 2019). Once a maximum tolerated weight compensation was determined through behavioural observations, time attached to the lift was increased, and heart rate, respiratory rate, behavioural scoring, muscle enzyme activity and blood flow to distal limbs were measured. The horses displayed avoidance behaviour at 18% and 4% weight compensation on the front and hindlimbs, respectively (Montgomery et al., 2019). The average maximum time was 2.25 hours of attachment to the lift. Respiratory rates increased, and breathing was shallow. The main complications were compromised breathing and aversion behaviour (e.g., tail swishing, kicking at the abdomen, reluctance to move, and struggling against the sling), indicating significant discomfort, which was believed to be due to the Anderson sling lifting under the thorax and abdomen (Montgomery et al., 2019), which are not normally weight-bearing structures. These limitations of the Anderson sling led to the development of a harness supporting the horse around its load-bearing structures (a component of this harness, the breastplate, is the subject of this thesis) that will provide an opportunity to use the rehabilitation lift to its full potential. The study by Montgomery et al. (2019) was intended to test the lift on horses and fine-tune the initial design. This thesis focuses on the development of a component of the harness, which was a breastplate for front limb support. A harness prototype was developed in a previous study (Steinke et al., 2019a), but further modifications were required to reach a 50% weight reduction. These further modifications are the subject of this thesis, with the development of an air-pressurized breastplate supporting the horse's front limbs. Future plans for the lift include the implementation of automatic tracking to follow the horse’s movement to avoid manually driving the lift.

3.2.4. Harness design

The original full-body harness was previously tested in Steinke et al. (2019a). Previous harness development led to the breastplate's creation to support the front limbs, providing support over a greater surface area. Harness development focused on anatomical structures that would normally support the weight (i.e. bones of the front and hindlimbs), considering potential complications if proper support was not achieved. Length of rehabilitation (up to six weeks) and assumed desired percent weight compensation (i.e. load reduction of 50%) were other important considerations for harness development. This weight reduction was determined based on other studies (e.g., Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981) and the complications they observed at 75% weight reduction. Safety was a priority in development, aiming to design a harness that could be placed on the horse with minimal personnel (i.e., one person) and quickly detached in an emergency, without any loose components or straps where the horse could get tangled in the harness. Prior to the research described in this thesis, the first rehabilitation harness prototype was made of cotton/nylon with sheepskin inserts (removable for cleaning) and high-strength seatbelt webbing to provide support around load-bearing structures (i.e., the front and hindlimbs) (Steinke et al., 2019a). The support straps were redirected away from the thorax and abdomen and focused on the chest, shoulders and legs, considering skeletal structure, muscles, major nerves and blood vessels to minimize possible complications, such as restricted blood flow and pressure-induced tissue trauma. Load/strength testing of the initial harness prototype tested in

Steinke et al. (2019a) was completed (> 500 lbs), with no sign of material failure. A load reduction of 40% (front: 125 of 303 kg [60% of 506 kg]; hind: 80 of 203kg [40% of 506kg]) was achieved before complications (abnormal posture – spreading of the front limbs) arose (Steinke et al., 2019a). Due to this abnormal posture, modifications were needed. The focus was directed to weight reduction in the forelimbs to improve comfort and posture (e.g., spreading of the legs) before modifying the hindlimb support further. The focus was directed to the forelimbs due to injuries being more common in the forelimbs (Hayton and Sneddon, 2004) and due to the higher weight ratio supported by the forelimbs (i.e., approximately 60% supported by the forelimbs and 40% by the hindlimbs (Clayton, 2016)). After measuring the pressure applied to the horse's chest and shoulders, an H-frame and figure-eight pattern of straps on the forelimbs were added to reduce pressure on the shoulders and redirect pressure to solid structures (i.e., bones of the limbs and sternum) and over a greater surface area, respectively. Posture was improved, and a greater load reduction was achieved in the forelimbs (46% [140 of 301.2 kg]) during the next phase of testing (Steinke et al., 2019a). Respiratory rate and pattern were normal, and no aversion behaviour was observed (Steinke et al., 2019a).

The high-strength lightweight seatbelt webbing made the support straps easy to handle and sew into the cotton/nylon material. This integration of straps resulted in one solid piece being applied to the horse easily by one person. The harness was lightweight (easily rolled up and carried by one person or placed in a large bag) and tightly fitted to the horse, making it impossible for the horse to become entangled in straps if it reacted badly and needed to be detached from the lift. The harness could be draped over the horses back and then spread out and buckled up. Because most horses are used to wearing a blanket, the harness was accepted well.

An H-frame was used with the harness prototype (Figure 3.2) to remove inward pressure on the shoulders and direct the straps outward. A quick-release buckle was attached to the top of the H-frame to allow for immediate release in the event of an emergency. The crossbar was padded with quilted leg wraps and vet wrap to protect the horse's withers from injury if they came in contact with the solid crossbar. Racecar seatbelt attachments were used with the seatbelt webbing to attach harness components to the H-frame. Seatbelt buckles were used for quick-release at the top of the frame to attach the frame to the lift. Seatbelt tighteners were used to attach the harness or breastplate to the H-frame.

Figure 3.2. The H-frame used with the harness prototype to remove inward pressure on the shoulders and direct the straps outward.

3.2.5. Harness design related work

In comparison to other slings that generally have multiple separate components, this sling is designed for ease of use and safety in one complete piece. Other slings are similar in design in having forelimb and hindlimb components. However, they differ in having the abdomen piece supporting some weight. These slings are generally designed for short-term lifts (2-15 minutes maximum) and to completely support the horse. This harness is intended to only support 50% of the weight long-term (for up to six weeks). Most slings also only have one pick-up point, whereas the harness has two to allow for separate control over the front and hindlimbs. Slings have been made from various materials, including netting, mesh, ropes, fire hoses, canvas, and wide heavy webbing. The harness materials are low-cost and easily obtainable at a fabric store, allowing for easy access and high strength support. The soft slick material allows for smooth movement over surfaces, and the simple figure-eight pattern allows for easy application and placement over solid bone structures. The quick-release buckles were racecar seatbelt buckles rated for high loads and easily released under high tension, which can be ordered or obtained from a racing association. Further modifications were focused on front limb support, incorporating an air-pressurized chest support (breastplate) to increase comfort, increase the support surface area, and control factors thought to contribute to the development of pressure ulcers and other tissue trauma. Once development has been finalized, the front limb support device will be integrated into the nylon harness along with a hindlimb support.

3.2.6. Breastplate design

This part of the thesis was a design project with the following aims: 1) to test and modify a front limb support device (breastplate) intended to effectively reduce the weight on the front limbs by 50% while maintaining reasonable comfort and 2) to validate its use in conjunction with the weight compensation lift. The breastplate was built in collaboration with RMD Engineering, Inc. through an internship program (Mitacs Accelerate), which provided access to computer programmers and instrumentation technicians for breastplate programming and electrical components; engineers for assistance with design, modifications, and material properties; and machinists to aid in the fabrication of components (e.g., the building of air manifolds, milling of Styrofoam mould, and cutting of the Styrofoam fitting templates for chest curvature). Initial material research, testing of products and materials for use on the breastplate, fittings on the Styrofoam model and research horse, and trials were completed by the author. Ordering of materials, modifications and repairs were completed with assistance from RMD Engineering, Inc. The load testing of Prototype II and III was completed by RMD Engineering, Inc. Work completed on the breastplate was a team approach, involving input from all parties in their areas of expertise. These included design engineering, materials selection and testing (RMD team) and input on lift application, equine anatomy, physiology and biomechanics, as well as behaviour (Montgomery research team). Modifications were the result of trials completed on the research horse and then discussed as a team, following testing of each modification. Because of the complex nature of designing and testing such a device, a multidisciplinary team approach was needed throughout the design, building and testing of the breastplate.

Through the initial design, testing, and building process the breastplate described in this thesis evolved from a rigid fibre-glass shell to a flexible, loose-webbed material. Through problem-solving, research, and prototype design improvements for simplifying the building process, a more functional, practical device was developed. Three prototypes were designed and tested for this thesis. Modifications to an existing prototype were made when possible; otherwise, a new prototype was built. Prototypes were tested in a similar manner, including weight tests and fitting tests on a model horse and research horse for comfort. Once comfort was obtained, the testing proceeded to weight compensation trials. If discomfort was observed during these trials, the trials were terminated, and modifications were made before continuing.

This study focuses on the design of the breastplate and modifications that were made to increase comfort and reach a 50% weight reduction in the forelimbs, along with minimizing potential complications. The focus was directed to the front limbs to target one area at a time before moving to the hindlimbs. This was done because, in previous testing, modification of both the front and hindlimbs led to complications in determining the source of discomfort. Due to injuries being more common in the front limbs (due to higher weight distribution), the forelimbs were addressed first (Hayton and Sneddon, 2004).

The first prototype (Prototype I) consisted of a solid fibreglass structure, lined with silicone air pockets (providing soft cushioning), customized to the research horse's shape. Because of the resulting rigidity during the building process of Prototype I, a new prototype was needed. Prototype II was made of metal plates connected via seatbelt webbing, integrated into silicone, and lined with air pockets, which still did not have enough flexibility to adjust to the horse's shape. The current prototype, Prototype III, was made of fibreglass mesh, integrated into silicone, and lined with air pockets. This prototype has excellent flexibility, following the curvature of the chest and abdomen, moves with the horse and has successfully been tested to a 50% weight reduction with no observed aversion behaviour or changes in respiratory rate during a series of short-term tests (i.e., 30 minutes to 1 hour) with the weight compensation lift. The design and building process of the breastplate is described below and in detail in Appendix B. A description of the testing of each prototype is included below, along with the resultant design modifications.

3.2.7. Breastplate related work

Most rescue slings do not have a breastplate to support the forelimbs, with the exception of two slings. The sling-shell system has a breastplate like design, including two custom-made glass-fibre-enhanced plastic shells connected via a short girth (Schatzmann, 1998). This sling is used only for recovery from anesthesia and not for rescues. Another sling that had a similar design is the Horse sling by Musselman (1913), but the only information found on this sling is the patent. The Horse sling consists of a wide chest-band similar to a breast collar that connects to another wide-band running under the abdomen directly behind the elbows. Other slings use wide webbing to support the front limbs. The breastplate tested in this thesis is more flexible in comparison to the sling-shell system, which would be rigid, but is similar in design to the Horse sling front support by Musselman. However, different materials were used and a slightly different design (i.e., one complete piece versus two-piece chest support). In addition, the breastplate also has air pockets to alternate pressure, which is not a feature in the Horse sling. The rationale for designing a breastplate was to allow for pressure to be spread out over a greater surface area (approximately three times greater surface area than the seatbelt webbing in the previously designed harness) and to relieve pressure in certain areas (which was made possible through the increased surface area), restoring blood flow and permitting for cooling/drying of skin, through the cycling of the air pockets.

3.2.8. Research horse

The horse used for harness design testing with the rehabilitation lift was a 23-year-old Thoroughbred mare. Only one horse was used in this design project to improve safety for both the horse and handlers through the use of a horse familiar with the dynamic weight compensation lift that had been used in similar trials preceding this phase of the research program. The horse was a research horse explicitly acquired for testing the lift. Therefore, it was familiar with the harnesses and weight compensation testing procedures. Numerous modifications were made that significantly improved the breastplate comfort and safety for the horse and handlers, which will be discussed in this chapter. Additional modifications have been suggested (not completed as part of this thesis) in working towards a final prototype. Once a final prototype has been developed, future trials will involve testing several healthy horses, followed by client-owned horses with limb injuries.

3.2.9. Testing models

Initial tests with the breastplate were completed on a Styrofoam horse model (Figure 3.3), similar in size to an average horse, which was acquired for fit and safety testing. Fit testing was a multi-step process, including measuring material templates on both the model horse and research horse. A three-dimensional (3D) model was created from a spray foam mould of the model horse. Once the 3D model had been created, Styrofoam templates were cut out to measure the shape and proper curvature of the research horse. Using the measurements obtained from the Styrofoam fitting templates, a Styrofoam mould was milled to replicate the shape of the research horse to build prototype I and, later, used for weight and strength testing of other prototypes. Safety testing included load testing (the model horse was loaded with metal weights). In cases where a live test was required, the 23-year-old Thoroughbred Mare research horse was used as described in section 3.2.8.

Figure 3.3. EARL, the model horse, used for initial safety testing and fitting of the rehabilitation harness prototypes (example displayed above, harness prototype and H-frame used in previous studies) and breastplate.

3.2.10. Prototype material strength testing

A series of material and strength tests were performed to test the strength and safety of the breastplate, as well as its comfort before it could be used to support weight on a live horse. All breastplate design modifications were subjected to the following stages of testing: 1) fittings on either the Styrofoam model horse or the live research horse to ensure the breastplate could be safely applied to the horse 2) material safety testing (lifting at least 500 lbs (227 kg) and 3) short-term testing with the research horse and rehabilitation lift, gradually increasing to a 50% weight compensation to test for breastplate fit and comfort under different load conditions. First, the horse was observed wearing the breastplate to assess comfort and movement. If the breastplate did not fit correctly, caused discomfort or noticeable bunching of the skin or interference with normal movement, modifications were made. When the horse was comfortable in the breastplate, and the breastplate had been load tested to 227 kg, weight compensation trials began. The tests performed on each prototype are summarized in Table 3.1.

Once a breastplate shell was built, the breastplate was fit tested. First, the breastplate was fitted on EARL, the Styrofoam model horse (Figure 3.3). Once the breastplate was satisfactorily fitted to the model, the breastplate was applied to the research horse to determine comfort and fit while standing and walking. The comfort and fit tests allowed the horse to wear the breastplate for two hours, moving freely around the stall, eating, and getting used to the breastplate. When required, the design and building process continued until a working prototype was ready. Comfort tests were completed over three days (day 1 with Prototype IIa and day 2 and 3 with Prototype IIb) to ensure the research horse was comfortably able to move around the stall without interference before weight compensation tests began. The prototype was then strength tested for safety prior to testing with the live horse and attachment to the dynamic rehabilitation lift.

Strength testing consisted of attaching the breastplate and H-frame (Figure 3.2) to a load cell to verify the weight applied. The breastplate was then loaded with 227 kg to ensure it could safely support over 150 kg without failure. Once the breastplate was confirmed to be able to safely support 50% of the front-end weight (150 kg; 300 kg/2 = 150 kg) in a 500 kg horse, weight compensation trials began.

For the weight compensation portion of the study, the horse was brought into the stall before each trial and allowed to acclimatize to the stall. Weight was increased by 10 kg increments, and observations were noted. If complications were observed, trials were terminated, and modifications were made before continuing. Trials were short-term (up to 1 hour) focused on obtaining a 50% weight reduction. The weight had to be incrementally increased to allow the horse to adjust to the weight reduction and support provided by the lift. If discomfort was observed before a 50% reduction was reached, modifications were required to increase comfort. Weight compensation trials were completed over four days (testing day 1 was completed with prototype IIb on the research horse and EARL, and testing days 2-4 were completed with prototype III on the research horse). The weight reduction was not held at a 50% weight reduction once achieved in the final testing sessions due to changes in the horse's behaviour (i.e., handlers familiar with the horse could detect unease in the horse), limitations in lift programming, and an uncontrollable environment. Due to these limitations, it was not safe to attempt a 50% weight reduction for an extended period (i.e., a few hours). Consequently, long-term testing (i.e., hours, days, weeks, up to six weeks) will be completed in the future but was not part of the current design testing phase.

Table 3.1: Tests performed and the main components of each breastplate prototype.

Prototype Number	Tests performed	Components of Prototype
Prototype I	Strength test (> 500 lbs with Styrofoam mould and metal weight) Fit test (EARL & research horse)	Rigid Fibre-glass shell Metal plate support Solenoids Pressure gauges Air manifolds Individual air lines Individual air pockets (221) Humidity sensors (2) Thermocouple wires (32) Arduino
Prototype IIa	Fit test (EARL & research horse) Comfort test (Trial Day 1 on research horse)	Metal plates connected via seat-belt webbing embedded in silicone Four sections of air pockets
Prototype IIb	Fit test (research horse) Comfort test (Trial Day 2 & 3 on research horse) Strength test (500lbs with Styrofoam mould and metal weight) Weight compensation (Trial 1: testing on research horse and with EARL to fine-tune lift)	Metal plates connected via seat-belt webbing embedded in silicone Four sections of air pockets
Prototype III	Strength test (500 lbs with Styrofoam mould and metal weight) Fit test (research horse) Weight compensation trial (Trial 2-4: 1 trial without breeching and 2 trials with breeching strap on research horse)	Woven polyester scrim coated with PVC (Polyvinyl chloride) (P911 Mesh [MSP911_ _100] embedded in silicone Four sections of air pockets Four metal triangle attachments for the H-frame/lift

3.2.11. Physiological and behavioural measures

Respiratory rate was measured during weight compensation trial four (final test session – testing day 4) due to a slight change in breathing observed in trial three at 150 kg. Each trial was performed on a separate day after the necessary modifications were made. There were four trials in total with the research horse. Extra testing was completed with EARL to fine-tune the lift programming. The main pain assessment parameter was behaviour, as respiratory rate was indicated to be a poor pain measure by Bussières et al. (2008) due to confounding factors. Behaviour was scored using a modified behavioural scoring table from Montgomery et al. (2019) and Bussières et al. (2008) during all weight compensation trials.

Once baseline variables were measured and recorded, the breastplate was placed on the horse and attached to the dynamic weight-compensation lift (described in detail above). The dynamic lift was used to apply weight compensation to support the horse's front limbs, with the goal to achieve up to 50% weight compensation. Weight was incrementally increased at 10 kg intervals, starting at baseline (0 kg), and held for approximately 1 minute to allow the horse to adjust and observe any changes in behaviour or noticeable changes in physiological measures (i.e., grunting or shallow breathing). Respiratory rate was taken (in trial 4) at milestones where complications were observed with previous tests and prototypes, monitoring significant increases in weight compensation applied (i.e., 50 kg, 75 kg, 100 kg, and 150 kg). 75 kg was included as 50 kg was the weight achieved in the first weight compensation trial before discomfort was observed. Once 50% weight reduction was reached (with prototype III). In trial four a 50% weight reduction was held for five minutes before the horse displayed unease. Weight was slowly reduced in increments (trials 1-3) to allow the horse to adjust to supporting more weight (approximately 30 seconds) on their limbs. The quick-release was tested in trial four to ensure the horse could be released in the event of an emergency. Therefore, weight was not decreased incrementally in trial four. Trials were approximately 30 minutes to one hour. Although significant discomfort and aversion behaviours were not observed with prototype III, the horse did not appear to be comfortable enough in the breastplate to spend sufficient time (greater than 1 hour) at a 50% reduction.

Based on the results of these tests, further modifications were needed to increase comfort before "holding" the horse (i.e., 50% weight reduction for 30 minutes to one hour) at a 50%

weight reduction. Behaviour was scored at baseline and throughout the trial. The behaviour assessment was used to record any avoidance behaviours (e.g., "Swishing tail, kicking the abdomen, bowing of the back, sharp raising of the head, wide spreading of the legs, reluctance to move when asked to move, struggling against the sling when asked to stand still"; Table S1 Montgomery et al., (2019)) that occurred during the trial. If avoidance was observed, weight reduction was reduced until the behaviour disappeared. The weight reduction was noted, as well as any areas that appeared to be causing pain (i.e., digging in or pinching of the breastplate). Once observations were made and recorded, the trial was stopped for that testing day, and design modifications (e.g., trimming areas of the breastplate that were digging in and causing bunching of the skin and hair, such as between the legs and behind the front legs (elbow), changes of support material, changes to the H-frame, or addition of materials) were made (i.e., over days, weeks, months depending on the extent of the changes) before continuing testing. Major modifications included changes in supporting material in each prototype, as well as changes to the H-frame in an attempt to keep the breastplate in place during lifting, eventually resulting in the use of a strap around the haunches (i.e., breeching) to keep the breastplate from sliding forward towards the chest. These modifications are described in more detail in each prototype section.

3.3. Prototype I

3.3.1. Prototype I design

The aim of Prototype I (Figure 3.4) was to build a strong structure capable of supporting horses that allowed for movement; complete control over all aspects of the breastplate in order to gather data on the proper cycle to maintain good blood flow; proper pressure to fully support the horse without compressing air pockets; and the ability to test pressure, temperature and humidity to determine airflow and avoid moisture build-up between the horse and breastplate. This level of complexity (through the building process with all necessary components) required a rigid structure to protect all 221 air hoses from being compressed with the addition of a steel frame to attach support straps and fibreglass to integrate the frame.

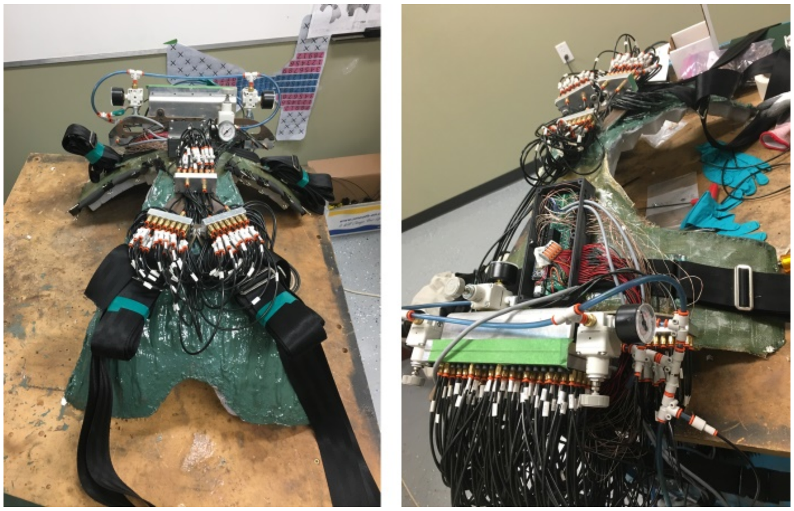


Figure 3.4. Prototype I breastplate with all components including support straps, manifolds, pressure gauges, solenoids, air hoses, temperature and humidity sensors, and the Arduino for programming and control (described in Appendix B).

The first prototype of the breastplate was made of fibreglass and silicone air pockets designed for complete control of each individual air pocket (221 individual air pockets). The Prototype I design included a flexible fibreglass shell (resin from Pro Form Products Ltd., Ontario, Canada, [PF175]) and fibreglass cloth (Stage 2). Its rigidity was increased with the addition of auto body filler (PF164) (Pro Form Products Ltd., Ontario, Canada) that was used to protect the hoses and the steel frame along with fibreglass in order to attach support straps and all components to the breastplate. The fibreglass shell was filled with 221 individual silicone (Dragon Skin™ 30, Smooth-On, Inc., Macungie, PA) air pockets. Silicone was chosen due to its use in other pneumatic air actuators (Ainla et al., 2017; Sonar and Paik, 2016; Suh et al., 2014) and because it provides a “medically safe and compliant interface with human skin” (Sonar and Paik, 2016). It also has superior physical properties and flexibility, a shore hardness value of 30 A, tensile strength of 500 psi, a 100% Modulus of 86 psi, and an elongation @ break value of 364% (“Dragon Skin 30,” 2020). It is important to note that this prototype will require customization for each horse due to the resultant rigid structure. Thirty-two thermocouple wires were attached to the silicone air pockets to provide temperature readings. Two humidity sensors were used to provide measures of moisture created from the use of the breastplate. The plan was to circulate air between the breastplate and the horse to try to remove moisture and increase dryness in areas where moisture collected from the use of the breastplate.

The silicone air pockets were tested up to 10 psi, which resulted in the failure of the silicone. The silicone air pockets were tested to failure to determine the maximum psi the air pockets could withstand (i.e., maximum psi that could be used in the air pockets). Exact pressures to support the horse would need to be determined in testing, as increasing weight would result in increased compression of air pockets (observed during Prototype I testing with metal weight). Therefore, psi of the air pockets would have to be increased with increasing weight compensation to avoid compression of the air pockets. The different breastplate zones were categorized into low, medium, and high-pressure areas visually based on angle or direction of support provided by the supporting structure (i.e., breastplate). Vertical surfaces were assumed to be low pressure, and horizontal surfaces were determined to be high pressure as most of the weight would be supported by the horizontal surfaces pulling upward. Surfaces that were on angle or curves were assumed to be medium pressure. Large manifolds were used to control each air pocket individually in high, medium, and low-pressure zones. Therefore, separate solenoids, pressure gauges, manifolds, and hoses were needed to obtain complete control. Based on this categorization of high, medium and low pressure areas, it was decided that a 1-in-2 cycle (one deflated and one inflated) would be used for the low-pressure areas and a 1-in-9 cycle (one deflated and eight inflated) for medium and high-pressure areas. Cycling time would have to be determined, but a 60-second cycle was used for Prototype I. This categorization was chosen by RMD Engineering, Inc., based on how much each zone contributes to weight-bearing. The idea was to maintain the greatest amount of blood flow in vertical pressure areas and maximize surface area in areas providing horizontal support (upward lift). Areas under higher pressure would need more surface area contact to spread the load over a greater area. The areas under low-pressure would not need as much surface area to result in the same pressure per square inch as the high-pressure areas. Therefore, fewer air pockets were deflated in a section under higher pressure to minimize the concentration pressure per square inch.

The air pockets were designed for cycling inflation and deflation to minimize constant pressure and relieve pressure intermittently to allow for the return of blood flow to the area under pressure (i.e., where the air pocket contacts the skin) for a prolonged period (days to weeks). The idea is to increase comfort and safety, enabling long-term use with minimal complications through altering pressure and providing flexibility to allow for normal daily movement. The ability to have complete control over all aspects of the breastplate resulted in the high complexity and many components leading to a sizeable rigid structure. The rigidity, weight and large components made the breastplate challenging to apply to the horse. It also raised safety concerns for both the horse and handlers. Cycles vary throughout the literature (e.g., 1-in-2 cycle (alternating), 1-in-4 cycle (Malbrain et al., 2010; Talley, 2018)), and therefore, would need to be determined through testing. This testing would consist of a multifactorial analysis – pressures resulting in capillary closure, time before tissue damage occurs, and time for blood flow to return to the area for horses, which was not a part of this thesis. With changes in the design and building process, the complexity was reduced from a 1-in-2 and 1-in-9 cycle to a 1-in-4 cycle for the entire breastplate. This reduction in complexity allowed the air-lines to be incorporated into the silicone and highly reducing the components needed to control the air pockets. This reduction in complexity allowed for a much lighter, smaller, and more flexible structure. It also decreased the time required for the building process, as well as ease of modifications. Prototype I was nearly impossible to modify, as all components were separate and had to be individually removed and reapplied, and the components within the fibreglass could not be modified. Prototype III (current prototype) is comprised of four sections of air pockets with integrated air-lines pre-poured and attached to the silicone with embedded webbing. This integration of air lines allows for a flexible structure and no external components attached to the breastplate, except for the air hose. Prototypes II and III are described in detail below.

3.3.2. Prototype I testing

The breastplate was strength tested under a 227 kg load (Figure 3.5) and tested for inflation and deflation under loading. Complications included the separation of materials, the breastplate sliding forward, twisting with the cycling of air pockets and a lack of flexion in the breastplate. One main complication was that the horse lost weight between seasons, and the breastplate no longer fit. This complication is important to consider as a horse in rehabilitation could have weight loss, along with muscle atrophy, resulting in a change in size. Because the horse was measured in multiple ways (i.e., initial measurements, material prototype, and fitting templates) to create the breastplate, it was assumed that she would stay consistent in weight, as the horse was healthy and was not expected to have a significant loss of weight. However, given that this was a prototype, significant time passed before a final product was available for weight compensation testing, as the material was researched, ordered, built, fitted to the EARL model and research horse, modified, tested and modified again when necessary. Because the breastplate was explicitly designed for the research horse, this prototype could have been used if the horse had maintained a consistent weight. Because of the change in size of the research horse and difficulty making modifications or fixing complications, a new prototype was required. Design modifications (i.e., a more flexible structure, better bondage of silicone to supporting material to seal air pockets to hoses, and a way to keep the breastplate from sliding forward) were needed to allow further testing to continue. Details of complications, the knowledge gained, and possible solutions are summarized in Table 3.2.


(A) (B)

Figure 3.5. The breastplate and H-frame were weight tested over 227 kg for safety (A) and (B).

Table 3.2: Complications observed, the knowledge gained, and possible solutions for breastplate design obtained during testing with Prototype I. The testing (and table) were completed with the help of Brendan Loewen and Paul Thiessen, WCVM class of 2021 summer research students.

Complication	Knowledge Gained	Possible Solution
Breastplate moves forward and twists under hoist	Weight and cycling of air pockets caused breastplate to slide forward and Styrofoam mould to slide back. This could cause the horse to slip out of the breastplate. Air pockets on an angle along with force acting backwards during the inflation/deflation cycle walks the object backwards in the breastplate.	No cycling of air pockets on an angle (on the chest area not directly under horse) or no air pockets, just padding.
Height/Shape of air pockets	Square air pockets do not inflate enough to fill gaps between the horse and the breastplate.	Different shape/more stretch for next design or more flexible breastplate to increase contact area.
Little flex in the breastplate	Need flex in breastplate to follow contours, so all air pockets make contact. This also became an issue with fit to a specific horse and weight gain or loss, which causes their shape to change. Although rigidity does make it easier to handle and place on the horse.	More flexible structure/support for the breastplate. Some rigidity to shape to the horse to make it easier to apply.
Leakage of air pockets	Air pockets that were sealed develop leaks with use. Even causing leaks through Velcro and silicone above fibreglass when silicone air pockets were attached and sealed to the fibreglass via adhesive Velcro bonding.	Each pocket individually sealed to hose with mechanical versus a chemical bond—use of a nut/clamp to attach silicone to the hose.
Danger to horse and equipment	Need many people to help place breastplate (at least two holding breastplate and one holding horse to apply breastplate). Testing also involves numerous people (one person to hold the horse, one to run hoist, and one/two to detach from the lift in an emergency). Breastplate also very heavy for one person to hold away from their body to apply to the horse.	Simple fibreglass shell that cannot be easily damaged, is easy to place by one person and follows the horse's body shape for minor complications in an emergency.
Weight of breastplate	Heavy and difficult to place on a horse.	Simplify breastplate, reduce components and weight.
Time to fix/build	Takes numerous hours/weeks/months to make a simple change due to dry/cure times and products used. It took six months to build the breastplate with individual pours and attachment of all components.	Start with a simple fibreglass shell for greater weight distribution. Mould is already made; a simple fibreglass shell could be made from the mould in a few days and be ready to test. OR Simplify/change materials and building processes.
Hard to make adjustments/changes	When fitting to the horse, it is not a simple change. Cannot adjust the shape/size/contour easily with all air pockets and components attached. New problems surface through different tests (e.g., fit versus weight compensation).	With less components can cut to fit and adjust after testing and complications arise. Once we know the best shape/size/contour/problem areas we can add the rest of the components to reduce complications further.
Compression of air pockets* **	Force backwards pulls air pocket back. When the air pocket deflated that force is removed from the air pocket. When the air pocket re-inflated straight up versus pulled back like previously, object in breastplate moved and twisted. Need more inflation/deflation to circulate air.	Change in air pocket design to prevent backwards force and allow for better airflow.

**** Compression of air pockets during inflation can lead to movement of the object in the breastplate when they deflate and re-inflate. This could also hinder airflow on top of the air pockets when circulating air to dry out areas.*

Attempts were made to fix the complications presented in Table 3.2. Different materials were tested (e.g., Velcro, fleece, silicone, seatbelt webbing and standard webbing) (see Appendix A, Figure S24). The loop side of the adhesive silicone was found to be the best for attachment to the silicone and the fiberglass. Therefore, the silicone was removed from the fibreglass (see Appendix A, Figure S25 & S26), the entire fibreglass shell was lined with adhesive Velcro (see Appendix A, Figure S27), and the silicone air pockets were re-attached. While repairing the breastplate, some of the hoses were blocked with silicone and with testing, the silicone started to lift again. It was concluded that a different, more flexible support material was needed, and a material that more readily bonded to silicone (i.e., Prototype II – metal plates with holes drilled in them, connected via seatbelt webbing) was used to avoid separation of materials.

The breastplate was also fit tested on the research horse (Figure 3.6), and due to rigidity, the breastplate did not fit tightly to the horse or bend up when the straps were tightened, which may have resulted in potential damage to the breastplate when weight was applied. Figure 3.7 demonstrates the integration of the breastplate into the previously tested nylon harness.

Figure 3.6. Research horse in the air-pressurized breastplate at the Western College of Veterinary Medicine (WCVM).

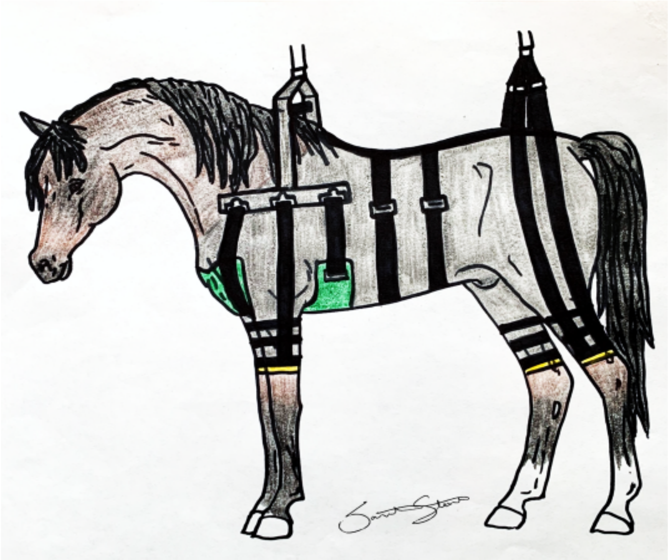


Figure 3.7. Drawing of breastplate design incorporated into the previously tested harness. The harness was successfully tested to 46% and 40% weight reduction in the front and hindlimbs, respectively, prior to breastplate design and testing.

3.4. Prototype II

3.4.1. Prototype II design

The next prototype of the breastplate was made of metal plates connected via seatbelt webbing (Figure 3.8) for strength. The task of finding a material that silicone binds strongly to was challenging, limiting materials that could be used to support the horse with sufficient bonding so that the air pockets did not peel off the support structure or lift during testing (which occurred with breastplate Prototype I, even after adding additional bonding with Velcro – discussed in Appendix B Supplementary Material). Testing of numerous materials (e.g., jeans, felt, Velcro, etc.) revealed that Velcro was the only material we could find that silicone did not just peel off of. However, even after attempts to seal the air pockets, Velcro was insufficient, and a new material was needed (i.e., metal plates connected via seatbelt webbing) to better bond silicone and also provide greater flexibility in the support material.

Figure 3.8. Second prototype breastplate (Prototype IIa) made of steel plates connected via seatbelt webbing. The seatbelt webbing ran through the steel plates and was riveted together. Holes were drilled in the metal plates to allow for greater bonding of silicone.

In Prototype II, slight difficulties were encountered with silicone lifting off the metal plates with use. However, the air pockets were now sealed separately from the supporting material. Therefore, lifting of the silicone did not result in leakages of air pockets. Multiple metal plates were used to allow for a more flexible structure (bending between plates) while maintaining the required material strength to support a horse. One significant difficulty was creating attachment points for the seatbelt webbing as all of the weight supported by the breastplate was directed to these four attachment points. The metal plates had holes drilled in them to facilitate silicone bonding around the plate and slots cut for attachment to the lift with the seatbelt webbing. The metal plates and seatbelt webbing were then covered with silicone and bonded to pre-poured and cured silicone air pockets with integrated air lines between pockets. The air pockets were separated into different inflation/deflation sections (four sections for a 1-in-4 cycle) with separate air lines to allow for the cycling of the pressure applied by the device. The air pockets inflated and deflated in a one-in-four cycle resulting in three inflated pockets to one deflated pocket in a 60-second cycle. This cycle was chosen to simplify the cycling from Prototype I (1-in-2 and 1-in-9). This change in cycling also allowed for simplifying the breastplate's building process, allowing the air pockets to be poured in batches, with layers (see Appendix A, Figure S28 & S29), including air lines integrated into the silicone. This reduction of air lines also significantly reduced the thickness of the breastplate and the weight. The deflated air pockets were staggered throughout the breastplate to maintain even contact. The breastplate production was sped up and simplified so that all areas (sternum, chest and sides of the abdomen) used the same cycling rate. Therefore, fewer manifolds and components were needed to control airflow. There was still a concern for low, medium and high-pressure regions. However, for design testing purposes and short-term trials, simplification was needed. For long-term tests, the high, medium and low-pressure regions can be reconsidered and tested to determine the proper cycling rate. This reduced complexity also reduced the number of silicone pours and separate components that needed to be glued together with silicone. Three moulds (a top mould that included air pockets (See Appendix A, Figure S28, A & S29, A), a middle mould that included the air lines (see Appendix A, Figure S28, A & S29, B) and a bottom mould sealed in the air lines (see Appendix A, Figure S28, B & S29, C)) were used to create one batch of air pockets, and only four batches (Figure 3.9) were required to cover the breastplate.

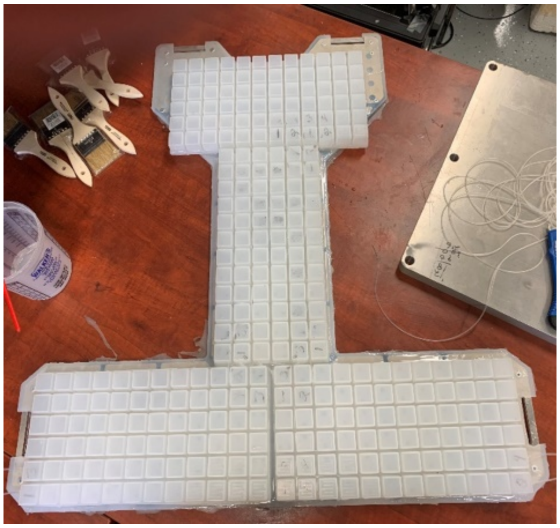


Figure 3.9. The assembling of the air pocket sections onto the breastplate structure (silicone-covered metal plates and seatbelt webbing). Four air pocket sections were used to fill the breastplate. This pouring of air pockets in sections sped up the building and modification of the breastplate. Sections were connected via silicone air lines to create one continuous flow of air

throughout all sections. Air pockets were separated into a 1-in-4 cycle to allow for the relief of pressure intermittently.

3.4.2. Prototype II testing

The horse tolerated the breastplate well during the two-hour fit test, but several areas caused the horse some discomfort. The breastplate placed significant pressure on the inside and back of the horse's front legs. This pressure on the inside of the legs resulted in significant bunching of the skin around the breastplate, forcing the breastplate into a slight 'v' (Figure 3.10). The horse spread her legs both forward and out (Figure 3.11) in an attempt to relieve the pressure. Her legs also trembled and were unsteady.

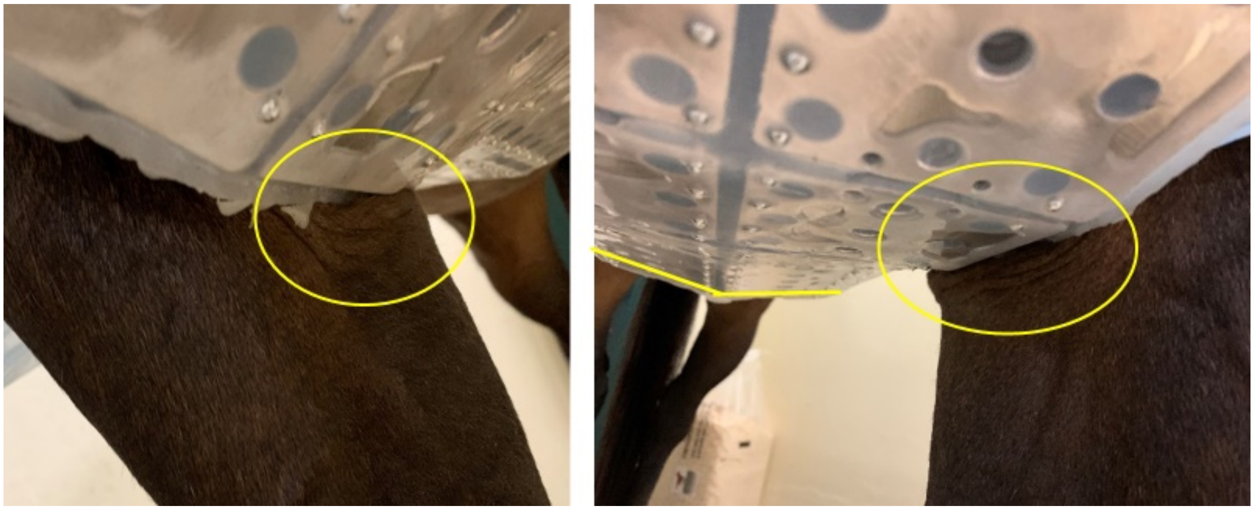
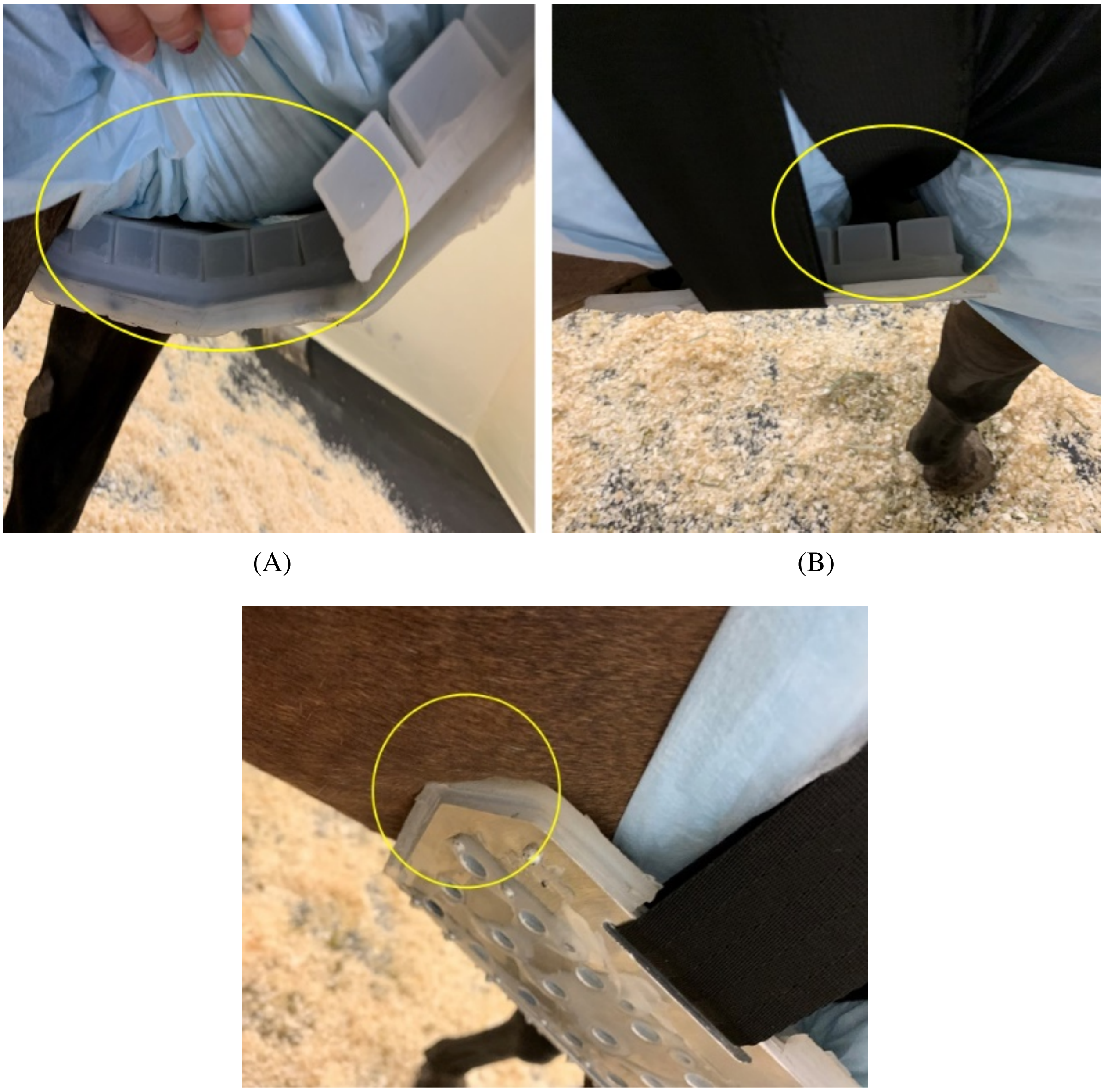

(A)
(B)

Figure 3.10. First fitting of the second prototype on the research horse. Breastplate modifications were required in the sternum area. The breastplate applied significant pressure to the inside of the horse's leg as determined visually by bunching of the skin and hair (A and B) along with forcing the breastplate into a slight "v" configuration (B).

Figure 3.11. Horse spreading front legs due to the pressure caused by Prototype IIa. The horse stood with a broad base in an attempt to reduce pressure on the insides of the legs.

Even though it was more flexible than the first prototype, the second prototype's rigidity resulted in significant gaps between the breastplate and the horse’s abdomen immediately behind the elbow and on the chest (Figure 3.12). These areas could not be removed entirely because they were there to maximize the surface area supporting the horse. Another reason to keep the abdomen side pieces of the breastplate was to provide padding between the horse and the support straps to prevent rubbing and concentrated pressure squeezing in on the abdomen. Additionally, the breastplate cut into the abdomen on the rear edge, due to the curvature of the abdomen outward behind the elbow. Further design modifications were needed before continuing trials. The complications, knowledge gained, and possible solutions are summarized in Table 3.3. The breastplate was fitted on the horse again to measure specific areas requiring modification and to sketch out the areas needing removal, which resulted in Prototype IIb.



(A)

(B)

(C)

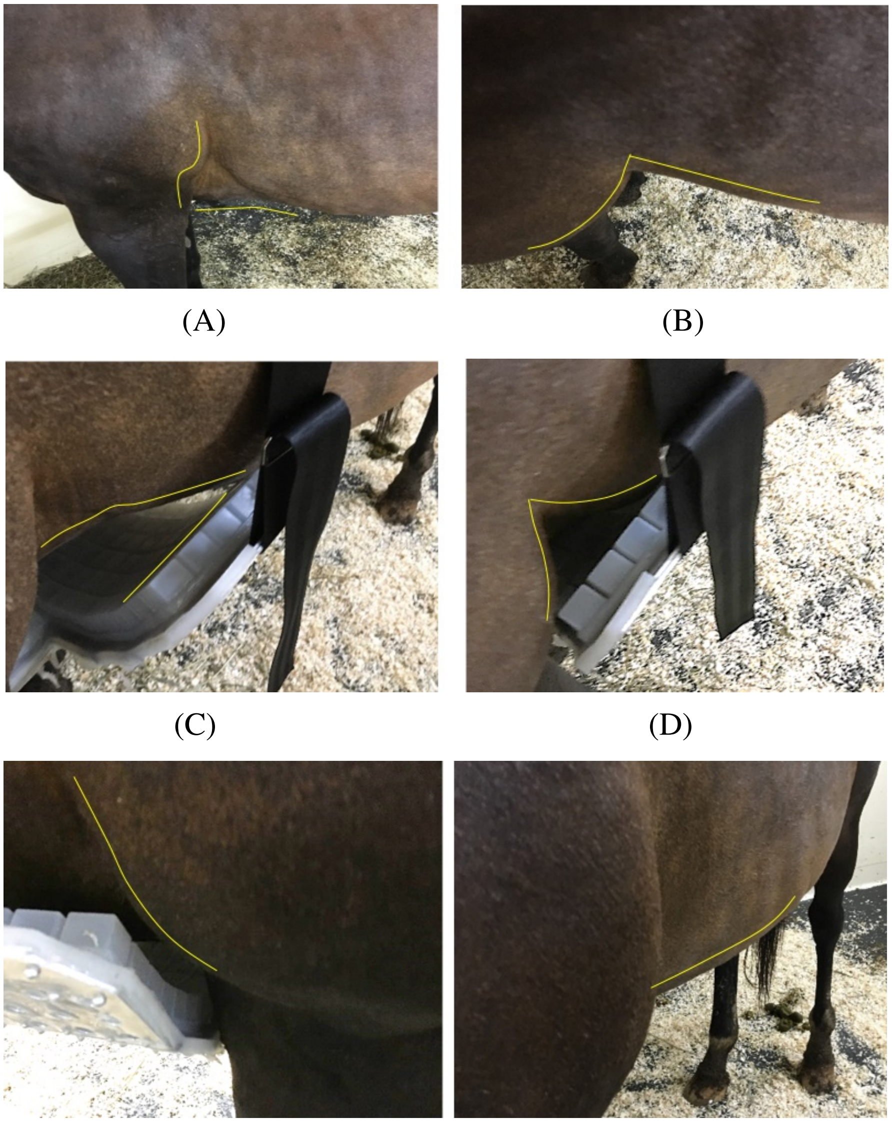
Figure 3.12. The breastplate modifications required on the abdomen and chest. The rigidity of the breastplate resulted in large gaps between the breastplate and the chest (A), as well as the abdomen (B). It also cut into the horse’s abdomen on the edge furthest to the haunches (C).

Table 3.3: Complications observed, the knowledge gained, and possible solutions for breastplate design obtained during trials with Prototype IIa.

Complication	Knowledge Gained	Possible Solution
Significant pressure on insides of legs visually determined through displacement and bunching of skin and hair, V-shape of breastplate and spreading of the legs.	Breastplate sternum piece is too wide for the research horse.	Trimming the width of the sternum piece to allow gaps between insides of legs and breastplate.
Significant pressure on the back of legs (elbow) visually determined through displacement and bunching of skin and hair.	Breastplate slides forward, and the abdomen piece placed pressure on elbows.	Cut out pieces of abdomen piece to allow more room for legs.
Digging into the abdomen at the back of the abdomen piece.	Not enough flex in breastplate horizontally.	Need more horizontal flex in breastplate to follow the contour of the abdomen.
Limited flex in breastplate resulting in gaps behind the elbow.	Not enough flex in breastplate to follow contours of the horse, so all air pockets make contact. The solid metal pieces could cause injury to the horse if displaced in an emergency.	More flexible structure/support for the breastplate. Horizontal flex and vertical flex needs to increase so that the breastplate can follow the curvature of the chest and abdomen, maximizing the contact area and maintaining even contact. Different support material with no rigid structures.
Multiple personnel required	Need many people to help place breastplate (at least two holding breastplate and one holding horse to apply breastplate). Testing also involves numerous people (one person to hold the horse, one to run hoist, and one/two to detach from the lift in an emergency). The breastplate is still heavy for one person to hold and apply to a horse.	Lighter and easier to handle support material.
Weight of breastplate	Heavy and difficult to place on a horse.	Simplify breastplate, reduce components and weight.
Time to fix/build	Metal plates cannot be easily cut to make modifications requiring downtime.	Find a material that is easily cut or trimmed to make modifications—a material not requiring special equipment to modify.

Modifications to the breastplate were sketched out based on an additional fitting of the horse (Figure 3.13). Some necessary measurements of the horse were made, assuming horses would have similar conformation (i.e., narrowed space from chest to sternum and between front legs, movement of the legs forward and backward during walking, and a barrel/abdomen that curves out slightly behind the elbow). The narrowest point between the horse's front legs was four inches, allowing room for approximately 3.5 airbags to fit on the breastplate section passing between the front legs. The shape was drawn on the existing breastplate (Figure 3.14), considering that the horse's leg will change position front to back during movement. Based on the width between the legs and accounting for the movement of the legs, several modifications were made – six airbags per row for the first three rows (closest to the chest) and then three per row to allow for more space between the legs and behind the shoulder (at the point of the elbow). The main pressure points were between the legs and behind the elbow, pushing into the elbow from the back, visually determined through displaced and bunching skin, as well as spreading of the legs.

The rigidity of this prototype did not allow for enough flexibility behind the shoulder to adjust for the curvature of the trunk (i.e., the fact that the horse gets wider the further you go back or caudal from the elbow). The side-to-side flexibility of the section sitting behind the shoulder needed to be modified before building the next prototype (addressed in prototype III below). The circumference of the horse's abdomen was measured immediately behind the elbow at 72.5 inches, with the circumference gaining one inch with every inch moved further backwards or caudal (away from the elbow). This curvature highlights the need to have side to side (horizontal when placed on the horse) as well as up and down flexibility (vertical when placed on the horse) to increase the surface contact area. Increasing the flexibility would reduce the need for customization between horses allowing for one breastplate to fit a broader range of horses and adjust to its changing shape when moving.

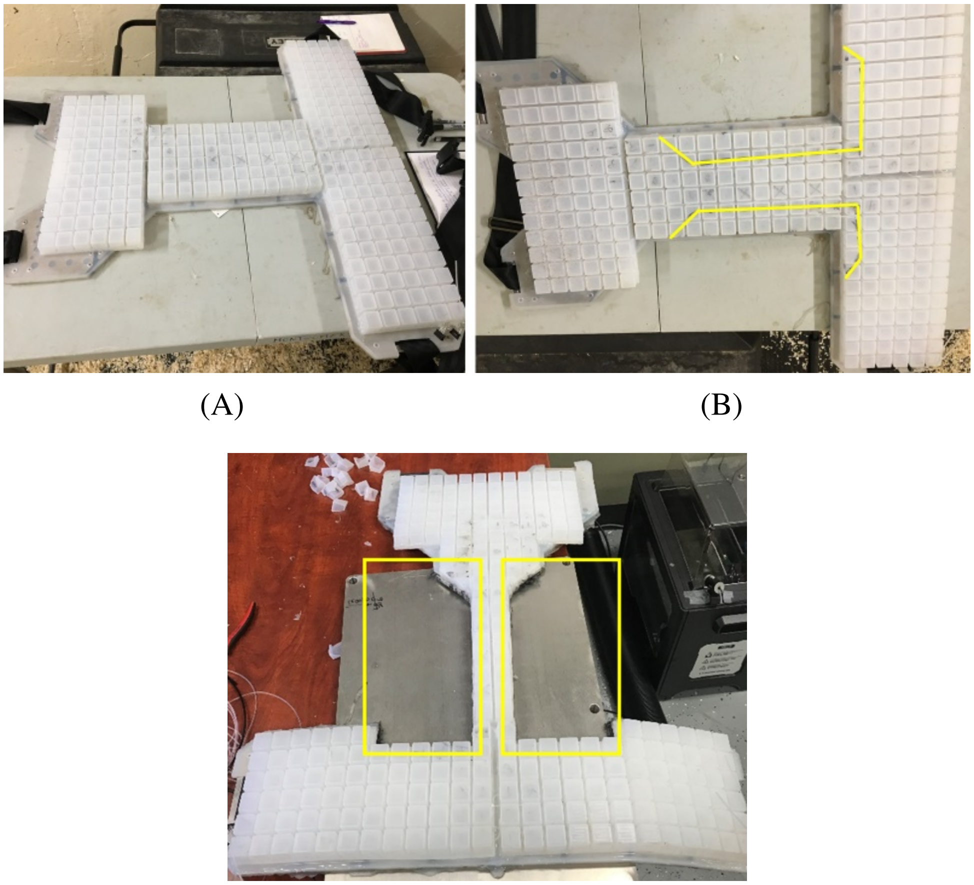


(A) (B)

(C) (D)

(E) (F)

Figure 3.13. Second fitting of Prototype II on the horse to indicate further design changes required on the breastplate. The rigidity of Prototype II resulted in significant gaps between the breastplate and the abdomen and chest. (A) and (B) highlight the shape of the horse behind the elbow. (C) and (D) display the difference between the shape of the breastplate and the shape of the horse's abdomen, requiring greater flexibility in the breastplate. (E) illustrates the conflict between the breastplate and the shape of the elbow. When the breastplate was tightened against the horse, it cut into the elbow and shoulder. (F) illustrates the shape of the abdomen conflicting with the breastplate and the limited flex horizontally.



(A)

(B)

(C)

Figure 3.14. Sketches on the breastplate to indicate areas requiring removal to adjust its shape. (A) is the second prototype (IIa) at the start of trials. (B) is the sketch made on prototype IIa indicating the area that needed to be removed. (C) is the breastplate after the removal of the ill-fitting areas (Prototype IIb).

The above-described modifications to Prototype IIa, which resulted in Prototype IIb, appeared to reduce the pressure between the legs and most of the pressure on the elbow, visually observed through no bunching of the skin and hair, no spreading of the legs and no hindrance in movement. Prototype IIb significantly improved with the modifications that were made from Prototype I and Prototype IIa. Therefore, another comfort and fit trial (two hours) was completed, allowing the horse to get used to wearing the modified breastplate. The horse could eat and move around the stall for two hours. Then the breastplate was removed. The horse seemed to be comfortable for the entire two hours the breastplate was worn. The piece behind the horse's elbow did still rub slightly, but it did not seem to bother the horse or cause discomfort.

Before the breastplate could be used for weight compensation trials, it was stress/load tested to 227 kg (500 lbs) by RMD Engineering, Inc. to ensure safety (Figure 3.15).

Figure 3.15. Strength testing set up for the prototype IIb breastplate. The breastplate was loaded with 227 kg, which was verified by the load cell attached above the H-frame on the breastplate.

Trial day 1 weight compensation lift

The breastplate was applied to the horse, and the horse was then attached to the lift. When weight compensation was added (up to 50 kg), the lift started "bouncing" (as if it was trying to adjust and find the correct weight). The bouncing of the lift was thought to be due to sensitivity or give with the silicone air pockets (not a solid material). The sensitivity programming was adjusted, and the lift was zeroed for the breastplate's current weight by RMD. The trial was resumed at 3 psi (see Appendix A, Figure S32, A) instead of 1 psi inflation pressure on the silicone air pockets to see if stiffer air pockets (see Appendix A, Figure S32, B) would reduce the adjustments the lift was making. The horse was very uncomfortable, and the trial was terminated until the lift sensitivity programming problems could be further addressed.

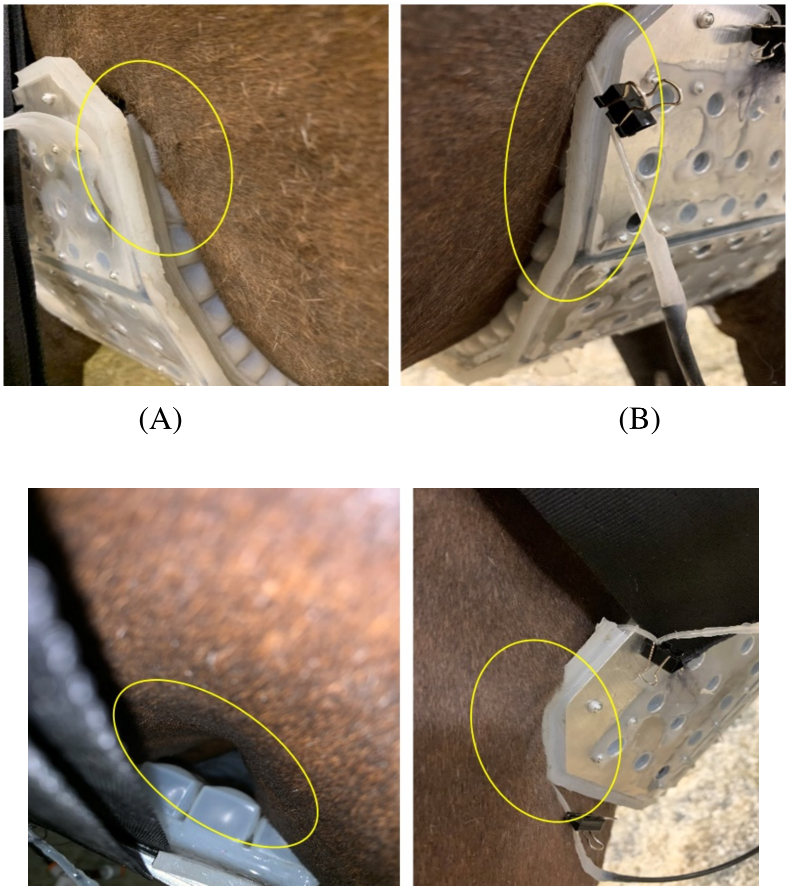
In addition to the lift sensitivity issues, the remote control for the lift (which displays the weight compensation values and readings from the load cell) was reading different weights than the setting for the weight compensation trial. For example, the weight compensation was set to 10 kg, and it was displaying 50 kg being supported in the front. Further adjustments to the programming were then implemented. The lift was re-calibrated and zeroed for the new breastplate. Further fine-tuning to the programming of the lift was completed by a specialist at RMD on a separate day.

Weight compensation tests consisted of increasing weight reduction in 10 kg increments, and observations were made at each increment for avoidance behaviour and abnormal posture that could indicate discomfort. If a maximum weight reduction was reached (i.e., the horse appeared uncomfortable and displayed abnormal behaviour), the weight was incrementally decreased to relieve any discomfort (e.g., abnormal posture). This weight was then noted along with any sources of discomfort and the necessary modifications were made.

On the first weight compensation trial (testing day 1), a maximum weight reduction of 50 kg was reached when abnormal behaviour and discomfort appeared. When the breastplate supported 50 kg of the horse's weight (approximately 16% of the front limb weight), it still cut into the skin at the back of the horse’s legs and abdomen. The air pockets on the sides of the abdomen where it was cutting in were completely depressed, and there were significant gaps between the abdomen and the breastplate near the elbow (Figure 3.16). The horse leaned back in the breastplate, placing its legs far forward, which appeared to be an attempt to relieve the pressure on the backs of the legs, almost to the point of lying down. Complications are outlined in Table 3.5 below. The testing revealed that further design modifications to the breastplate were needed before trials could continue. Total trial time (11:15 AM to 11:25 AM) was 10 minutes due to discomfort present in the horse. For this reason, the maximum weight was not held. The observations are included below in Table 3.4 at each weight compensation increment.

Table 3.4: The trial involving breastplate Prototype IIb.

Weight Compensation (kg)	Observations
0	
10	
20	
30	The breastplate edge pushed into shoulder/digging in.
40	The breastplate edge pushed into shoulder/digging in.
50	The breastplate cut into the back of the elbow, causing significant discomfort. Horse spread legs forward, leaning backwards to relieve the pressure on the elbows. Air pockets at the rear of the abdomen piece completely depressed. Gaps between abdomen and breastplate.



(A) (B)

(C) (D)

Figure 3.16. Breastplate problem areas during the weight compensation trial of Prototype IIb. The air pockets most caudal were completely depressed on both sides (A) and (B) when weight compensation was activated. There was still a large gap between the breastplate and horse behind the elbow (C), and immediately in front of the gap, it cut into the shoulder (D).

Based on these results, the suggested modifications included: 1) widening the H-frame that attaches the breastplate to the lift and extending the attachment arm back towards the abdomen to try and pull the breastplate back and away from the elbow (Figure 3.17) to reduce bunching of the skin; 2) increasing flexibility around the abdomen (horizontally – to follow the widening curvature of the abdomen) to reduce the gap between the abdomen and breastplate and avoid digging into the abdomen; 3) consideration of a breeching strap (i.e., a strap around the haunches) attached to the H-frame to ensure the horse did not slide out of the breastplate backwards, with the haunches attached to the breastplate. The addition of sheepskin under the tail strap was considered to protect the skin from rubbing. The complications observed, the knowledge gained, and possible solutions to the problems are summarized in Table 3.5 below.

Figure 3.17. The Prototype IIb and H-frame on the horse used for weight compensation trial day 1. The yellow circles highlight the areas that required modification. The bar running across the top of the horse required an extension to pull the breastplate straps out and up to try and reduce pressure “squeezing” inwards on the abdomen.

The modifications made included extending the H-frame's side arms in an attempt to pull the breastplate backwards away from the elbow, reducing pressure and bunching of skin. Only one modification was made at this time to observe the change made with the H-frame adjustments. Later, a breeching was added to assist in pulling the breastplate backward away from the elbow, as the H-frame could not achieve this alone. The modification to the H-frame to make the crossbar adjustable will require a more complicated design change to allow for adjustability while maintaining strength, and therefore, was not implemented at this stage. Improving flexibility would also require additional modifications, involving a new support material and prototype design.

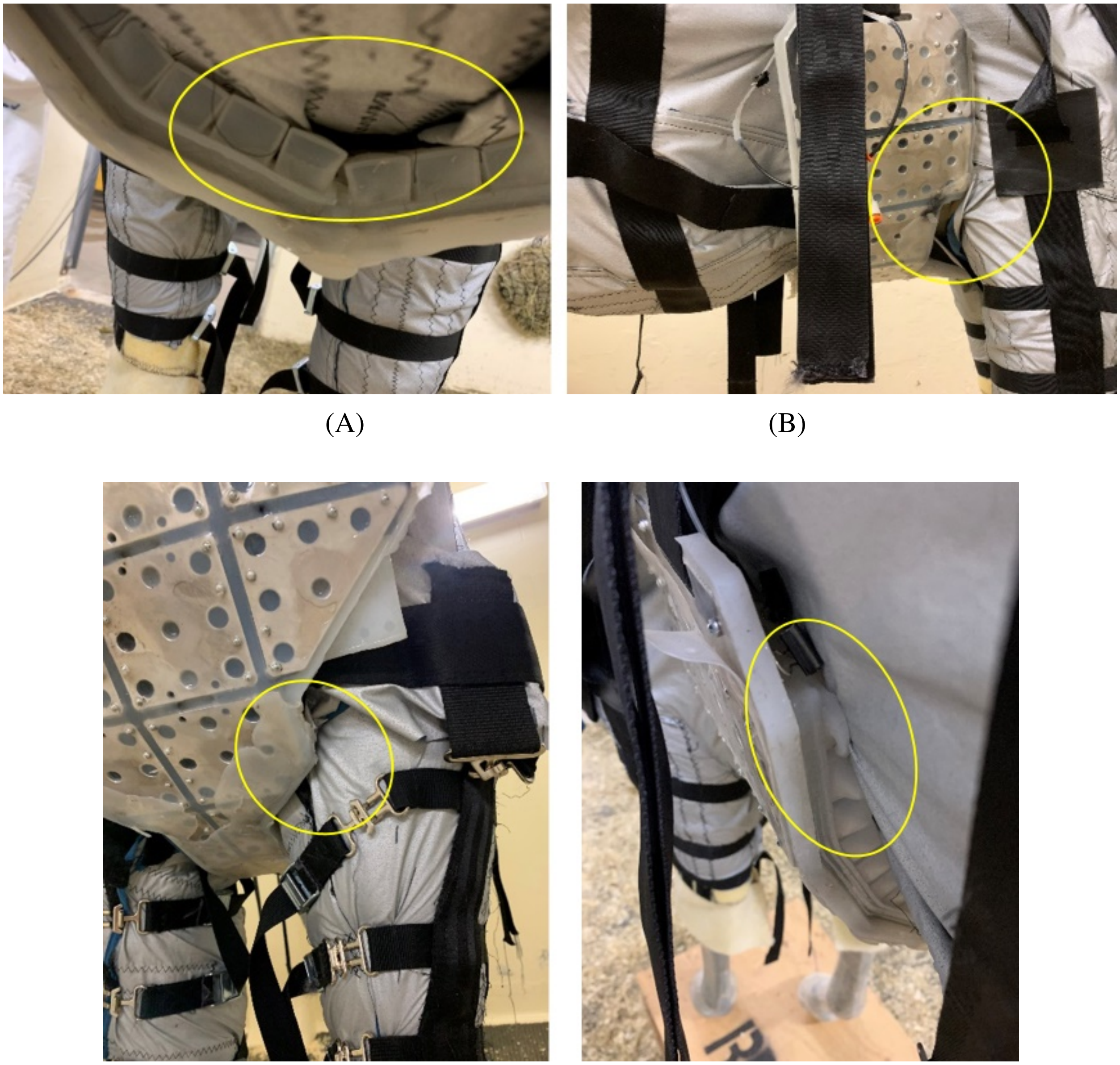
Table 3.5: Complications observed, the knowledge gained, and possible solutions for breastplate modifications obtained during a single weight compensation trial with Prototype IIb.

Complication	Knowledge Gained	Possible Solution
Significant pressure on rear of legs (elbow) visually determined through displacement and bunching of skin and hair.	Breastplate slides forward, and the abdomen piece placed pressure on elbows causing the horse to lean back, placing legs far forward in an attempt to reduce pressure on the backs of legs.	Extension of the H-frame backwards to try and pull breastplate away from the elbow. Possible tail strap or breeching to hold breastplate back.
Complete depression of air pockets and digging into abdomen at the back of the abdomen piece.	Not enough flex in breastplate horizontally even with weight compensation. Pressure needs to be removed from sides of the abdomen, "squeezing" inward on the horse, directing straps up and out versus up and in.	Need more horizontal flex in breastplate to follow the contour of the abdomen. Extension of the middle bar of the H-frame to allow adjustment for each horses' width.
Breastplate slid forward, and horse leaned backwards, spreading legs out and forward due to pressure on elbows.	Still significant pressure on the elbows when using weight compensation. The breastplate slid forward when the horse leaned backwards, which could result in the horse slipping out of the breastplate.	Extension of the H-frame backwards to try and pull breastplate away from the elbow. Possible tail straps or breeching to hold breastplate back.
Limited flex in breastplate resulting in gaps behind the elbow.	Not enough flex in breastplate to follow the horse's contours, so all air pockets make contact, even with weight compensation. The solid metal pieces could cause injury to the horse if displaced in an emergency.	More flexible structure/support for breastplate. Horizontal flex, as well as vertical flex, needs to increase so that the breastplate can follow the curvature of the chest and abdomen, maximizing the contact area and maintaining even contact. Different support material with no rigid structures for next prototype.
Weight of breastplate	Heavy and difficult to place on a horse.	Simplify breastplate, reduce components and weight.
Time to fix/build	Metal plates cannot be easily cut to make modifications requiring downtime.	Find a material that is easily cut or trimmed to make modifications—a material not requiring special equipment to modify.
Lift bouncing when weight was applied.	Lift required further fine-tuning and re-calibration with the new prototype (Prototype II)	Programming specialist at RMD performed further fine-tuning and calibration.
Remote for lift reading different values for weight compensation (i.e., 10 kg versus 50 kg)	Lift required recalibration with the new breastplate prototype.	Re-calibration was performed by a specialist at RMD.

Weight compensation lift trial with EARL model horse

The H-frame horizontal attachment arms were extended backwards towards the abdomen to try and pull the breastplate backwards and away from the elbow. Trials were resumed after this modification (within a few days, as the attachment arms had to be cut and all components reattached). We continued testing with the model horse to ensure the lift was working correctly and that the lift programming complications observed in the earlier trial were no longer present. The glitches in programming were resolved with calibration to the new breastplate and changes in sensitivity of the load cell to remain at a constant tension. Further programming was completed by RMD.

Testing with the model horse showed that a wider frame might help the breastplate fit better with the bottom making contact first to wrap up and around the abdomen (on the model horse there was a gap underneath due to the size and rigidity of the metal plates – Figure 3.18, A) and to pull outwards to avoid the pressure on the sides of the horse's shoulder. It appeared to continue to place pressure on the abdomen and elbow, even on the model horse (Figure 3.18, B and D). Based on the model horse's stance (i.e., the front legs are staggered, with one leg placed further back than the other), it was determined that the front of the breastplate may also cut into the legs with the movement of the leg forward (Figure 3.18, C). Complications observed, the knowledge gained, and possible solutions are summarized in Table 3.6 below.



(A) (B)

(C) (D)

Figure 3.18. Complications observed on the model horse in lift testing trials. After H-frame modifications, there were still gaps between the abdomen and the breastplate (underneath on model horse) (A). The breastplate still cut into the backs of the legs near the elbow (B), even with the extended attachment arms on the H-frame. There was the possibility of pressure being applied during movement in the breastplate as the chest piece cut into the model horse on the front of the leg (C) that is further forward. The air pockets were depressed on the sides of the abdomen (D).

Table 3.6: Complications observed, the knowledge gained, and possible solutions for breastplate design modification during lift testing trial with Prototype IIb.

Complication	Knowledge Gained	Possible Solution
Significant pressure on the back of legs (elbow) visually determined through tight contact with the model horse's leg.	Breastplate slides forward, and the abdomen piece placed pressure on the elbows.	New support material needed with greater flexibility to follow the contours of the horse.
Gap at sternum between breastplate and horse	Gap at the sternum, which could result in greater "squeezing" in on the abdomen.	Greater flexibility in the support material.
Complete depression of air pockets at the back of the abdomen piece.	Not enough flex to follow contours of horse.	More horizontal flex to follow the contour of the abdomen.
	Pressure needs to be removed from the sides of the abdomen, "squeezing" inward on the model horse, directing straps up and out versus up and in.	Extension of the middle bar of the H-frame.
Limited flex in breastplate resulting in gaps behind the elbow.	Not enough flex in breastplate to follow contours of the horse, so all air pockets make contact, even with weight compensation. The solid metal pieces could cause injury to the horse if displaced in an emergency.	More flexible structure/support for the breastplate. Horizontal flex, as well as vertical flex, needs to increase so that the breastplate can follow the curvature of the chest and abdomen, maximizing the contact area and maintaining even contact. Different support material with no rigid structures.
Possible interference with legs moving forward.	There could be interference with the horse's leg when moving forward due to the placement of the breastplate.	Change of material to allow for greater movement and flex with walking.

3.5. Prototype III

3.5.1. Prototype III design

The third and current prototype (Figure 3.19) involved the use of woven polyester scrim coated with PVC (Polyvinyl chloride) (P911 Mesh [MSP911_ _100] obtained from Michel's Industries, St. Gregor, SK) as weight supporting material in the breastplate to increase the flexibility of the structure (for a comparison of materials in prototype II and III see Figure 3.20). The webbing was incorporated into the silicone and attached to the air pockets. Steel hooks were sewn into the webbing to attach the breastplate to the lift. The breastplate needed to be more sling-like, wrapping around the horse and bending with its movement. This change in material allowed for a better fit, potentially reducing the need for customization between individual horses. It allowed the breastplate freedom to move with the horse to increase comfort. The silicone air pockets were removed from the metal support frame (see Appendix A, Figure S31) and used on the new breastplate prototype (Figure 3.19). For these trials, the air pockets were connected so that all air pockets were inflated at the same time, as testing of the cycling pattern and rate were not the focus of these trials (i.e., a 50% weight reduction was the aim). The air pockets have the capacity to change to a 1-in-2 or a 1-in-4 cycle for future testing when the focus can be directed specifically to the testing of the computer program, cycling rate, and cycling pattern. Quick-release buckles were used on the H-frame to ensure that the horse can be released quickly in the case of an emergency.

Figure 3.19. The breastplate silicone was removed from the previous support material (steel plates), and fibreglass webbing was incorporated for support. The fibreglass webbing was placed in a silicone mould in the shape of the breastplate. Silicone was poured and cured to encase the webbing. Silicone air pockets were attached to the silicone encasing the webbing.

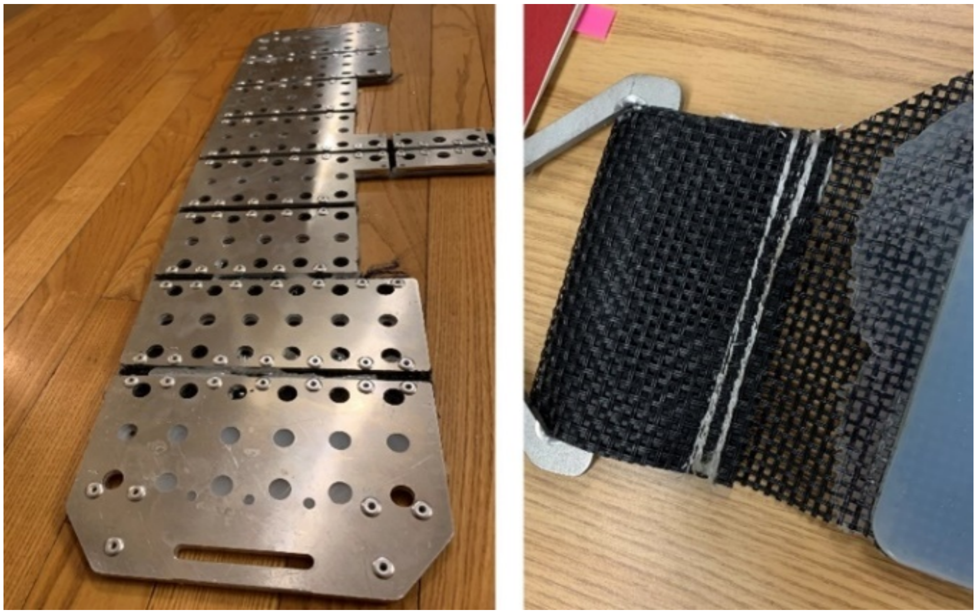

(A) (B)

Figure 3.20. Prototype II and III material comparison. (A) displays the metal plates and seatbelt webbing used in Prototype II and (B) shows the webbed material used in Prototype III.

3.5.2. Prototype III testing

The breastplate Prototype III was strength tested to 227 kg for safety (Figure 3.21, A). The air pockets were then fully inflated and checked for any leaks (Figure 3.21, B). Any leaks found were repaired. Several pockets became sealed during the modifications. Therefore, new lines were used to connect air pockets to ensure all pockets were connected and would have equal pressure during testing. Sections that were filled in during the silicone pouring process (previously removed from the elbow area due to pressure) were removed.


(A) (B)

Figure 3.21. (A) The breastplate was strength tested to 227 kg for safety. (B) The air pockets were then checked for any leaks.

The breastplate was wrapped in sheepskin padding and vet wrap (Figure 3.22) to protect any sharp edges of the breastplate from cutting the horse after trimming back the support webbing. These edges will be incorporated in the silicone mould in the next prototype to provide extra padding to protect the horse from the edges of the webbing.


Figure 3.22. The breastplate after being wrapped in sheepskin padding and vet wrap to protect sharp edges of the fibreglass webbing from cutting the horse.

Once the breastplate was sufficiently padded and deemed safe to apply to the horse, it was fitted to the research horse (Figure 3.23) to ensure the horse was comfortable in the breastplate before weight compensation trials began. Safety straps were added to the breastplate to attach the breastplate to the horse before attachment to the lift. This addition of straps also allowed the breastplate to be worn without attachment to the lift for fit tests. The horse was led around the stall to ensure there was no interference or discomfort with walking. The horse appeared relaxed, and no change in behaviour was observed.


(A) (B)

Figure 3.23. Fitting on the research horse (A) and (B) to ensure the horse was comfortable in the breastplate before weight compensation trials began.

Once the breastplate was deemed comfortable for the horse, the weight compensation trial two involving breastplate Prototype III (i.e., first trial with Prototype III) was completed. The weight compensation was increased in 10 kg increments, and observations were made at each increment (Table 3.7) for avoidance behaviour and abnormal posture that could indicate discomfort. The weights with noted observations are included in Table 3.8. The maximum weight reduction reached was 110 kg with the horse beginning to appear uncomfortable and display abnormal behaviour. The weight was incrementally decreased to relieve any discomfort. Total trial time (1:45 PM to 2:20 PM) for trial two was 35 minutes.

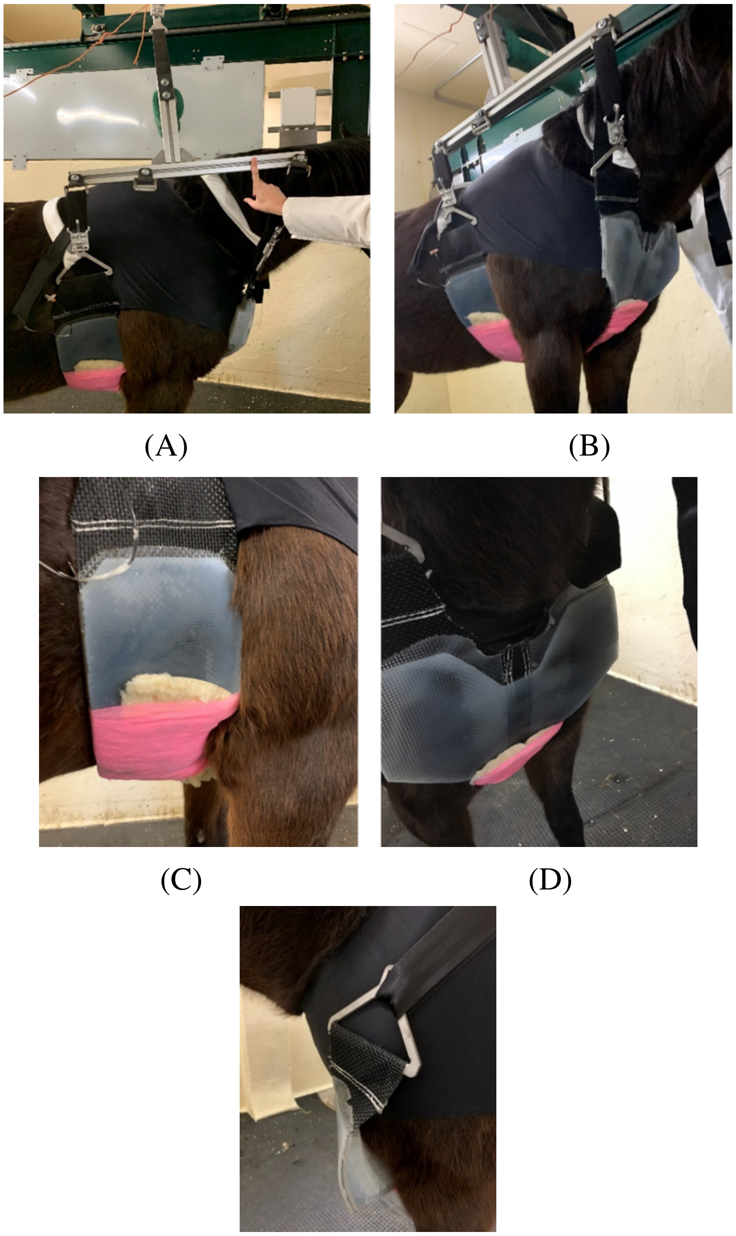
Table 3.7: The first trial involving breastplate Prototype III (weight compensation trial 2).

Weight Compensation (kg)	Observations
0	
10	Resting hindfoot, relaxed.
20	
30	
40	Elbow corner pushing into shoulder/digging in.
50	
60	Stopped resting foot briefly.
70	Resting hindfoot, looks to be falling asleep. Elbow joint/bone interference. Breastplate appears to be cutting in more with each increase in weight reduction.
80	The horse would not be able to walk because of elbow pressure – likely uncomfortable. No aversion behaviours were observed yet.
90	H-frame still appeared to be pulling the breastplate forward. Extensions did not help keep the breastplate back from the elbow.
100	Cut out fibreglass around the neck, could interfere with breathing if lower head to eat.
110 (max)	Agitation – kicking and uncomfortable (max weight reached during this trial). Scrunching lips and snorting.
100	Comfortable up to 100 kg – agitation stopped when weight decreased.
90	The breastplate was placing pressure on muscle in the horse's shoulder. The horse is tense.
80	
70	Resting foot again.
60	
50	
40	
30	
20	
10	
0	

Overall behavioural score throughout trial: Bright, lowered head and ears = 0, No apparent signs of sweat = 0, Occasional kicking at abdomen = 0-1, Standing quietly, no pawing = 0, No evidence of discomfort, head mostly straight ahead = 0, Interest (head up, ears up, watching activities through head movement = 0-1, Seeks human interaction = 0, Avoidance behaviour (kicking at abdomen at 110 kg reduction) =1

The breastplate fit well, and the horse seemed comfortable up to 100 kg of weight reduction (Table 3.7) (Approximately 33% weight reduction; 100kg/300 kg = 0.3333*100 = 33%; 16.6% short of 50% weight reduction). Flexibility had significantly improved with the new material (woven polyester scrim with PVC coating). However, the breastplate appeared to be sliding forward during the trial (Figure 3.24). As more weight was added, it slid further forward, placing more pressure on the elbow (Figure 3.24, C). A breeching strap would be beneficial as a design modification (added in future trials [trial 3]) to hold the breastplate in place as the horse would not be able to walk in the current prototype due to the pressure on the elbow. The H-frame did not remain level during the testing and had to be shortened (Figure 3.24, A) in order to support the weight evenly so as not to stress one end more than the other and to prevent uneven pressure applied to the horse. The fibreglass material around the neck needed to be trimmed (Figure 3.24, D) so that it would be level with the silicone and not digging into the neck when the horse lowered its head. A breeching strap was added for future trials (i.e., weight compensation trial day 3) to prevent the breastplate from sliding forward and seemed to fit well with the breastplate (Figure 3.25), holding it in place during the subsequent weight compensation lift trials. The horse was led around the stall to observe whether there were any problems that limited movement. The horse moved with no restriction or discomfort and did not seem bothered by the additional straps.

The next weight compensation testing day with Prototype III (weight compensation trial 3) involved adding the breeching strap to keep the breastplate back and away from the elbow. Like previous trials, the weight compensation was started at 10 kg and increased by 10 kg increments. Observations were made at each increment (Table 3.8) for aversion behaviour that could indicate discomfort. The weight reduction increments with noted observations are included in Table 3.8. After the weight reduction goal was reached (150 kg or 50% weight reduction), the weight reduction was incrementally decreased. The weight reduction was not held at 150 kg because the horses breathing pattern became slightly laboured (i.e., breathing with more effort). Total trial time (approximately 1:10 PM – 1:40 PM) was approximately 30 minutes. Overall behavioural scoring for the trial is included at the bottom of the table, as behaviours are indicated when observed.



(A) (B)

(C) (D)

(E)

Figure 3.24. The first testing of Prototype III showed that the H-frame required shortening to the level indicated in the picture (A). The H-frame was too high in the front, which could apply uneven pressure to the horse and result in complications (B). The breastplate was digging into the back of the shoulder (C), putting pressure on the muscle causing it to tense. The webbing on the breastplate required trimming (D) to avoid interference with the neck when the horse lowered

its head. The webbing needed to be on an angle to the side (E) instead of straight up in the front of the breastplate.

(A) (B)

Figure 3.25. Fitting of the breeching strap to hold the breastplate in place and avoid it sliding forward and placing pressure on the elbow. The tail strap design around the hindquarters (A). The breeching strap held the breastplate away from the elbow (B).

The addition of the breeching strap held the breastplate in place and did not place pressure on the elbows (Figure 3.26). There were only slight postural changes as the weight increased, including changes between resting of the hind legs and shifting of weight. The horse remained relatively comfortable up to the goal of 150 kg of weight reduction (Table 3.8). It was suggested to move the breeching strap higher in the next trial for better placement, placing pressure higher up from the hind legs due to the forward placement of the hind legs during lifting.

Table 3.8: Trial three (second trial with prototype III) involving the addition of the tail strap to prototype III.

Weight Compensation (kg)	Observations
0	
10	Comfortable.
20	Comfortable, resting left back leg.
30	Resting.
40	Resting, relaxed in face.
50	Resting back leg. Suggest changing neck angle to a V-neck with straps angled outwards to the side and not straight up to avoid pressure on neck by steel hook.
60	Not resting foot, but relaxed and sleepy in face and eyes.
70	Resting hind leg again, tightened breeching to pull breastplate backwards, more alert in face.
80	Chewing and grinding of teeth, twitching in muzzle, stretching up in neck. Resting back foot.
90	Still resting back foot.
100	Still resting leg, slight twitching in lips. Breastplate is barely touching elbows. Bottom lip is quivering, grinding teeth, nice deep breaths.
110	Relaxed in face, flipping lips, nipping, switched legs resting (shifting weight). Tucking up bum underneath, possibly due to rump strap being too low on leg.
120	More alert but resting back right.
130	Twitching bottom lip, resting back right.
140	Chewing motion of teeth, playing with tongue and curling lip. Horse leaned backwards, spreading legs slightly. Lift fluctuating more in weight readings.
150 (goal)	Slight changes in breathing pattern were observed, but the horse still appeared comfortable. Resting back left leg, curling lip.
140	Breathing still slightly laboured (i.e., breathing with more effort), curling of lip.
130	
120	
110	
100	Alert but appeared comfortable.
90	Comfortable.
80	
70	
60	
50	
40	
30	
20	
10	
0	

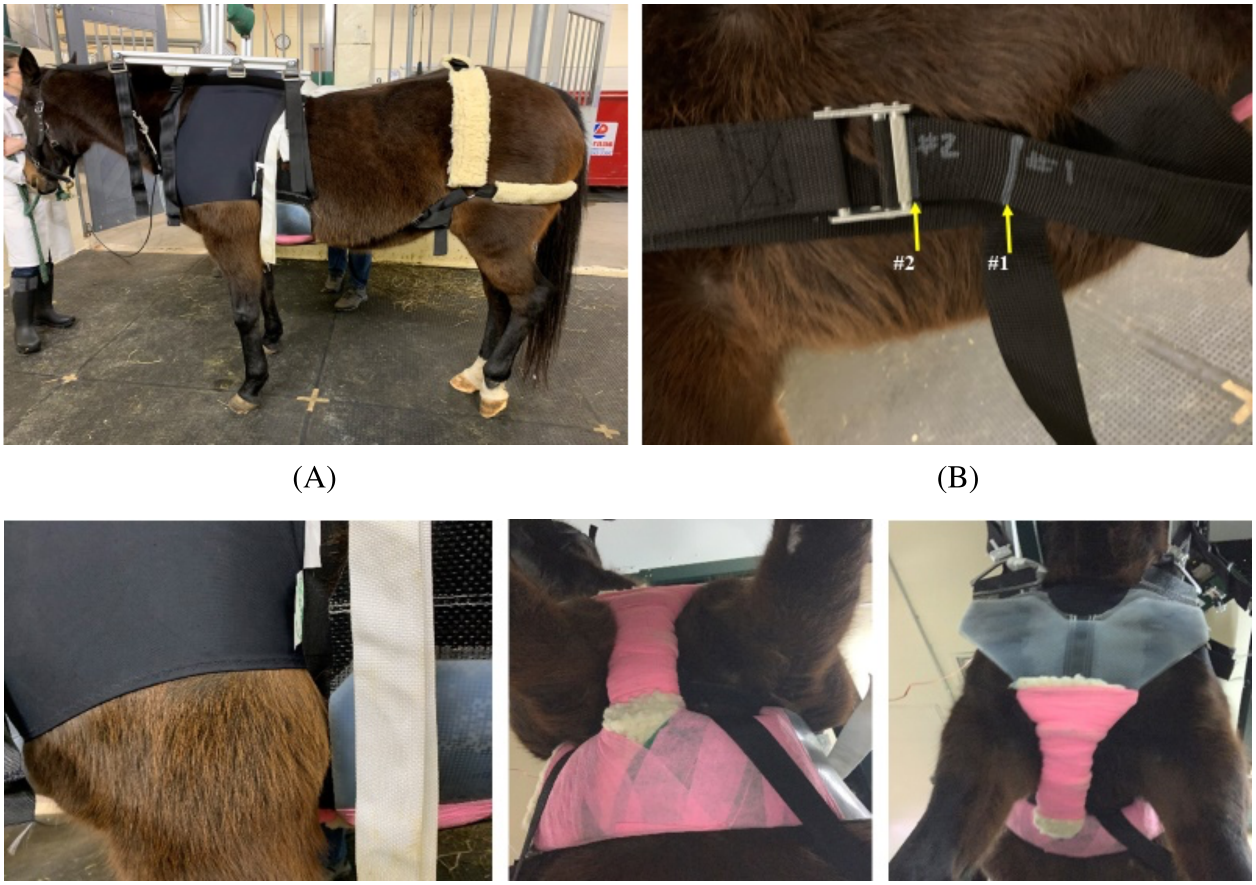
Overall behavioural score throughout trial: Bright, alert, occasional head movements = 0-1, No apparent sign of sweating = 0, Quietly standing, no kicking = 0, Quietly standing, no pawing = 0, Intermittent head movements laterally or vertically, occasionally looking at flanks (1-2 times/5 min), lip curing (1-2 times/5 mins) =0-1, Was not fed, Walking was not attempted, Interest (head up, ears up; watching activities through head movement) =1, No avoidance behaviours observed, with the exception of slight spreading of legs at 150 kg = 0-1.

(A) (B)

(C) (D)

Figure 3.26. Images demonstrating the necessary modifications for the next prototype and the improvements with the addition of the breeching strap. (A) The support straps needed to be angled to the side to create a straight line to the H-frame versus going straight up from the chest and twisting to the outside to attach the frame. (B) The tail strap worked well to keep the breastplate away from the elbow and avoid any pressure or pinching at the elbow. (C) The steel hooks twisted and cut into the shoulder when attached to the H-frame due to the straight-up design versus angling out to the side of the support straps. (D) Displays the placement of the breeching strap, which was moved higher up towards the tail in the next trial in order to improve the forward placement of the hind legs with increasing weight compensations.

The fourth trial involved the breeching strap and Prototype III, with the breeching strap moved higher (Figure 3.27, A). Again, the weight compensation was increased in 10 kg increments, and observations were made at each increment (Table 3.9) for pain or behaviour that would indicate discomfort. The quick-release was tested in this trial to ensure the horse could be detached quickly in an emergency with a 50% weight compensation load (150 kg) on the buckles. The weights with noted observations are included in Table 3.9. 50% weight compensation was achieved (and held for five minutes) without significant discomfort or aversion behaviours. The horse was weighed before the trial at 493.5 kg. The weight removed was 150 kg resulting in a 50.66% (493.5 x 60% = 296.1 kg and 150/296.1 x 100 = 50.66%) weight reduction. The breastplate seemed to stay in place with the breeching strap holding it back from the elbow. The breastplate was pulled further back at the beginning of the trial (Figure 3.27, B), which seemed to be a better placement of the breastplate during lifting. Respiratory rate was taken at specific increments where complications were observed with previous tests and prototypes (i.e., 50 kg, 75 kg, 100 kg, and 150 kg). 75 kg was included as 50 kg was the weight achieved in the first weight compensation trial before discomfort was observed. Resting respiratory rate was between 16 and 20 breaths per minute (bpm) at baseline (0 kg), which increased to 20 and 24 bpm at 150 kg. Total trial time (1:14 PM – 1:57 PM) was 43 minutes (quick-release was pulled at 43 minutes).



(A) (B)

(C) (D) (E)

Figure 3.27. Observations during the third weight compensation trial with Prototype III (Trial 4) and higher breeching strap placement. (A) The breeching strap was moved higher underneath the tail providing more strength pulling straight backwards versus upward on the hind leg and buttock. (B) The markings on the breeching strap show the adjustments during increasing weight compensation. (C) The breastplate is close to the elbow but not placing pressure on the elbow (a gap was still observed). (D) The breastplate appeared to be placed more to one side on the chest and may not have been completely centred on the horse. This image displays the placement of the breastplate over the sternum. (E) This image shows the placement of the breastplate on the chest. There appeared to be sufficient room for the horse to move without limitations imposed by the breastplate.

Table 3.9: Trial four involving the tail strap and Prototype III, with the tail strap moved higher.

Weight Compensation (kg)	RR (bpm)	Observations
0	16-20*	Resting back right leg.
10		
20		Interacting with people, alert.
30		
40		Still Resting back leg but started shifting weight to left leg then stood on all four feet.
50	16	Dropped head, shifting weight to reposition in front legs, then shifting in hind legs.
60		Interacted with people. Droopy bottom lip, chewing, stretching neck. Resting back right leg.
70		Raised head, more alert. Resting back right. Still standing normal, gap still present. Normal posture. Breastplate was not placing pressure on the elbows
75	16-20	Resting back right. Listening to other horse coughing in clinic, then directed ears backwards toward lift. Shifting and looking backwards.
80		Repositioned again as started to increase weight. All feet contact, then rested back left. Tightened breeching strap 2 inches on each side – Marked #1 to start and moved to #2. Sleepy, ears backwards listening.
90		Chewing, sleepy moving head a little to look around. Front legs spread further apart (slightly base-wide). Twitching of lips.
100	20-24**	Resting back right. Dropped head, curled lips and nipped, looked backwards, head above withers. Leaning forward into lift, twitched bottom lip, and closed eyes.
110		Raised head again, twitching upper lip. Resting back right. Still gaps behind the elbow. Horse appears to be "resting" in sling.
120		Straps appear to be squeezing in on the abdomen and steel hooks were quite tight. Raising head and ears directed backwards to lift.
130		Tightened breeching straps another 2 inches on each side to #3. Bottom lip hanging and twitching, snorting. Appears slightly uncomfortable with tightened rump strap.
140		Raising head and twitching of lips. Standing base-wide.
150	20, after 5 minutes 24	Calm at 150 kg for just over 6 minutes. Raised head and looked to rear. Gap between breastplate and elbow. Agitated. Quick-release tested successfully.

*** Respiratory rate: small range of 16-24 bpm (16-20 out of 20-24; 20-16 = 4/20 = 0.2*100 = 20%; 24-20 = 4/24 = 0.167*100 = 17%; 24-16 = 8/24 = 0.333*100 = 33%), even at a 50% weight reduction.*

Overall behavioural score throughout trial: Bright, alert, occasional head movements = 1, No apparent signs of sweat = 0, Quietly standing, no kicking = 0, Quietly standing, no pawing = 0, Intermittent head movements laterally or vertically, occasional looking at flanks (1–2 times/5 min), lip curling (1–2 times/5 min) = 1, Interest (head up, ears up; watching activities through head movement) = 1, Seeks human interaction = 0, Only avoidance behaviours – slight spreading of legs and agitation with harness = 1

The tail strap was slowly tightened as weight compensation was increased to avoid pressure on the elbows during the trial (Figure 3.27 & Figure 3.28). At the beginning of the trial, the tail strap was moved higher underneath the tail (in comparison to the last trial) for better placement (Figure 3.27, A). The breastplate remained in a better position when the tail strap was applied with more tension at the beginning of the trial, holding the breastplate further back (Figure 3.27, C), resulting in a gap between the breastplate and elbow at 150 kg. The breastplate was placed slightly off-centre (Figure 3.27, D & E). Therefore, it could have caused pressure to be applied unevenly, which could have been the reason for some discomfort. 150 kg (50% weight reduction) was reached in two short-term (total duration per trial of approximately 30-45 minutes) trials successfully with no aversion behaviours observed (Table 3.9). The quick-release buckles were tested at 50% weight reduction. It took some strength to release, but the principle worked well, and the breastplate stayed in place. A drawing of the breastplate on the horse is included in Figure 3.28.

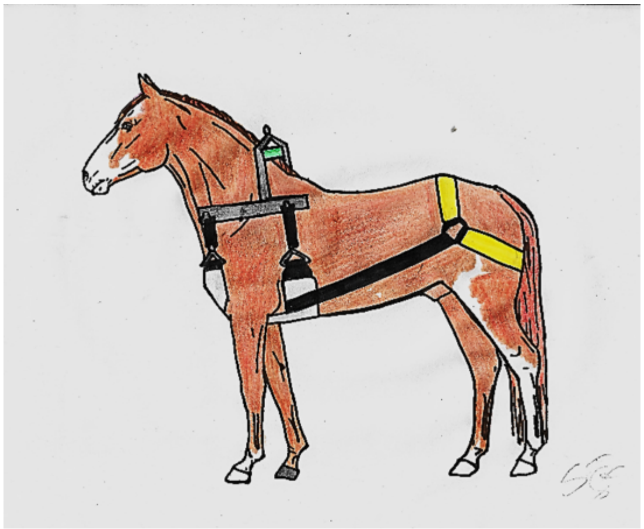


Figure 3.28. Drawing of third breastplate prototype design with a tail strap. The rehabilitation harness component was successfully tested to 50.66% weight reduction in the front limbs.

3.6. Discussion

This design study involved the development and testing of a breastplate designed for front limb support together with a computer-controlled weight compensation lift. The study was part of a multi-phase research program. The specific objective was to test and modify the design of an air-pressurized breastplate for front limb support of the horse up to 50% weight reduction. Front limb injuries tend to be more common (Hayton and Sneddon, 2004), and a higher ratio of weight is supported by the front limbs (Clayton, 2016). This breastplate is to be used in combination with a dynamic weight compensation lift to reduce the weight supported by the horses' legs by up to 50%. The hypothesis of this design project was that it would be possible to design a breastplate for use with the weight compensation lift that allowed for the removal of 50% of the front-end weight without causing discomfort to the horse. This percentage was based on other studies reporting 75% as too great of a weight reduction resulting in atrophy and osteopenia (Hutchins et al., 1987). Therefore, it was proposed that a 50% weight compensation would be sufficient (McClintock et al., 1987). A 46% weight reduction was achieved previously with the nylon harness tested in Steinke et al. (2019a). Comfort of the breastplate was determined primarily through behavioural scoring and an additional measure, respiratory rate testing in the final trial. The objectives of the current project phase were met through testing, which involved strength and safety testing, fittings for comfort, and weight compensation trials in determining usability together with the weight compensation lift. A secondary objective was to determine any sources of discomfort that became evident once the support device was used together with the lift. Long-term trials (up to six weeks) were not a part of this thesis as all harness components need to be completed (e.g., hindlimb support) before long-term trials can begin.

Testing of the current breastplate design (Prototype III) was successful in reducing the weight supported by the front limbs by 50.66% short-term (30-45 minutes), while providing an additional feature of alternating pressure (made possible through greater surface area) and cooling/drying of the skin (through gaps between air pockets and deflation of air pockets). The greater surface area provided the opportunity to cycle air pockets and briefly relieve pressure in areas to restore blood flow, while still providing significant supporting surface area. Significant discomfort or avoidance behaviour was not observed, and the respiratory rate remained within a small range of 16-24 bpm, even at a 50% weight reduction. A respiratory rate of 10-24 bpm is considered normal. The recorded range of bpm during trials is at most a 33% increase from the lowest respiratory rate at baseline (i.e., 16-24 bpm (24 -16 = 8/24 = 0.333*100 = 33%) observed in the research horse. This percentage would be a maximum of 1/3 in the behavioural scoring table (Table 2.1). With added weight compensation, breathing could become shallow, although the breastplate avoids supporting under the abdomen, it does support under the sternum, which could hinder breathing over time. Other possible ways to measure changes in respiration or oxygen uptake includes measuring VO_2 max (with limitations in accuracy and safety during lift use) or serial blood gas (which would require further analysis and is not an immediate measure available in real-time testing situations). The mask used to measure VO_2 max could further affect breathing, resulting in inaccurate measurements. This not only raises a safety concern in affecting breathing during lift use but also extra equipment that could become entangled or cause injury if the horse became agitated during lift use. Hopefully, with continuing research in these areas, more discreet and self-contained measuring devices will be developed and tested (e.g., Greco-Otto et al., 2020; Sides et al., 2018), allowing for greater ability to measure the horse-harness interaction, specifically the effect of harness design on breathing rate and pattern. These observations were a significant improvement over the previous testing with the Anderson sling and nylon harness. Trials with the Anderson sling resulted in an 18% and 4% weight reduction in the front and hindlimbs, respectively, before significant aversion behaviours occurred (Montgomery et al., 2019). Behaviours included tail swishing, stomping of the foot, kicking at abdomen, snorting, raising the head, straightening of the spine, sudden retraction of the abdomen, leaning body weight into the sling, reluctance to move and pinning of the ears. The Nylon harness was able to obtain a 46% weight reduction with minor discomfort observed (buckling of the front left leg and slight bowing of front legs), and no abnormalities in respiratory rate were observed (Steinke et al., 2019a). These improved results show great promise as a tool for the support of horses with ambulatory difficulties to assist with rehabilitation in situations that would typically involve euthanasia due to the complicated nature of treating limb injuries. The outcome of this design-study thesis revealed that several modifications both to the lift programming and the support device are still necessary before beginning long-term trials. Further studies are needed to determine the exact weight reduction that best minimizes complications and allows for the shortest recovery time.

The front limb support design phase described here shows promise for the development of a new harness for equine rehabilitation. The breastplate is to be used in combination with a previously tested harness that was successful in reducing weight by 46% in the front limbs and 40% in the hindlimbs (Steinke et al., 2019a). The integration of these harness components, along with the rehabilitation lift, could prove to be valuable in equine rehabilitation by providing a device to assist veterinarians in treating injuries that are currently life-threatening. Although the development of such a device is a lengthy multi-year and multi-phase process, many harness design and lift programming modifications were made, making the use of this technology feasible and increasing comfort and safety for both the horse and its handlers.

Further changes to the lift programming were suggested for the next phase, including increased safety measures such as an emergency stop that quickly releases all tension, as current weight compensation must be manually reduced. The current emergency stop interrupts the lift in its current state when the button is pressed, which could be problematic. This feature could lead to injury if the lift is frozen with the horse suspended or if the horse stumbles and the lift is frozen with slack in the cables. Further safety measures include automatic movement of the lift with the horse (possibly through motion tracking), as it currently must be driven manually to follow the horse and human response time is not always fast enough to follow the horse in an emergency. The automatic movement would enable the lift to stay above the horse and respond to any movements, including movement off centre (sideways). The lift already keeps a consistent tension in the cables, catching a horse if it falls. Testing and development towards the ability of the lift to follow the horse will require new code programming and the ability to track movement. This improvement will be accomplished through further programming of the lift in the next research phase, which is time-consuming and requires additional resources and expertise. RMD Engineering, Inc. has indicated that automating the lift to follow the horse is part of their lift design plan. However, lift testing was required to fine-tune current programming and design before adding additional features. Data logging needs to be completed to analyze any role the lift programming may play in aversion behaviour displayed by the horse. The horse's response needs to be aligned with the computer data to determine the cause and effect of any changes in behaviour or adverse events. There needs to be a way to quickly release the tension applied by the weight compensation setting when the horse reacts; suggestions include a dial that allows a faster reduction in weight compensation with a more significant increment (e.g., one turn takes off 50 kg). Ideally, the lift would have a programmed response to quick accelerations by triggering a release in pressure or a reduction in weight while continuing to provide support but not freezing in place to increase the safety of operation in the event of an emergency.

Suggestions for the next phase include minor modifications to the current breastplate prototype, including an X shape with straps on angles to further remove pressure from the shoulders and elbow by pulling out and away from the horse during the increasing tension that is applied with greater weight reduction. More padding needs to be added to straps to reduce the pressure associated with higher loads. The middle bar on the H-frame should be adjustable to the size, specifically the horse's width. These modifications will also require changes in design and development. A new silicone mould will have to be created with an X-shape to encase the webbing in silicone. It is also suggested to cut the fibreglass webbing slightly smaller than the silicone mould so that all edges are protected by silicone to avoid sharp edges from contacting the horse. The middle bar on the H-frame will also require a change in design. This change will require the design of a bar that is adjustable but also strong enough to support weight pushing inwards on the crossbar when lifting due to the downward pull from the support straps. This change will require expertise in engineering and design to develop such a device with the right material, minimizing weight and maximizing strength. Therefore, these modifications will be part of the next research phase, including lift programming changes, which were beyond the scope of this project.

Ideally, in prototype testing for a rehabilitation environment, control over the environment and traffic should be of the highest priority to avoid any disruptions to the horse. The busy equine clinic is not ideal for testing, where the environment is uncontrollable. An ample space with plenty of room for the horse and personnel handling the horse should be a requirement for lift use. The quick-release buckles (pulled manually) took quite a bit of strength to pull once the tension was increased to 50% weight compensation. However, the principle worked well, and the H-frame stayed in place and did not seem to interfere with the horse when the quick-release was pulled. The H-frame should be attached close to the withers to avoid dropping on the withers if the quick-release is pulled.

There were several limitations associated with this study, including the use of only one horse due to the need for safety and familiarity with the equipment during the prototype design phases of the program. This horse had been used for all tests with the lift and, therefore, was seasoned to the weight compensation and harnesses. It is possible to use the current prototype (Prototype III) on a range of different sized horses due to the great flexibility in the new prototype. Another limitation was the unpredictable nature of a design study, where every step was directly governed by the outcomes of the preceding step. When a prototype is completed and ready for testing, it is built to the best of one's knowledge at the present time. With testing, new issues will arise, which is the nature of design research. As expected, based on the results of the tests, it took many different design iterations to reach a 50% weight reduction. Difficulties in bonding silicone to support materials, finding materials strong enough to support a horse while also allowing for attachment of support straps, air pockets, and flexibility to fit a range of horses was challenging. However, the general plan remained the same – weight and strength testing, fit testing and weight compensation trials to a 50% weight reduction. Many modifications and changes in design were required. The testing location environment was not always controllable due to its location within the teaching hospital and, therefore, environmental factors cannot be ruled out as factors that influenced behavioural effects. This was a serious issue with changes in behaviour due to unfamiliar horses and unpredictable activity in the clinic, causing the horse to become more reactive or uneasy during testing.

Future research should include an air-drying test to determine the amount of air needed to dry the hair and skin underneath the breastplate and reduce one of the risk factors for the development of pressure ulcers (i.e., moisture). This would require the circulation of air between the breastplate and the horse to dry the horse while the air pockets are cycling. This test would evaluate the amount of air that is required to minimize moisture collecting underneath the breastplate, which is a factor in pressure ulcer development (Coleman et al., 2014; Schwartz et al., 2018), as well as to determine the appropriate cycling time and rate to allow for drying before reapplying pressure. Constant pressure, shear forces, friction, and humidity/moisture are factors involved in pressure ulcer development (Schwartz et al., 2018). Further research is needed to fully understand the effect that moisture and humidity have on pressure ulcer development. However, Schwartz et al. (2018) recently found that the coefficient of friction (COF) increases with all sources of moisture (i.e., sweat, urine, and saline). This increase in COF resulted in elevated strain energy density and shear strain values in both the skin and deeper tissues, indicating an increased risk of pressure ulcer development. Therefore, it is important to reduce both friction and moisture (two inter-dependent factors) to prevent pressure ulcers (Schwartz et al., 2018), as moisture appears to increase frictional forces. This increased friction is likely due to capillary force or the "meniscus effect" in which water creates a resistance force or bond with the surface through liquid bridges formed between surfaces. The strength of this bond depends on the fluid film thickness of the liquid and surface roughness. Although moisture can increase pressure ulcer risk, the leading risk factor is pressure, causing tissue damage when blood supply to an area is impaired (Mitchell, 2018). The aim of the breastplate is to reduce pressure as much as possible by applying it over a greater surface area (attempting to decrease peak interface pressure). Additionally, alternating pressure through the cycling of air pockets, relieving areas intermittently to aid in blood blow, minimizing ischemia and tissue damage will be tested in the next research phase. It is hypothesized that this will minimize moisture between the breastplate and skin.

Furthermore, the ideal airbag inflation pressure and cycling pattern for pressure to be applied and removed for blood to return to the area will need to be studied. The pressure could be measured through pressure sensors or pressure mapping to determine how much pressure is applied and identify areas of high pressure. This would be helpful in determining the correct cycling pattern in high pressure areas to minimize pressure and also detect pressures that could restrict blood flow. The ideal pressure applied by the breastplate to minimize tissue damage, sweat production to avoid moisture from collecting, airflow to dry out the area and temperature of the skin underneath the breastplate are all critical factors in avoiding tissue damage that could lead to more complications during the use of the breastplate and rehabilitation lift. Therefore, further functional design testing is required to produce a final harness prototype that will minimize all complications and achieve a high level of safety.

Once the next prototype of a front limb support device and testing of its airbag system has been completed, the focus will move to the hindlimbs. Once the hindlimbs have been successfully supported to a 50% weight reduction, long-term testing (up to six weeks) can begin with healthy horses. Once long-term testing has been completed on healthy horses, the harness can be used to test client-owned horses with limb injuries in an attempt to help them recover with minimal complications.

3.7. Conclusion

In conclusion, the above-described lift programming and harness design components show great promise in the field of equine rehabilitation. The objectives accomplished include successfully supporting 50% of the horse's front limb weight, achieving reasonable comfort with a newly designed breastplate while attached to a dynamic weight compensation lift. This breastplate is a significant improvement (50% weight reduction versus 46% and 18% weight reduction) over previously tested devices, which obtained 18% and 46% weight reduction with the Anderson sling and nylon harness, respectively. Musculoskeletal injuries are often challenging to manage due to weight-associated complications. The breastplate design tests described in this thesis were able to successfully achieve a 50% weight reduction from the front limbs (over a 30-45 minute test period, holding 50% weight compensation for 5 minutes) with no significant discomfort, which is an improvement over the previous testing with the Anderson sling in which significant discomfort was observed (e.g., tail swishing, stomping of the foot, kicking at abdomen, snorting, reluctance to move and pinning of the ears). Additional functional design improvements and testing of the harness hindlimb support will take place in the next phases of this research program.

Animal care protocol number:

#20140059; Dr. Julia Montgomery

CHAPTER 4 ACCELEROMETRY-BASED STEP COUNT VALIDATION FOR HORSE MOVEMENT ANALYSIS DURING STALL CONFINEMENT

4.1. Introduction

During rehabilitation from an injury, horses are frequently confined to a stall for the initial phase of their rehabilitation. This confinement can be problematic with reduced movement and overloading of healthy structures in an attempt to reduce the pain of the injury. Movement is essential in healing tissues by promoting blood circulation, which delivers nutrients and oxygen to the tissues. Detection of reduced movement during stall confinement could significantly influence treatment outcomes (Hurkmans et al., 2003) by allowing for early recognition of complications and the implementation of preventative measures.

Although experienced veterinarians can subjectively assess most gait events (e.g., lameness), they are limited by the temporal resolution of the human eye and inter-observer agreement (Hardeman et al., 2019; Serra Bragança et al., 2018). Two experienced veterinarians have been shown to disagree on the degree of lameness when observing the same horse at the same time (Hardeman et al., 2019; Serra Bragança et al., 2018; Starke et al., 2012). Objective gait analysis removes these biases and provides a more reliable assessment of small changes in movement. Objective tools also decrease the need for a human to consistently monitor an animal, when a device (e.g., a small wearable sensor) can be used to provide accurate, up-to-date reports on the amount of movement and any changes that could indicate the development of a problem. A few studies have looked at an objective analysis of equine gait (e.g., Fries et al., 2017; Maisonpierre et al., 2019) but not during stall confinement. Usually, continuous movement is analyzed, such as walking or trotting in a straight line. Most analyses have been performed in a straight-line at a trot (particularly subjective analysis in lameness exams), with the horse maintaining a consistent speed for at least 25 consecutive strides (Hardeman et al., 2019; Keegan et al., 2013; Pfau et al., 2016). Stall confinement poses potential challenges in that many different movements could occur (and may not be continuous or consistent). These movements include pawing, laying down and turning on the haunches or forehand (resulting in movement only in the fore or hindlimbs, but not both).

An objective analysis of a horse's movement during stall confinement could aid in early detection of complications during recovery (e.g., reduced quantity of movement), and therefore, allow for early intervention and preventative treatment. Step counts are a potentially important measure of movement. They could aid in early detection of increased risk of severe complications, such as SLL. This early detection could significantly affect treatment outcomes in horses with musculoskeletal injuries, with the possibility of preventing or reducing the risk of SLL and other immobility-associated complications. Step count provides a simple number for easy comparison, over days or weeks, versus more complicated measures such as changes in stride length, asymmetry or spatially tracking (i.e., mapping) movement throughout the day. Studies of gait variability in humans have demonstrated that an inertial measurement unit (IMU) can be used to quantify movement by determining step count (Barden et al., 2016).

Although IMUs and accelerometers have been used to analyze equine movement, to our knowledge, no studies have specifically looked at the validity, ideal location, and inconsistent movement in a stall. Further, we are unaware of any studies that have evaluated IMU use for rehabilitation monitoring in a stall or tested IMUs during stall confinement. Other studies have looked at locomotor activity levels (Fries et al., 2017; Maisonpierre et al., 2019), step frequency (step count) (Fries et al., 2017), footfall timing (Starke et al., 2012), stride rate, timing and asymmetry (Keegan et al., 2011). These studies were completed in a straight line, on a lunge line or grazing in a paddock. Several of these studies referred to the best location for the sensor. However, they did not do a direct comparison of the best body location for a particular task and the validity of the sensor for that task. They also suggested that research be completed to analyze horses in a stall. The monitoring completed in a paddock during grazing would be the closest testing to stall monitoring (Maisonpierre et al., 2019). However, different movements would likely be observed due to space and task (e.g., grazing). During grazing, a horse walks with its head down slowly, moving forward in search of food, one small step at a time. Fries et al. (2017) found that an accelerometer (Animal ActiCal) could differentiate between levels of activity and gaits. They found placement at the hindlimb to be the most accurate, although step count was doubled at the walk (i.e., when the horse was walking), and placing the sensor at the withers was problematic. Maisonpierre et al. (2019) found that an accelerometer (ActiGraph) could differentiate between movement types and that pasture size affects the amount of movement in horses. Both studies used accelerometers successfully to track movement and indicated that horses move different amounts based on the size of the area they are confined to, and that accelerometers can be used to determine step count in horses.

In a stall, the food is generally on the ground in a pile or hung in a hay net. This results in the horse standing in one spot and shifting their weight when eating or quick pacing movements around the stall when excited. This difference in movement (i.e., standing and lifting of feet or pacing around the stall versus slowly walking one step every few seconds to minutes) could result in different algorithms being required to reliably track movement. The stall would likely result in more crossing over of the limbs (i.e., turning on the forehand or haunches) and standing due to space constraints. Therefore, it is essential to analyze movement for the specific environment and for the movements that are most likely to occur.

Early detection of risk factors (e.g., decreased movement and off-loading of the injured limb, resulting in shifting of weight and increased weight-bearing on the other limbs), could indicate the condition that led to the horse’s stall confinement is worsening or other problems are developing, and subsequent implementation of preventative measures are necessary (Baxter and Morrison, 2009; Belloli and Zizzadoro, 2010; Gardner et al., 2017; Hutchins et al., 1987; Keegan, 2007; Maisonpierre et al., 2019; Medina-Torres et al., 2013; van Eps et al., 2010). A decrease in movement could indicate an increase in pain associated with the initial problem or the onset of complications and provide vital information to direct interventions and rehabilitation protocols. A device to track movement during stall confinement could provide veterinarians with up-to-date and continuous monitoring of mobility without constant supervision. It could also provide early detection of sudden changes in the horse’s activity level. The use of such a device would allow veterinarians to monitor treatment progress continuously, decreasing the number of lameness exams and assessments by providing a consistently updated objective progress report without subjecting the horse to unnecessary pain or having to remove it from the stall for assessment. An IMU is ideally suited for this purpose, as it can easily be attached to a limb or surcingle, measuring accelerations of body segments in locomotion along all three reference axes. Ideally, such a device should be affordable and easy to use. An Apple Watch is an affordable, user-friendly, and readily available IMU that can easily be synchronized with other devices allowing for a quick transfer of data and immediate analysis. Software is available via several recording and data logging apps (e.g., SensorLog and Vibration) that are affordable (<$10 CDN) and easy to use.

Therefore, this study aimed to determine the concurrent validity of an IMU for step count assessment and its ideal placement for quantifying the movement of horses during stall confinement. The specific objectives were to: (1) compare IMU-based step counts to a visually-determined criterion measure (video) for three different types of movements in a stall environment, and (2) to compare three different body positions to determine the ideal location on the horse to assess movements in a stall environment. The hypothesis was that an IMU would be able to reliably (ICC >0.75) quantify equine movement (lifting of the limbs) based on step count determination in horses during stall confinement.

4.2. Materials and Methods

The study was approved by the University of Saskatchewan's Animal Research Ethics Board and adhered to the Canadian Council on Animal Care guidelines for humane animal use. For client-owned horses, informed client consent was obtained.

4.2.1. Horses

Six horses of varying breed, sex and age (Quarter Horses, Arabian and Paint cross, Thoroughbred; mares and geldings; 4 -23 years old) (Table 4.1) participated in the study. None of the horses included in the study had been recently diagnosed with a musculoskeletal problem. The number of horses used was consistent with previous studies (e.g., Fries et al., 2017; Maisonpierre et al., 2019). Two different stalls of similar size were used in two different environments: a rehabilitation stall (used to test two out of the six horses) and a stall within a personal barn (four out of the six horses). The rehabilitation stall was 16 ft (192 inches) by 14 ft (168 inches), and the personal barn was approximately 14.2 ft (170 inches) by 9.6 ft (115 inches). The rehabilitation stall (at the WCVM) was located within a busy clinic, and the horses used in this setting had limited exposure to stall confinement. The stall testing in the personal barn consisted of horses that were comfortable in a barn environment around familiar horses and handlers. The same handler completed all trials with all horses.

Table 4.1: The breed, age and sex of each horse included in the study.

Breed	Age (years)	Sex
Quarter Horse	18	Mare
Thoroughbred	23	Mare
Quarter Horse	10	Gelding
Quarter Horse	4	Gelding
Appendix Quarter Horse	20	Gelding
Arabian X Paint	18	Gelding

4.2.2. Movement analysis

The validity of the accelerometer-based step count was determined using three different movement conditions: free movement (FM), circles (C), and figure-eights (F8). These movements were selected to mimic the different kinds of movements horses typically display in a stall environment. The FM mimics a horse in its natural environment, randomly moving around the stall for a specified period of time (five minutes in this study). The circles were selected to mimic a horse pacing in the stall, consistently moving in circles around the stall, which was displayed in some earlier preliminary trials and the testing in the rehabilitation stall. All six horses performed the free movement and circle conditions. Two of the six horses were tested in a rehabilitation stall equipped with a specially designed rehabilitation lift used in other studies (e.g., Montgomery et al., 2019 and Steinke et al., 2019a). A figure-eight is the specific movement that would be pre-programmed into the Equine Rehabilitation Lift at specified intervals with the ability to move the horse around the stall intermittently in a confined space during rehabilitation from injury. This movement was chosen due to limitations in the slewing ring, only being able to turn 359 degrees. Therefore, this movement was tested on select horses to ensure monitoring could be completed accurately via an IMU. The horses tested in the rehabilitation stall performed this movement due to the larger size of the stall and the possibility of this pattern being a rehabilitation maneuver in the future with the use of the lift.

The testing took place in two different environments in an attempt to minimize the effect of several factors that could not be controlled in the original environment (i.e., a busy equine clinic at the university). The additional four horses included and tested in the personal barn could not be transported to the rehabilitation stall, as they were located hours away. Each horse completed four test sessions (see Appendix A, Figure S33). Each session consisted of three five-minute FM trials, one five-minute C trial and, if applicable, one five-minute F8 trial. Three FM trials were completed in each session due to some free movements having little to no movement. Trials with no movement were removed from the study.

The circle and figure-eight movement conditions involved walking the horse around the stall in a circle or figure-eight pattern, respectively, for five minutes, reversing direction approximately half-way through. Sensor locations were selected based on previous studies that used IMUs and accelerometers (e.g., Bragança et al., 2017; Fries et al., 2017; Keegan et al., 2013), as well as commercially available systems that contain accelerometers and gyroscopes (for example, the Lameness Locator) (Keegan et al., 2013, 2011; Mccracken et al., 2012). Orientation was based on ease of use, attachment at the proper location (i.e., directly at the point of the withers), ease of attachment and stability at that location. Therefore, the limb IMUs were placed with a different orientation than the withers (Figure 4.1, A & B versus C). Synchronization of the accelerometer recordings to the video was achieved via a hand signal in the video (thumbs up when activated and thumbs down when deactivated), and the number of steps was determined between these two points. The accelerometer and video recordings were stopped and started between each trial to separate trials and movement conditions.

4.2.3. Equipment

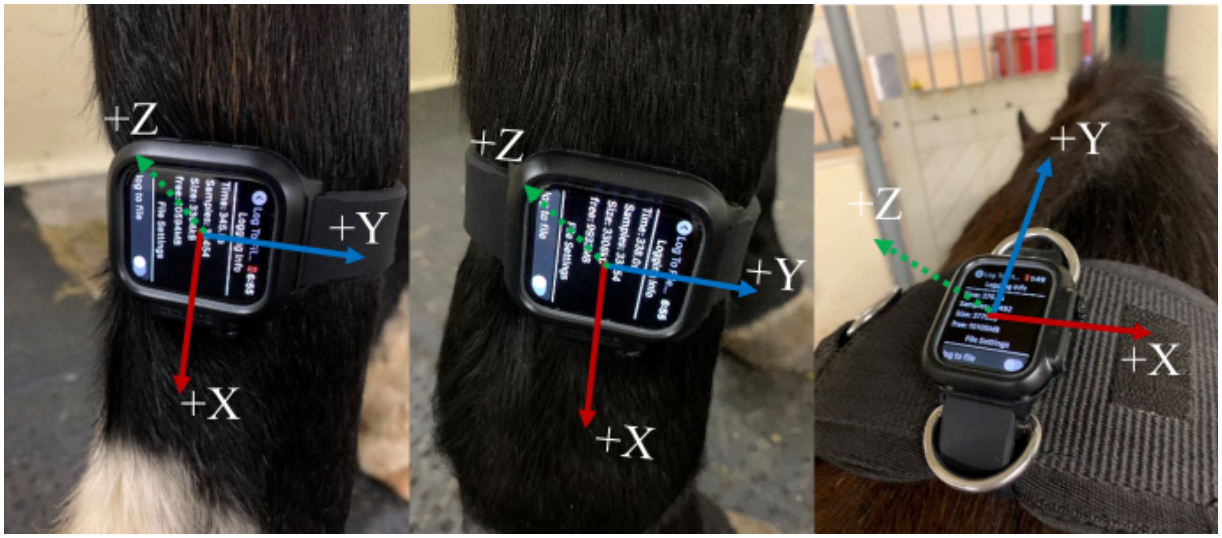
A single inertial measurement unit (Apple Watch Series 4 (44 mm), Apple Inc.) (Figure 4.2) was placed at the withers (W), on the right forelimb (RF) and hindlimb (RH) (Figure 4.1) to track movement and determine the best location for step count accuracy using data from all three axes of the triaxial accelerometer (Figure 4.3).

(A) (B)

(C) (D)

Figure 4.1. Accelerometer locations. The locations in which the accelerometer was placed for movement analysis trials. (A) right forelimb cannon bone (metacarpus), (B) right hindlimb cannon bone (metatarsus), (C) withers attached to surcingle. (D) display with all three IMU locations.

Figure 4.2. Apple Watch IMU used in the experiment.



(A) (B) (C)

Figure 4.3. Accelerometer axes based on sensor location and orientation. Axes are indicated in the positive directions. (A) RH -Y-axis: forward (anteroposterior), X-axis: downward (vertical) and Z-axis: to the right side (mediolateral). (B) RF -Y-axis: forward (anteroposterior), X-axis: downward (vertical) and Z-axis: to the right side (mediolateral). (C) W -Y-axis: forward (anteroposterior), and X-axis: to the right side (mediolateral) and Z-axis: upward (vertical).

Three IMUs were used in the study to collect data at all locations at the same time, so direct comparisons of the different locations could be made for the same trial. The IMU determined step count was compared to the visually determined step count (video-based criterion measure) to assess the validity of the sensor for stall confinement movement analysis. All trials were video-recorded using a GoPro Hero 7 White (GoPro, Inc., San Mateo CA) (Figure 4.4). The camera was set to record at 60 frames per second at a resolution of 1080p with a wide field of view. The sampling rate of the IMU accelerometer was set to 100 Hz for all trials. The video recording was started, the IMUs were activated, five minutes of walking was recorded, and the video was stopped after all IMUs were deactivated. The five-minute time period was determined via the time elapsed on the GoPro video recording application, which was observed externally through a mobile phone. Videos were deleted at the end of the testing day after being uploaded to a laptop for analysis to free up memory on the SD card.

Figure 4.4. The GoPro Hero 7 White used to video-record trials.

4.2.4. Data analysis

Accelerometer versus video-based step counts were compared to determine the validity of the sensor method and the most accurate location for sensor placement. A step was defined as the visual determination of the lifting of the heel off the ground and a flexed carpus. When the accelerometer was placed on a limb, only the steps from that limb were counted, given that the accelerometer would only pick up movement from the limb to which it was attached. Step counts were specific to the location in which they were attached. When the accelerometer was placed at the withers, the steps of both front legs were counted. The raw accelerometer data were processed using a zero-lag, fourth-order Butterworth low-pass filter set to a cut off frequency of 10 Hz. A peak-detection algorithm (Appendix B) was implemented in MATLAB R2020a (The MathWorks Inc., Natick, MA) to identify the series of steps for all three axes using local maxima and minima methods as described by Barden et al. (2016) and Kobsar et al. (2014). The algorithm was refined through straight-line walking and walking in large circles in an arena to ensure consistent forward movement. Any potential outliers (steps greater than three standard deviations from the median) were removed via a median filter (Barden et al., 2016; Kobsar et al., 2014). The algorithm used was adapted from an algorithm that has been used to successfully analyze walking (i.e., to detect steps and strides) in humans.

4.2.5. Statistical analysis

An intraclass correlation (ICC) analysis was used to determine the absolute levels of agreement (validity) between the two methods (sensor step count versus video-based step count). A model 3 (3, 1) ICC was used (Brahms et al., 2018), which uses two-way mixed single measures to evaluate the agreement between methods on the dependent variable. Based on the ICCs, the level of agreement was classified as poor (<0.4), moderate (0.4-0.75) or excellent (>0.75) (Shrout and Fleiss, 1979). In addition to the ICC analysis, the mean percent error and step count difference (the number of steps) between methods was also determined. The ICC analysis was assessed using IBM SPSS Statistics 26 (IBM, Armonk, NY).

4.3. Results

The ICC, average % error and average step count differences (for all movement trials combined) are shown in Table 4.2.

Table 4.2: Results for the three accelerometer axes according to sensor location at the right forelimb, right hindlimb, or the withers. The three locations were tested at the same time. All movements were combined to determine the best overall location. W – Withers; RF - Right Forelimb; RH – Right Hindlimb; ML – Mediolateral; AP – Anteroposterior; VL - Vertical; SD – Sample Standard Deviation. The vertical axis on the right front leg was the most valid measure.

Location	**Axis**	**ICC**	**Average % error**	**Average number of steps – Video (SD) [COV]**	**Average number of steps – IMU (SD) [COV]**	**Average step count difference**
W	VL	0.923	60.3	139.8 (142.2) [1.0]	89.3 (114.2) [1.3]	51.2
	AP	0.974	43.6		111.1 (130.2) [1.2]	31.3
	ML	0.992	20.7		144.5 (154.6) [1.1]	15.4
RF	**VL**	**1.00**	**6.8**	69.8 (70.7) [1.0]	**70.1 (71.5) [1.0]**	**1.3**
	AP	0.997	21.3		76.1 (72.0) [0.9]	6.3
	ML	0.999	9.0		71.1 (71.8) [1.0]	2.2
RH	VL	0.999	15.2	65.8 (69.3) [1.1]	64.3 (69.9) [1.1]	1.8
	AP	0.988	23.4		76.1 (79.3) [1.0]	11.1
	ML	0.990	21.7		72.3 (79.3)[1.0]	8.7

The vertical-axis at the right-forelimb location had the highest validity (1.00), lowest percent error (6.8%) and step count difference (1.3) when all movement conditions were combined (Table 4.2). The mediolateral axis was close in validity, percent error, and step count difference (0.999, 9.0% and 2.2, respectively). The level of agreement determined by the ICC was “excellent” in all trials, indicating a high level of agreement for all sensor axes and locations. One hundred and four trials were completed in total. Therefore, all locations and movements were calculated over the 104 trials. Table 4.3 shows the ICC, average % error, and average step count difference results according to movement condition and sensor location. In the FM condition (71 trials), the right-forelimb had the highest validity (0.999), and the lowest percent error (9.6%), and step count difference (1.1) on the vertical axis. However, in the F8 (9 trials) and C (24 trials) movement conditions, the right-hindlimb appeared to be the most valid (1.00 and 0.997, respectively) with the lowest percent error (0.6% and 0.9%, respectively). The F8 also had the lowest step count difference in the hindlimb (1.0). However, the right forelimb had the lowest step count difference (1.6) during the circles. The validity of both limbs were similar (≥0.996) in the C and F8 conditions, as well as the percent errors being below 1%. The standard deviation in Table 4.3, including all movement types, is quite large due to free movement having substantially lower step counts in comparison to circles and figure-eights and also having a large number of trials (71 versus 9 and 24). Coefficients of variation are higher for all movement types (>1) indicating high variance within the data. With free movement included in all movements there is a large variation in the number of steps due to moving at free will versus being led around the stall in circles and figure-eights. Two FM trials were removed from the final analysis due to no movement (steps) in the video.

The ICC, average % error and average step count difference results (for all movement trials at each location) are shown in Table 4.3.

Table 4.3: Results for the three accelerometer axes according to movement condition. The three locations were tested at the same time. FM – Free Movement; C – Circle; F8 – Figure-eight; W – Withers; RF - Right Forelimb; RH – Right Hindlimb; MT – Movement Type; ML – Mediolateral; AP – Anteroposterior; VL - Vertical; SD – Sample Standard Deviation. The vertical axis on the right front leg was most valid for free movement. The vertical axis on the right hind leg was most valid for circles and figure-eight.

MT	**Location**	**Axis**	**ICC**	**Average % error**	**Average number of steps – Video (SD) [COV]**	**Average number of steps – IMU (SD) [COV]**	**Average step count difference**
FM	W	VL	0.851	73.5	48.6 (49.4) [1.0]	21.4 (32.7) [1.5]	27.2
		AP	0.959	54.9		31.5 (45.2) [1.4]	17.1
		ML	0.992	25.8		47.4 (55.0) [1.2]	7.3
	RF	**VL**	**0.999**	**9.6**	24.4 (23.9) [1.0]	**24.1 (24.1) [1.0]**	**1.1**
		AP	0.976	29.3		30.5 (28.7) [0.9]	6.1
		ML	0.997	12.2		25.0 (25.9) [1.0]	1.9
	RH	VL	0.990	22.0	21.6 (23.4) [1.1]	19.6 (23.6) [1.2]	2.1
		AP	0.982	26.8		25.2 (26.8) [1.1]	4.8
		ML	0.990	25.4		21.6 (24.8) [1.2]	2.8
C	W	VL	0.505	30.1	329.0 (50.1) [0.2]	241.7 (93.8) [0.4]	93.7
		AP	0.704	19.3		281.6 (81.4) [0.3]	60.8
		ML	0.853	10.4		352.4 (76.0) [0.2]	35.9
	RF	VL	0.996	1.0	167.9 (18.4) [0.1]	169.3 (18.2) [0.1]	1.6
		AP	0.951	4.0		174.1 (16.1) [0.1]	6.3
		ML	0.980	2.1		170.9 (16.3) [0.1]	3.2
	RH	**VL**	**0.997**	**0.9**	168.0 (45.2) [0.3]	**166.5 (41.4) [0.2]**	**1.9**
		AP	0.831	17.4		190.7 (29.9) [0.2]	28.1
		ML	0.270	17.1		182.3 (25.1) 0.1]	30.7
F8	W	VL	0.429	33.4	334.4 (52.7) [0.2]	225.2 (56.4) [0.3]	109.2
		AP	0.683	18.8		274.4 (71.1) [0.3]	60
		ML	0.928	6.6		339.7 (65.9) [0.2]	22.8
	RF	VL	0.999	0.9	166.9 (26.1) [0.2]	168 (26.5) [0.2]	1.6
		AP	0.979	4.6		174.2 (25.9) [0.1]	7.3
		ML	0.995	1.4		167.9 (22.8) [0.1]	1.7
	RH	**VL**	**1.00**	**0.6**	161.6 (25.9) [0.2]	**160.9 (26.1) [0.2]**	**0.9**
		AP	0.857	12.6		181.7 (29.6) [0.2]	20.1
		ML	0.907	9.1		175.6 (26.7) [0.2]	14

All axes and locations in the free movement condition had “excellent” levels of agreement (ICC>0.75). Most levels of agreement in the circles and figure-eights were above 0.75. However, a few were below, particularly for the withers location in the anteroposterior and vertical directions. Overall, these numbers indicate that an IMU has excellent validity in comparison to a manual step count (criterion measure) for stall monitoring. The IMU recorded step count agreed well with the criterion measure with ICCs much higher than 0.75 (most are above 0.9) and low percent errors and step count differences. Standard deviations were large in comparison to the step counts for free movement because horses could move freely and the means are higher. Therefore, horses may have taken two steps in one trial and over 50 steps in another trial. The figure-eight and circle conditions include much larger step counts as the handler tried to keep the pace as steady as possible based on the willingness of the horse to move in the specified pattern. Therefore, the total number of steps taken were within a smaller range. Coefficients of variation are low for circles and figure-eights indicating low variance in the data and higher for free movement (>1) indicating high variance.

In regards to the sensor and algorithm peak detection abilities, the sensor recorded smaller movements at the withers as opposed to the limbs (i.e., movement of the withers mediolateral or vertical versus movement of the limbs through the lifting of the limb) and had a much lower signal amplitude, which made it harder for the algorithm to differentiate between peaks (as the difference between the peak threshold and the rest of the signal was less). The highest amplitude for the withers was only 10% of the amplitude recorded at the forelimb and hindlimb.

4.4. Discussion

This study investigated the concurrent validity of an IMU for step count analysis to determine its potential usefulness and ideal placement for quantifying the movement of horses during stall confinement. The specific objectives were to: (1) compare IMU-based step counts to a visually-determined criterion measure (video) for three different types of movements in a stall environment, and (2) to compare three different body positions to determine the ideal location for IMU placement. The hypothesis was that an IMU would be able to reliably (ICC >0.75) quantify equine movement (lifting of the limbs) by determining step count in horses during stall confinement. The hypothesis was supported in that the sensor-based step count showed excellent levels of agreement with the video-based criterion. This agreement demonstrates that IMUs can be used to accurately track step count in horses during stall confinement. Consequently, an IMU shows promise as a tool for use in monitoring recovery in horses when movement is vital, given that changes could indicate the development of a severe problem.

The results demonstrate that the vertical axis for the forelimb and hindlimb locations were the most accurate for step count determination during stall confinement. While both locations were best in different conditions (e.g., free movement vs. figure-eight or circles), they were close in validity, percent error and step count difference. The right forelimb vertical axis had the highest accuracy in all movements combined. This same location and axis (right forelimb, vertical axis) also had the highest accuracy in free movement. However, the hindlimb was more accurate in the circles and figure-eight movements. The results demonstrate that with a greater quantity and consistent pattern of movement the sensor was more accurate, with percent error being the lowest for the figure-eight (0.6%) and circle (0.9%) movements, respectively, when the horse was consistently moving for the entire five minutes. The average step count difference and validity of the sensor appeared to be consistent through all movement types, except for the withers in the vertical direction where ICC, percent error and step count difference were consistently worse. The free movement produced greater variation in percent error, while figure-eight and circles had comparatively low percent error. This variation was likely due to the difference in movements and the smaller overall step count in the free movement condition.

When interpreting these results, it is important to understand that the ICC measures the level of agreement between the two independently determined variables, sensor and video step count. When there is a greater number of steps counted in the video, there should also be a corresponding greater number of steps for the sensor data and vice versa. However, the percent error (based on the difference in step count) measures the relative discrepancy between the true value (video count) and the sensor count. This is very important as in a rehabilitation context, a comparison of values between days would be used to determine if the movement had decreased. If there are large step count differences or percent errors, then between-day comparisons may not have sufficient accuracy to be able to identify small decreases in movement. Accuracy is key in detecting small changes early on and in the possible prevention of life-threatening complications. The reason some ICCs were excellent (>0.75) with high percent errors and step count differences could be due to the larger number of trials and steps. For example, in Table 4.2, all ICCs were greater than 0.9, but the percent error is as high as 60.3%, and a step count difference of 51.2 steps. These calculations included 104 trials (total steps for all movements: 14,534 W; 7,263 RF; 6,841 RH) whereas the calculations that included 71 trials (FM total steps: 3,452 W; 1,732 RF; 1,531 RH; F8 total steps: 3,010 W; 1,502 RF; 1,454 RH; C total steps: 7,895 W; 4,029 RF; 4,033 RH), such as the free movement condition, resulted in similar percent errors and lower step count differences and also lower ICCs. It is important to focus on the free movement condition in Table 4.3, as rehabilitation monitoring would likely consist of monitoring a horse in a stall with random intermittent movements. Injured horses requiring monitoring are less likely to pace around the stall if they are in pain, and as such, the concern and reason for monitoring is usually not enough movement, possibly indicative of inadequate pain control or the development of immobility-associated complications. Therefore, free movement analysis would likely be the most valuable measure in this circumstance.

Different kinds of movement will affect the number of steps recorded in a specific location, as the step count was specific to the location in which it was placed. Only the right front limb steps were counted for forelimb and only the right hindlimb steps were counted for the hindlimb sensor placement. For this study, a step was classified as the lifting of the heel off the ground and a flexed carpus. The different movements observed in the free movement trials included the lifting of the feet while standing, moving over the haunches (i.e., only the forelimbs lift and move in a crossing-over fashion) or forehand (i.e., only the hindlimbs lift and move in a crossing-over fashion), or moving both forelimbs and hindlimbs to move around the stall. Some horses also pawed (which can make it difficult to tell whether an actual step was taken or the horse was just pawing with one leg) and paced in circles around the stall. Free movement, therefore, involves many different movement types that could affect the accuracy and amount of movement recorded by the sensors. The forelimbs may move more or less than the hindlimbs, and vice versa, affecting the amount of movement recorded based on sensor location. Therefore, a practical solution would be placing sensors on both a forelimb and hindlimb location, resulting in an average value for a rehabilitation assessment. The circles were selected to mimic a horse pacing in the stall, consistently moving in circles around the stall, which was displayed in some earlier preliminary trials and the horses that were tested in the rehabilitation stall. Presumably, this occurs because horses tend to move in circles around the perimeter of the stall (pacing or stall walking) when they become anxious or excited. This can also be accompanied by pawing and head shaking, also observed in some horses, indicating compulsive behaviours (stereotypies) or stress (Hausberger et al., 2009; Luescher et al., 1998) and could occur in a rehabilitation setting, where horses are in a strange environment with unfamiliar horses and handlers, leading to further injury. It is essential to consider these factors, as well as the location of the injury when considering the placement of a motion-tracking device for rehabilitation monitoring.

The withers location imposed potential challenges for step count determination in that the algorithm had to identify two steps correctly (i.e., both left and right front limbs) with possible interference from the hindlimbs (pelvis) and spine movement. In contrast, the limb locations only had to identify larger movements on that specific limb (i.e., the right fore or hindlimb). The withers had a much smaller signal amplitude, with the highest amplitude for the withers being 10% of the size of the amplitude for the forelimb and hindlimb. This difference between the limbs and withers made it more difficult to fine-tune the thresholds for the peak detection algorithm at the withers location. Further study is needed to determine definitive reasons for the differences in error between movement types and locations and whether this was due to inconsistent movement (e.g., standing and intermittently walking or taking a step) or the actual movement itself (e.g., pawing versus consistent walking steps) or the lack of movement (fewer steps in free movement). It may also be possible to identify a movement threshold that would indicate that the horse is moving based on the acceleration amplitude, as opposed to counting the actual number of steps.

Fries et al. (2017) evaluated whether an accelerometric device could quantify locomotor activity and step count in horses. The authors used three of the same locations (withers, forelimb and hindlimb) plus one additional location (the head) and evaluated grazing, walking at different speeds, trotting, and cantering. They also performed free movement for 20 minutes (instead of 5 minutes) in a paddock, which would likely be larger than a stall. Then they completed five minutes of grazing, three minutes of hand leading, trotting on a lunge for five minutes, cantering on a lunge for three minutes, and finally walking alone in a horse walker at five different speeds. Similar to this study, sensor-based step counts from specific trials were compared to video-based manual counts and the hindlimb was found to be most accurate and the withers to be problematic. They concluded that an accelerometric device (with the Actical Version 3.10

software automatically determining the step count) was sufficiently accurate for movement analysis in horses. However, they had to use raw data for analysis of the walk and trot (except the hindlimb location), as the step count was doubled. In the preliminary trials completed during this thesis, the pedometer in the Apple Watch IMU was used, and we also found the pedometer count to be very large in comparison to the manual video count and accelerometer data analysis. Steps were doubled or tripled in trials and did not match manual step counts or the accelerometer data. Fries et al. (2017) found that percent errors and limits of agreement were not acceptable for step count at the withers, head, and forelimb. In contrast, the current study found lower percent errors and excellent levels of agreement. The Fries et al. (2017) study also used a different placement on the forelimb, placing the accelerometer at the heel as opposed to the cannon bone location in this study. This may indicate that the difference in accuracy found in their study occurred as a result of a difference in sensor placement, suggesting that the sensor should be placed on the cannon bone for best accuracy. Fries et al. (2017) commented that their findings were not transferable to small amplitude movements in a confined area, such as in a box stall. They also suggested that further study should be completed "in confined areas, such as small movements in a stall, and test the ability of the accelerometer to detect behavioural activity in horses in the absence of minimal ambulation," which was completed during the free movement trials of this study.

In general, previous studies found inertial sensors or accelerometers to be sufficiently accurate, and some found locations that were more accurate than others (e.g., hindlimbs and forelimbs). Nevertheless, none of these studies quantified movement with a sensor in a small confined space, limiting movement and natural daily activities of the horses. Previous studies also did not evaluate all three accelerometer axes (mediolateral, vertical and anteroposterior), which could be problematic in determining which location is the most accurate in different types of movement, such as grazing, where the horse may not be moving in a straight line.

This study demonstrates the capability of a single IMU, placed on either the hindlimb or forelimb, for quantifying movement during stall confinement. The IMU could be used to provide early detection of movement reduction that could signal increasing levels of pain, immobility-associated complications and enable timely preventative interventions during recovery from injury and rehabilitation. Based on the results of this study, the use of an IMU for monitoring rehabilitation progress in injured horses has considerable potential. It could be a valuable tool for veterinarians and rehabilitation specialists. An IMU provides a more practical solution for rehabilitation monitoring, as watching recorded videos is tedious and time-consuming. The IMU data can be used to generate graphics that can be easily scanned for movement (peaks), or through further analysis, to determine the specific number of steps taken during the recording period. With the creation of software able to display step counts (similar to what currently exists for humans), real-time values could be displayed for regular monitoring without complicated data analysis. Such software would provide an up-to-date report of movement that could indicate any changes from previous days, much like the current Apple Watch Health Tracking app. With further research and development, this could be a very valuable tool in rehabilitation, based on recording, graphing, and displaying changes over days or weeks to months. The high validity indicates that an IMU can be used to continuously monitor the quantity of movement in a stall, which would indicate any abnormalities associated with reduced movement before those changes could become severe. For example, if a horse is moving less, it could indicate an increased risk for SLL. Continuous monitoring with an IMU could allow veterinarians to intervene early based on the slightest changes in movement to prevent life-threatening complications. Early detection of complications and preventative interventions during recovery from injury and rehabilitation is desirable to increase the chance of a successful recovery and return to regular use in horses.

An acceptable level of validity for monitoring rehabilitation cannot be definitively known at this point, as further study in injured horses is needed to determine the approximate decrease in the movement that is associated with the risk of developing SLL. Although the results demonstrate that IMU-determined step counts are valid and accurate in a stall in healthy horses during different types and amounts of movement, it is unknown how much of a change in movement results in complications such as muscle wasting, osteopenia, or SLL. It is also not known how long this decreased movement can persist before veterinarians need to identify it as a potential complication. If an IMU is used to monitor recovery from injury, the step count could be compared to those from previous days. Even slight declines over time could be enough to indicate that more significant intervention may be needed to increase activity to promote cyclic loading and blood flow, preventing life-threatening conditions from developing.

The movement tracking device used in this study would be beneficial for use with the rehabilitation lift and harness to guide rehabilitation protocols, returning step count to “normal” levels. With daily tracking and small changes easily detected, changes can be made to increase movement to maintain blood flow and prevent SLL from developing. Use of such a device would also contribute to the knowledge of whether a specific amount of movement prevents SLL, how much movement is “normal” when recovering from an injury to prevent complications, and help control pain to balance overloading (i.e., too much static weight or walking) versus unloading (i.e., not enough walking or loading).

This study has several limitations, including potential human error in counting steps and instrument (IMU) error in recording and analyzing data. However, considerable care was taken to avoid these errors. It also was not possible to select horses at random. The horses that participated in the study did so based on accessibility and availability. Future research should include further analysis and refinement of the algorithm to attempt to increase accuracy in all locations and during all movements. More horses could be included in the study over a longer duration (i.e., days). Further study should also investigate other variables, such as duration of time spent walking versus standing in stall confinement, limb kinematics in the stall, and changes in postural sway when standing for a prolonged period. All these variables could be valuable in evaluating and monitoring the risk of complications. The development of an application (i.e., iOS or Android app) to display simple numbers and tracking over days or weeks could provide a significant benefit to the rehabilitation process.

4.5. Conclusion

This study found that the front limb vertical axis was the most accurate for quantifying step count in a stall compared to a criterion measure. Although this was the most valid location and axis, the hindlimb was almost identical in terms of agreement. These results demonstrate excellent levels of agreement when compared to a visually based criterion, indicating that accelerometry provides an easy and valuable tool for veterinary medicine and equine rehabilitation monitoring. Therefore, for future use in rehabilitation monitoring, placement of the IMU should take into consideration the location of the injury (and supporting limb), given that the supporting limb is the limb at most risk for the development of SLL. Early detection of complications, such as SLL, is desirable to prevent unnecessary euthanasia and provide the best chance of a successful recovery.

Animal care protocol number:

#20180073; Dr. Julia Montgomery

Chapter 5 DISCUSSION

Limb injuries in horses can result in life-threatening complications that can be challenging to treat. One of the most dreaded complications is supporting limb laminitis (SLL), which is believed to occur due to the overloading of structures and immobility, restricting blood flow and causing failure of the suspensory apparatus of the distal phalanx (SADP). Both movement and weight reduction are important in these cases, as it is often the combination of overloading, due to unloading the injured limb, as well as reduced movement due to pain and confinement, that lead to complications. Once SLL develops, the prognosis is very poor, with a mortality rate of 50-75% (Gardner et al., 2017). Due to this extremely debilitating and painful condition, euthanasia is often necessary for the welfare of the animal. Other complications include muscle atrophy and osteopenia due to a lack of movement and confinement.

Many researchers and clinicians have attempted to recover horses and prevent laminitis through weight support methods (Bowman, 1995; Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981; Wattle et al., 1995). While some were successful in preventing SLL, other complications were associated with their use. Weight support methods that did not report any SLL complications include flotation tanks, rescue slings and forced recumbency. However, these methods have been associated with respiratory compromise, restricted blood flow, osteopenia, muscle atrophy, hair loss and accumulation of nasal secretions. Due to the static nature of these devices, the horse is unable to move to maintain muscle tone. They also tend to be typically all or nothing in terms of weight reduction, removing significant weight from the limbs, which would explain the loss of muscle mass.

One of the most significant risk factors of SLL is reduced mobility and overloading of supporting limbs (Hopster and van Eps, 2018; Medina-Torres et al., 2016; Orsini, 2012; van Eps and Burns, 2019). When movement occurs, the supporting limbs are relieved as weight is transferred to the injured limb briefly. Therefore, a critical factor in preventing SLL (as well as muscle atrophy and osteopenia) is to maintain normal movement. A method to track this movement and monitor any changes over days or weeks could be valuable in not only learning more about SLL and its pathophysiology but also in preventing it from occurring, potentially saving lives of horses that would otherwise be euthanized. The research presented in this thesis provides important new information in the field of equine rehabilitation, not only in the contribution to the development of a support device (lift and harness) but also in identifying and validating a method of quantifying movement while a horse is confined to a stall during rehabilitation. The tested sensor-tracking device would allow horses to be monitored more closely for subtle changes that could indicate the onset of problems and a need for intervention. Not only will this assist in equine rehabilitation, but in human conditions that result in ambulatory difficulties (e.g., orthopedic or neuromuscular impairments). An advantage of the IMU used in this study (i.e., the Apple Watch) is that it is relatively affordable and easily accessible. The creation of an affordable and user-friendly application, specifically tracking parameters of interest (e.g., step count) in different species, could prove to be highly beneficial in rehabilitation science.

The objectives of this thesis were to: 1) develop and test an air-pressurized computer-controlled breastplate for front limb support of the horse, to be used in combination with a previously developed dynamic weight compensation lift and harness, reducing the weight supported by the horse's front legs by 50% and 2) to test the use of an inertial measurement unit system to quantify step count in horses for several different stall movements and sensor locations. We hypothesized 1) that it would be possible to create a breastplate design for use with a dynamic weight compensation lift, which would allow for the removal of 50% of the front-end weight comfortably, and 2) that an IMU would be able to accurately (intraclass correlation >0.75) quantify equine movement (lifting of the limbs) through step count determination in horses during stall confinement.

These objectives were achieved, given that 50% of the weight from the forelimbs was successfully removed through a series of breastplate design modifications. We also demonstrated that IMUs could reliably monitor movement through step count determination during stall confinement in horses. The IMU was most valid in all movement types when placed on the forelimb cannon bone.

The progress made on the overall rehabilitation harness through breastplate design testing and modifications, as described in this thesis, allowed for a 50% weight reduction in the forelimbs with reasonable comfort in the short-term (30-45 minutes, with 50% weight reduction held for 5 minutes). The initial harness prototype allowed for a 46% weight reduction and the Anderson sling allowed for an 18% reduction in the forelimbs, when used together with a computer-controlled weight reduction lift. The breastplate's resultant flexible structure allows the horse to move freely, without limitations imposed by the breastplate. The added breeching strap has assisted in pulling the breastplate away from the elbows, alleviating the pressure that previously caused discomfort. The air-pressurized system integrated with the breastplate will allow for intermittent relief of pressure, as well as cooling/drying of the skin.

The next breastplate prototype (Prototype IV) will need to be built, and therefore, some suggestions to improve comfort were made along with changes to the lift programming. The minor design modifications suggested for future modifications to the breastplate prototype (Prototype IV) to improve comfort and usability are angled support straps, more padding (e.g., sheepskin and silicone) on the sides and around the edges, and an adjustable H-frame, to allow for wider or narrower adjustments based on the conformation of the horse. Suggested improvements to the lift programming include a quick-release emergency button for relieving all the pressure in weight compensation mode, a programmed response to quick accelerations resulting in the elimination of weight reduction, and programming to follow the horse’s movement. Future testing should be completed in a highly controlled environment, where there are no disruptions to the horses or handlers. As flight animals, environments that could trigger a flight reaction need to be avoided. Ideally, an ample space that allows for smooth movement of the horse and lift around the stall with handlers should be used for testing.

With the above-suggested modifications (to the breastplate, lift and lift environment), the next phase of the research program will be to finalize the breastplate design, conduct further testing of its airbag system, and to complete the design of the hindlimb support component. Hindlimb support is necessary, as there is a concern about the horse slipping out of the harness backwards and the harness sliding forward (observed in some trials, therefore, a breeching strap was added). As part of a larger multi-phase research program, this thesis's focus was on the forelimbs due to the forelimbs being at higher risk of injury (i.e., high loading during locomotion and higher weight-bearing when standing). Therefore, the forelimb support is the most important component as it supports a larger amount of weight. Once both forelimb and hindlimb support devices have been completed, long-term testing on healthy horses will be carried out, followed by long-term testing on client-owned injured horses in future program phases.

The movement monitoring device (Apple Watch IMU) will then be used to gain additional information for the rehabilitation of horses, both pre- and post-injury. By completing the long-term (i.e., six weeks) trials on healthy horses first and tracking "normal healthy" movement that can be compared to movement tracking in injured horses, valuable information could be obtained to assist in preventing complications in injured horses. By tracking normal movement with the lift in healthy horses (i.e., during initial long-term trials with the completed harness in healthy horses) and any complications that may develop, the research team would have baseline data that could be used to assist in preventing complications in injured horses. Once complications have been minimized in long-term trials with healthy horses, there will be known values that can be used to prevent complications in injured horses. Comparisons could be made to adjust movement, with pain and injury considered, to provide the best chance of a successful recovery. Through testing with the IMU, we have demonstrated that the IMU can reliably track step count in horses during stall confinement, even with inconsistent movement. The results of this study suggest that the best placement for an IMU is on the front or hindlimb cannon bone. Based on the location of the injury and safety to the handler, ideally, the front limb would be used for movement monitoring when a single sensor is used and when possible the use of two sensors on both a front and hindlimb location. The forelimb location using the vertical axis had the highest validity (ICC of 1.00), the lowest percent error (6.8%) and step count difference (1.3 out of approximately 70 steps) in all movement conditions. With the development of a movement tracking app, similar to what currently exists in humans through the Apple Health app, tracking the rehabilitation process could aid in the development of the rehabilitation protocol and any changes that need to be made during recovery. With further study, other parameters (e.g., stride time/length, spatial mapping, postural sway, etc.), in addition to step count, could be added for more in-depth monitoring of movement to aid in the prevention of life-threatening complications.

Both tools described in this thesis have considerable potential for equine rehabilitation, where the prognosis of limb injuries can be very poor. The breastplate design shows great improvement over previous weight reduction methods (i.e., rescue slings and forced recumbency). Flotation tanks successfully removed more weight (up to 75%), but complications were observed. Possibly a weight reduction of 50% in a flotation tank or swimming pool could provide another option for weight reduction (with or without movement in a pool versus a tank, respectively). In prior studies of the weight reduction lift by our research group with the Anderson sling (Montgomery et al., 2019), horses learned to 'sit' in the sling, often losing balance and affecting the weight compensation ability of the lift. This 'sitting' also resulted in significant weight being transferred to the hindlimbs, increasing the risk of overloading. The horses also spread their legs widely and resisted movement. When the hindlimb harness component was removed, to avoid the horse 'sitting' in the Anderson sling, significant pressure was applied to the chest. The chest piece also raised significantly when tension increased during increasing weight compensation, placing pressure on the neck that could potentially restrict the airway and blood flow in the neck. In these trials, behaviours indicating discomfort were observed, as well as respiratory compromise (increased respiratory rate and shallow breathing). The maximum weight that could be removed with the Anderson sling in preliminary trials, with significant discomfort and aversion behaviour, was approximately 46% (468 kg horse; 280.8 kg front; 128/280.8*100 = 46%) and 5% (468 kg horse; 187.2 kg hind; 10/187.2*100 = 5%) in the front and hindlimbs, respectively, or 29% of the total weight (138/468*100 = 29%). In contrast to the Anderson sling, testing with the same lift and horse achieved 46% and 40% weight reduction from the front and hindlimbs, respectively, using the first harness prototype with very minimal discomfort (Steinke et al., 2019a). The observed difference in behaviour with the first harness prototype was a considerable improvement in comfort compared to the previous phase with the Anderson sling. Other improvements of the harness made in comparison to the Anderson sling included quick-release buckles (2) attaching the horse to the lift allowing for quick-release of the horse from the lift in an emergency, and ease of application to the horse allowing one person to apply and remove the harness in one complete piece, as well as lightweight material and sheepskin padding on the chest and legs. With the Prototype III breastplate design described in this thesis, 50.66% of the weight could be removed from the front limbs (and held for 5 minutes) with no significant discomfort behaviours over a period of 30 to

45 minutes. The Anderson sling was only able to reach a maximum of 29% and 10% in the front and hindlimbs, respectively before discomfort behaviours were observed during initial testing (Montgomery et al., 2019).

Both rehabilitation tools presented in this thesis contribute to a limited field of knowledge in equine biomechanics and rehabilitation. Most of the research on support devices for recovery from injuries was completed in the 1980s (e.g., Hutchins et al., 1987; McClintock et al., 1987; Smith, 1981) using flotation tanks. Research on rescue slings with various uses was completed in the early 2000s (e.g., François et al., 2014; Fürst et al., 2008; Ishihara et al., 2006b; Steffey et al., 2009; Taylor et al., 2005), but began as early as 300-360 Common era (Schatzmann, 1998), while the forced recumbency study was published in the 1990s (e.g., Wattle et al., 1995). To our knowledge, no study has investigated an IMU for stall confinement movement monitoring. However, studies have been completed assessing step count in paddocks (e.g., Fries et al., 2017), and one of the outcomes was the suggestion to conduct studies in a stall environment.

In conclusion, the combination of a rehabilitation support system to aid in the recovery of ambulatory conditions and a device for monitoring movement during the rehabilitation of horses confined to a stall will be highly beneficial to equine veterinary medicine. With the successful reduction of 50% of the weight in the front limbs and the excellent validity of the IMU, both devices demonstrate the potential to be used in a rehabilitation setting with the possibility of preventing or reducing the risk of complications. With further developments in the next research phases, such as hindlimb support, testing in several horses, and the development of a movement monitoring app specifically for horses, these devices could give horses a second chance to fully recover from conditions that are currently life-threatening.

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APPENDIX A SUPPLEMENTARY MATERIAL

Rehabilitation Lift Operating Principles:

Four large support beams support the lift from the ground, which further supports two large beams with tracks that the gantry on additional support beams can move back and forth on. The gantry (containing two servo motors (winches) for attachment to the horse) spans the space between the two large support beams also with tracks. These beams support the mechanical and electrical components of the lift.

The remote control can allow for weight compensation or hoist mode, depending on the intended task. Weight reduction can then be dialled in on the remote for the front and rear support cables through two separate dials (Figure A.1, B). For safety, there is an emergency stop on both the remote and on the main power and control panel.

Using load cells and tracks on the beams, the lift has the ability to follow the horse and keep constant tension on the cables maintaining the programmed weight compensation. If the horse stumbles, the lift will respond to the acceleration in movement and catch the horse, maintaining a consistent load on the hoist. This is designed to allow the horse to lay down during lift use and provide support when stumbling.


Control of movement of lift (N, S, E, W)

Emergency Stop

Control of movement of lift (Up, Down, Rotation)

Control of increasing/ decreasing weight reduction on front legs

Display screen for weight placed on lift

Control of increasing/ decreasing weight reduction on hind legs

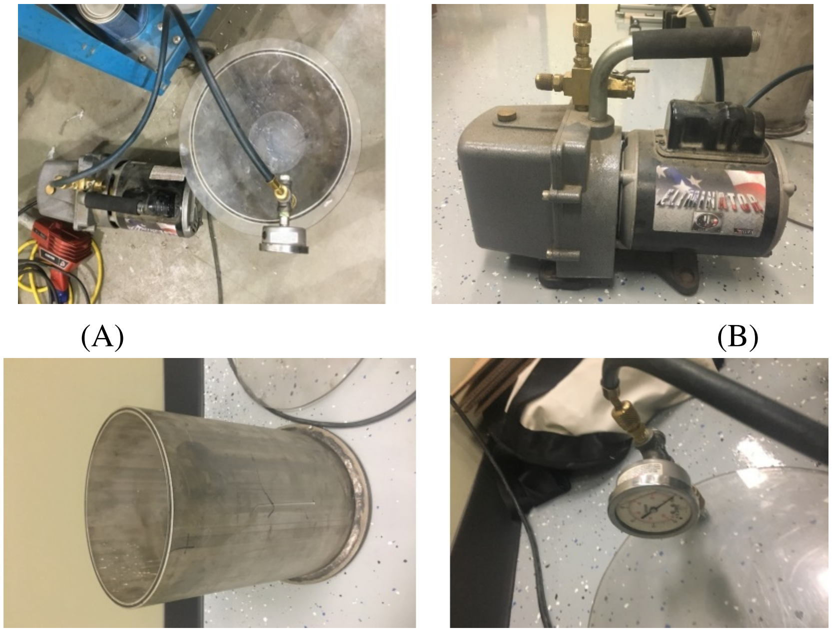
(A)

(B)

Figure A.1. The remote control for the rehabilitation lift, indicating the emergency stop, and control of movement (A) and control of weight reduction (B).

Prototype I:

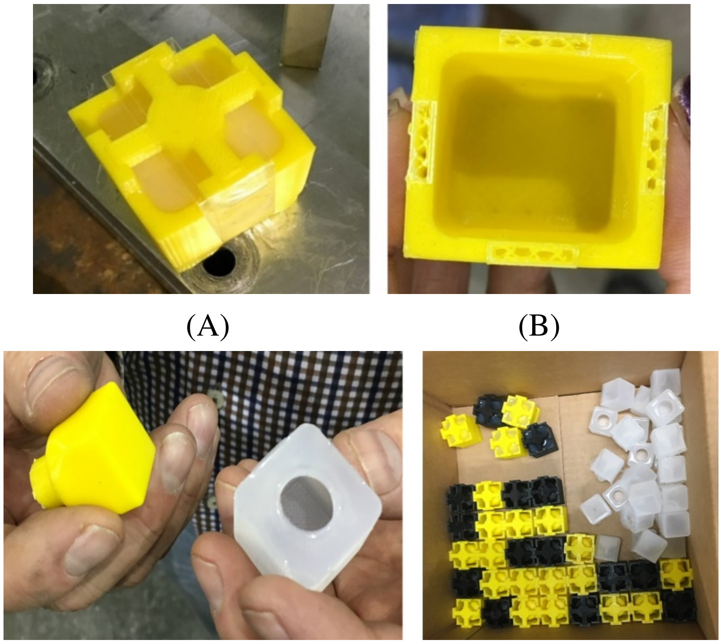
Initial design of the breastplate resulted from research and a series of tests to find materials capable of supporting a horse, with flexibility and strength in mind. The material had to be suitable for attachment of air pockets to redistribute weight, altering pressure and relieving the area supporting significant weight. First, research was completed on air pocket design and material. Blood pressure cuff material was obtained, but it was soon realized that the material was tough to bond correctly with a heat sealer, especially in a small air pocket (i.e., a 1-inch cube). It was also challenging to maximize surface area contact as the material would be in a dome shape when inflated and not square. Air actuators were next on the list, but none suited for attachment to a curved breastplate were found. Further research led to silicone air actuators that could be moulded to a specific shape (i.e., a 1-inch cube). Dragon Skin™ 30 (Smooth-On, Inc., Macungie, PA) had been used in skin effects and for medical prosthetics, was soft, super-strong and stretchy ("Dragon Skin 30," 2020). Therefore, Dragon Skin™ 30 was used for the air pockets. A one-inch cube was designed with a hole in the bottom for airflow. Then a plastic mould was 3D printed to shape the silicone. The two-part silicone was mixed (Part A & Part B) in equal quantities and poured in batches to create enough air pockets for the entire breastplate. Once the two parts were mixed, the silicone was placed in a vacuum chamber to remove air bubbles using a steel cylinder pressure chamber and a vacuum pump (Figure A.2). The silicone was left in the chamber until no bubbles were present. Once the air bubbles were removed from the silicone, it was poured into the 3D printed moulds. Silicone was allowed to cure overnight (cure time of 16 hours) ("Dragon Skin 30," 2020). Once the silicone had cured, an air hose and compressor were used to push the silicone air-pocket out of the mould. The silicone was then removed from the internal mould (Figure A.3), and the air pocket was ready to be attached to the silicone sheet shaped to fit the supporting structure. The air pocket strength was tested through use of a hand air pump with a pressure gauge. Four air pockets were tested to 10 psi before failure (Figure A.4).



(A) (B)

(C) (D)

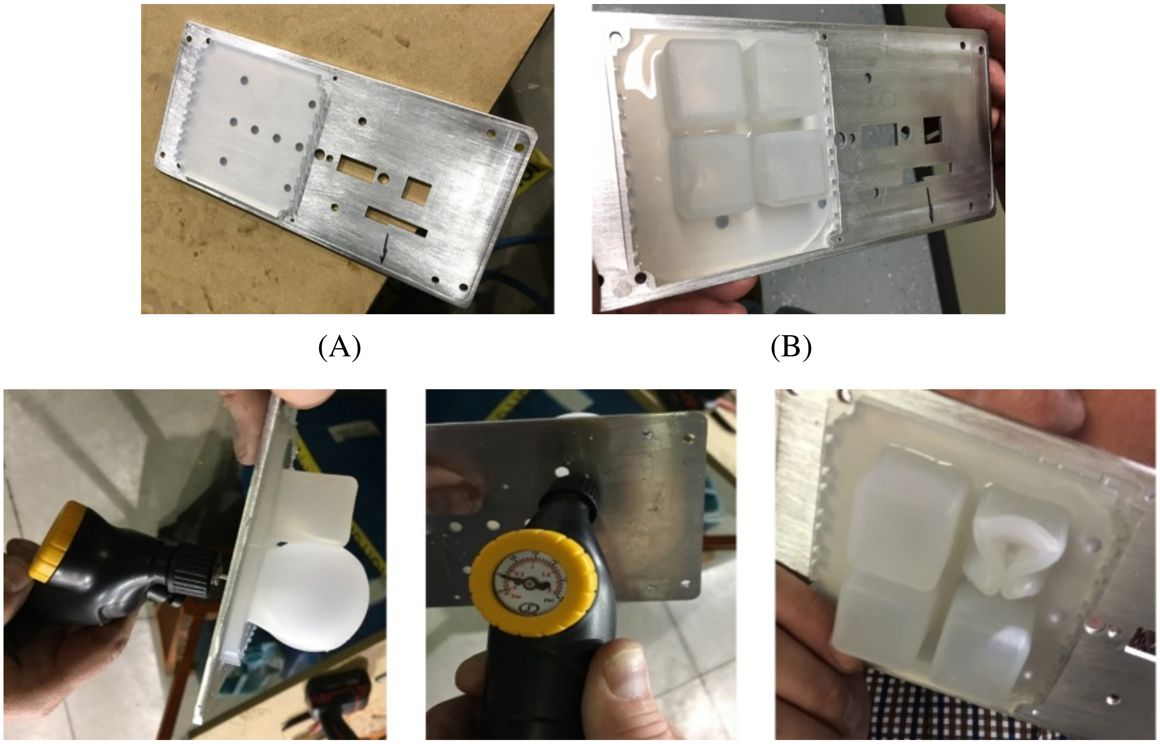
Figure A.2. Vacuum pump used to remove air bubbles from the silicone. (A) displays the entire set up, pump (B), steel cylinder pressure chamber (C), and gauge (D).



(A) (B)

(C) (D)

Figure A.3. Each air pocket was made from a 3D printed mould that was filled with silicone (A). The mould was designed to have a small hole in the bottom of the cube to allow air to be used for removal. Once the silicone had set, it was removed with an air hose to release the silicone from the mould (B), (C) and (D).



(A) (B)

(C) (D) (E)

Figure A.4. Once four cubes were ready, they were attached to a sheet of silicone (A) and (B). Once attached, the silicone air pockets were inflated using an air pump. The silicone was able to withstand 10 psi before failing. Both inflation (C) and (D) and deflation (E) were tested.

For the supporting structure, the distance between the horse's legs was measured. Once measurements were taken, the design (Figure A.5) was created in AutoCAD (Autodesk Inc., San Rafael, CA), computer-aided design software to create 2D and 3D drawings. Once the prototype was designed to specific measurements, it was printed on a large format printer and used to cut out the material to fit on the horse. A material prototype was created for fit and design on the model horse to plan out size, shape, and strap placement (Figure A.6). The material prototype was fitted on the model horse (Figure A.6), which indicated the chest and side pieces needed to be extended to cover more of the chest and abdomen. The material prototype was enlarged and fit to the model horse (Figure A.7). Once the design was determined large enough, it was fitted to the research horse. This fitting confirmed that the size was sufficient to maximize surface area while minimizing size and weight.

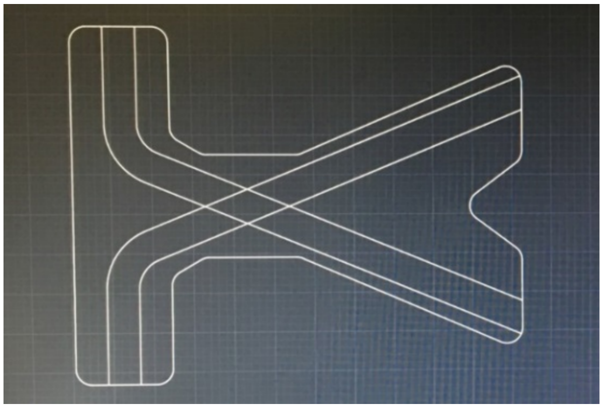
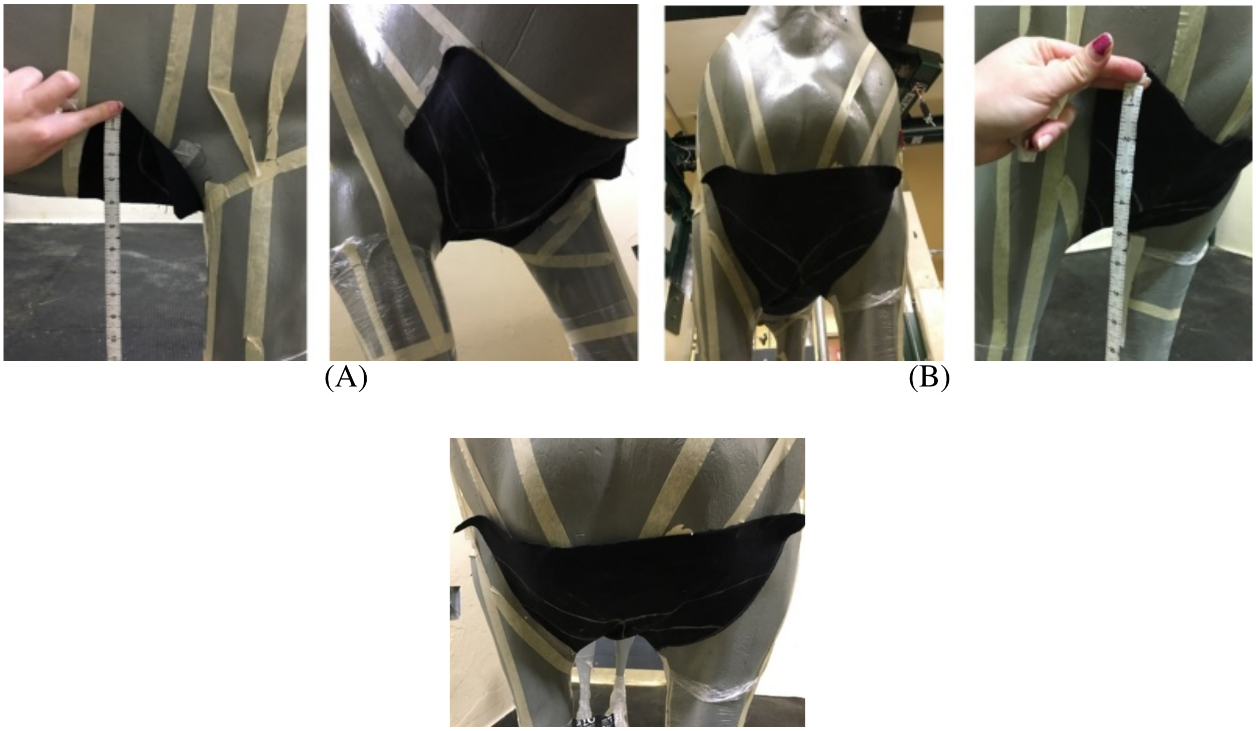


Figure A.5. AutoCAD drawing of the material breastplate size, shape, and strap placement.



(A)

(B)

(C)

Figure A.6. First fitting of material prototype based on research horse measurements. (A) - Abdomen/sternum, (B) and (C) - Chest.

(A) (B) (C)

Figure A.7. Second fitting of extended material prototype based on research horse measurements and fittings. (A) side view from the left side, (B) chest view and (C) abdomen/sternum view.

Once the size and shape were determined, the fibreglass cloth was cut. In order to create the right shape to fit a horse, a mould was made of EARL (Figure A.8), the model horse used for testing of the lift and harnesses. A second mould was milled from Styrofoam, which was designed from templates used to measure the research horse chest radius and size for more accurate sizing of the breastplate (Table A.1). EARL was assumed to be similar to the research horse in shape and size, and due to the difficulty in getting a live horse to stand still long enough to create a mould, it was considered a sufficient option for the original shape of the breastplate. EARL was wrapped in plastic, and then spray foam was applied. The spray foam mould of EARL was then filled with foam to create a negative mould. The fibreglass cloth was placed on the mould, and resin was applied to create a shell for the air pockets (Figure A.9). The resin was left for 24 hours to cure. Once it was cured, the shell was removed from the mould. The fibreglass shell was then lined with bubble wrap to fit test it on the model horse and research horse (Figure A.10). Bubble wrap was used to create the one-inch thick lining of the air pockets for the fit test to ensure proper fit with air-pockets. The shell fit well on the research horse with some flexibility to curve to the horse if needed.

Figure A.8. The breastplate was created from a spray foam mould of EARL, the Styrofoam model horse used for testing. We began by covering EARL in saran wrap and spray foaming on top to create a mould of EARL's chest. From the mould, we created a negative mould with spray foam, mimicking EARL's shape to create a fibreglass shell.

Figure A.9. The negative mould was used to shape the fibreglass shell made from two layers of fibreglass cloth and fibreglass resin.

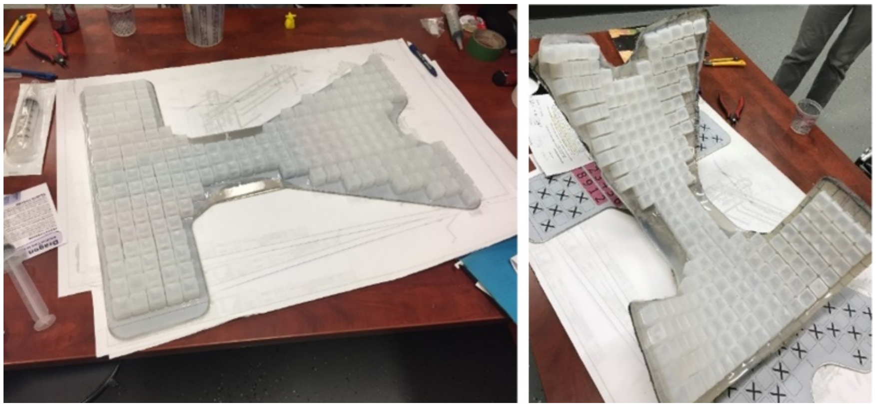
(A) (B)

Figure A.10. The fibreglass shell was then fit-tested on both EARL (A) and the research horse (B).

A one-inch grid was then created on the breastplate to determine the approximate number of air pockets needed to cover the entire surface, maximizing air-pockets and surface area. The air-pockets were then set in the breastplate to determine the gap needed between each air pocket with the breastplate's curvature. Once the gap was determined, the air pockets were added to the AutoCAD drawing of the breastplate. The breastplate shape was then used to create a mould for silicone to attach the air pockets. The same process as above was used to prepare and cure the silicone. All 221 air pockets were then attached to the sheet with the same Dragon Skin™ 30 silicone. The AutoCAD drawing of the air pockets was used for placement of each pocket (Figure A.11). Silicone was then applied to the fibreglass shell, and the sheet of silicone air pockets was applied to the breastplate (Figure A.12). Small air pockets were used to allow for the cycling of pressure. If one large air sac was used or a small number of air pockets, then it would be difficult to relieve pressure momentarily while still maintaining support over a large surface area.

(A) (B)

Figure A.11. A one-inch grid was created on the breastplate for each separate air pocket (A). 221 individual air pockets were attached to the fibreglass shell (B).



(A) (B)

Figure A.12. The silicone cubes were attached to the silicone sheet using the same silicone (A). When all the air pockets had been attached, the silicone sheet was placed into the fibreglass shell and attached with silicone (B).

Once the silicone had cured, a light was used to mark the holes for each air pocket (Figure A.13). A drill was used to drill holes for the air hoses through the fibreglass shell and silicone into the air pocket (Figure A.14, A). ¼ -inch hoses were heated with a heat gun and bent to a 90° angle (Figure A.14, B). Approximately ½-inch of hose was left on one side of the bend to pass through the fibreglass shell into the air pocket. The length of the hose was then measured and cut, depending on which manifold it needed to be attached (Figure A.15). Labels were then created for each hose to track location once the horses were encased for protection. Hoses were glued, with a hot glue gun, into the air pockets to keep them in place and seal each pocket. Air hoses were run to each air pocket allowing for individual control for testing. Hoses were fibreglassed over, with body filler, to avoid crushing of any hoses. A steel support frame was fibreglassed into the breastplate over the hoses for attachment of straps and 3D printed manifolds (later changed to machined steel manifolds for a better seal to prevent air leaks) to the breastplate.

Air manifolds were designed to allow for the proper cycle (1-in-2 or 1-in-9) for each area (low, medium, and high-pressure areas) and then 3D printed for low-pressure areas (5 small manifolds) and higher-pressure areas (1 large manifold for medium and high-pressure air pockets). Estimated pressure areas were determined based on the assumption that the bottom of the breastplate would support the highest load (over the sternum) and pressure being reduced on the sides of the horse (running vertically) versus underneath the horse (horizontally). Low-pressure areas were designated a 1-in-2 cycle, and high and medium-pressure were designated a 1-in-9 cycle. The rationale for this cycling was that high-pressure areas need a greater surface area to distribute the higher pressure over a greater surface versus concentrating the same pressure on a much smaller area (1-square inch for a 1-in-2 cycle versus 8-square inches for a 1-in-9 cycle). A 1-in-2 cycle would be one air pocket inflated and one deflated. A 1-in-9 cycle would result in one air pocket deflated and eight air pockets being inflated. Pressure (i.e., psi of air pockets) and timing of the cycle (i.e., seconds or minutes) between inflation and deflation of air pockets were to be determined in testing. Therefore, this cycle could change for the final prototype once the proper cycle is determined. The breastplate programming had the ability to change these parameters easily via the control laptop and would be based on blood flow during breastplate use with long-term (up to six weeks) weight compensation trials.

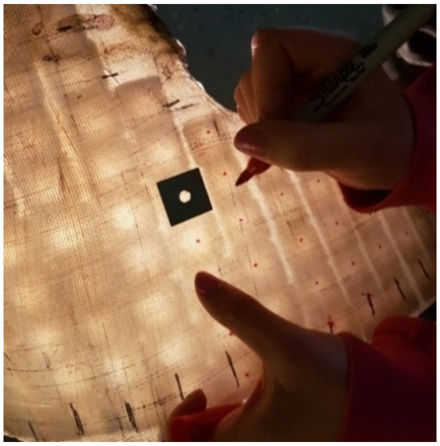
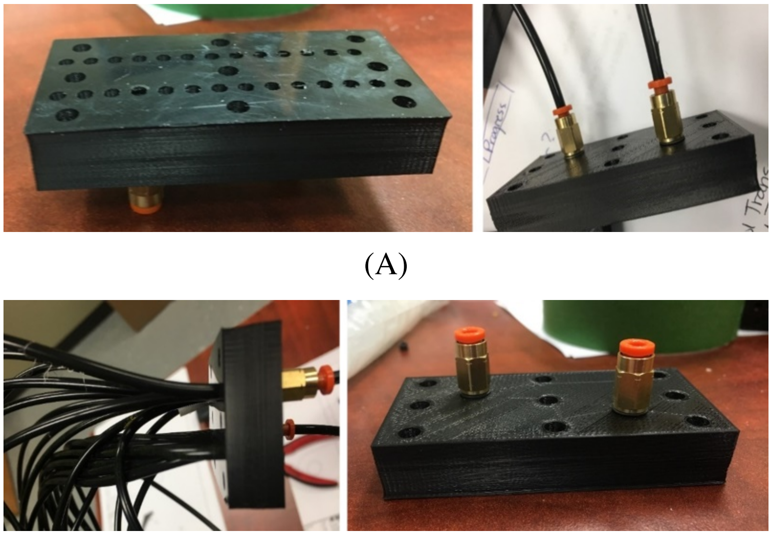


Figure A.13. A light was shone through the silicone to mark the holes in the bottom of the air pockets. A small metal disk was used to line up with the air pocket, and a permanent marker was used to mark each hole.

(A) (B)

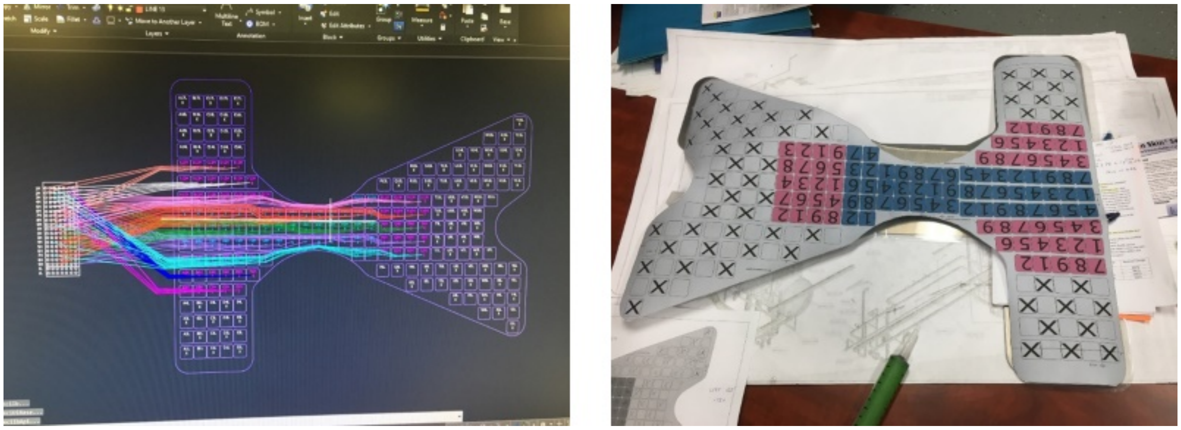
Figure A.14. Holes were drilled through the fibreglass into each air pocket with a drill (A). Air hoses were bent and installed into each air pocket to allow for individual control (B). The hoses were sealed with a hot glue gun and run to plastic manifolds that were 3D printed. All hoses were checked to be in working order, with no leaks inflating and deflating the air pockets.



(A)

(B)

Figure A.15. Once all hoses were installed and sealed with a hot glue gun, they were plugged into the appropriate manifold for control of airflow. Low-pressure areas were plugged into three small manifolds (A) placed at the chest area of the breastplate and two at the rear of the breastplate. Low-pressure hoses were controlled by smaller manifolds allowing for a 1-in-2 cycle of inflation and deflation through top and bottom row separation (B).



(A)

(B)

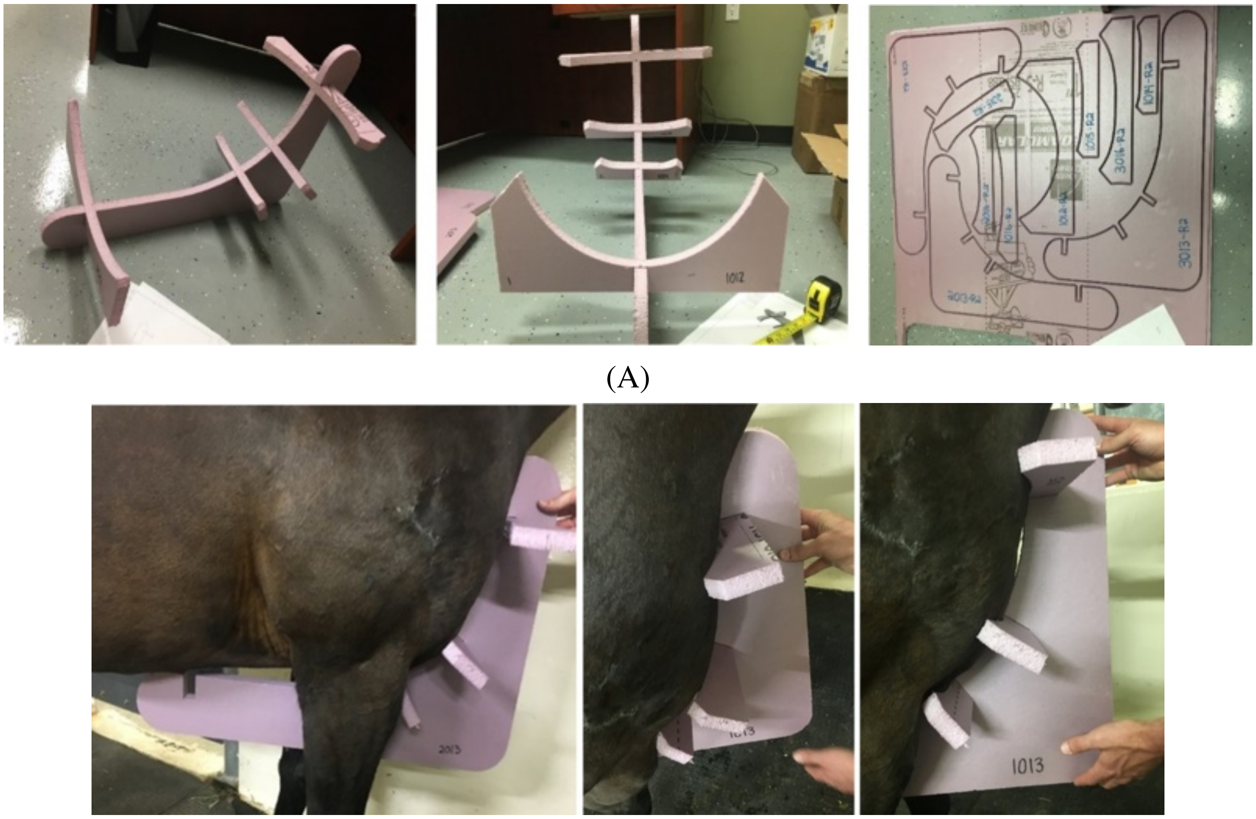
Figure A.16. The medium and high-pressure areas were set to a 1-in-9 cycle. Medium and high-pressure areas were labelled from one to nine (A), and all plugged into the large manifold at the back of the breastplate machined out of aluminum (B). Each hose was labelled with letters and numbers indicating the row, air pocket number and assumed pressure supporting the horse. The rows were first labelled with a letter, starting with A at the widest part of the breastplate (left side of the above image (B)) and ending at Y near the chest. Then a number indicating air pocket number starting from the bottom of the above image (B) and ending at the top. Last was the support pressures high (H), medium (M) or low (L) pressure. Hoses were planned in AutoCAD (B).

(A) (B)

Figure A.17. Hoses were then glued down based on the map in AutoCAD (A) and plugged into the manifolds (B).

Hoses were organized first in AutoCAD, a design and drafting software (Figure A.16, A & B) to plan out the route that would minimize overlapping. Hoses were then glued down with a hot glue gun based on the organized map in AutoCAD (Figure A.17, A) and plugged into the fittings in the steel manifold at the back of the breastplate (Figure A.17, B). All manifolds were assembled and attached, and all the hoses were connected to the manifolds. The low-pressure manifolds with the 1-in-2 cycle were connected to the central manifold at the back of the breastplate containing control for the medium and high-pressure 1-in-9 cycle.

Once all of the hoses had been added to the breastplate air pockets and checked for leakages, the autobody filler was ready to be added to protect the hoses further. Before the autobody filler was added, a new mould was created. The original mould was used to create a template in AutoCAD, adjusting for different sized horses. This template was then used to cut Styrofoam pieces shaped to fit the chest of the horse (Figure A.18). Three different sizes were created, a small, medium, and large template. This template could then later be used to size horses for the correct breastplate size. Five horses were used to create the sizing table to classify horses as small, medium and large (Table A.1). The research horse was measured with the Styrofoam templates to refine the shape of the breastplate mould further. Once the correct size for the research horse was determined and designed in the 3D software, a Styrofoam mould was milled (Figure A.19). The breastplate was then applied to the mould, and all hoses attached to the air pockets were encased in short-strand autobody filler (Figure A.20). Once the horses were covered, the steel frame for the support straps was applied on top of the filler (Figure A.21, A) and fibreglassed in with cloth and resin used to create the initial fibreglass shell (Figure A.21, B, B, C).



(A)

(B)

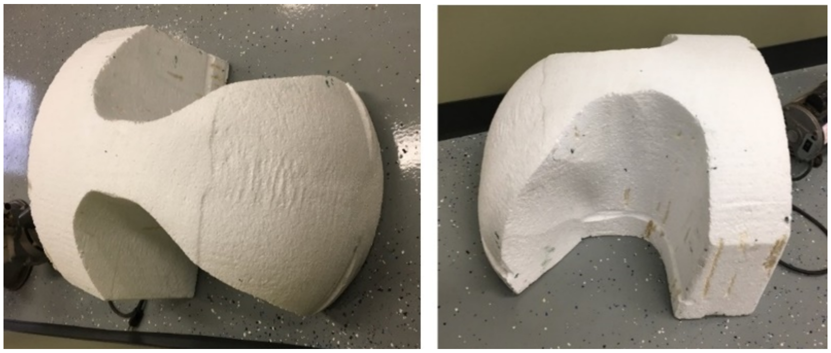
Figure A.18. Using Styrofoam fitting templates (A) the research horse was measured (B) to ensure we had the proper fit.

The fitting templates were then used to create a 3D model of the horse's chest. This 3D model was then used to mill a Styrofoam mould of the research horse to be used in building and material safety testing of the breastplate prototypes. Other horses of varying size and breed were also measured to create a small, medium, and large range for different sized breastplates (Table A.1).

Table A.1: Approximate horse sizing chart for small, medium, large breastplates.

Size	Height (hh)	Weight (lbs)	Breeds	*Chest Width (inches)	Body Condition Score (BCS)	Build
Small	13.0 - 14.2	650 - 900	Arabian, Large Pony, Morgan	<16	Small 5-7 Medium & Large <2	Petite
Medium	14.2 - 15.2	901-1200	Quarter Horse, Paint, Small Thoroughbred	16-17	Small >7 Medium 5-7 Large <5	Average build - refer to BCS
Large	15.2 – 17.0	1201+	Thoroughbred, Warmblood, Small Draft Horse	>17	Small & Medium >7 Large 5-7	Muscular

**It is difficult to classify horses into a specific category, due to differences in build with age, gender, breed, conformation, and height. Therefore, these are general categories.*

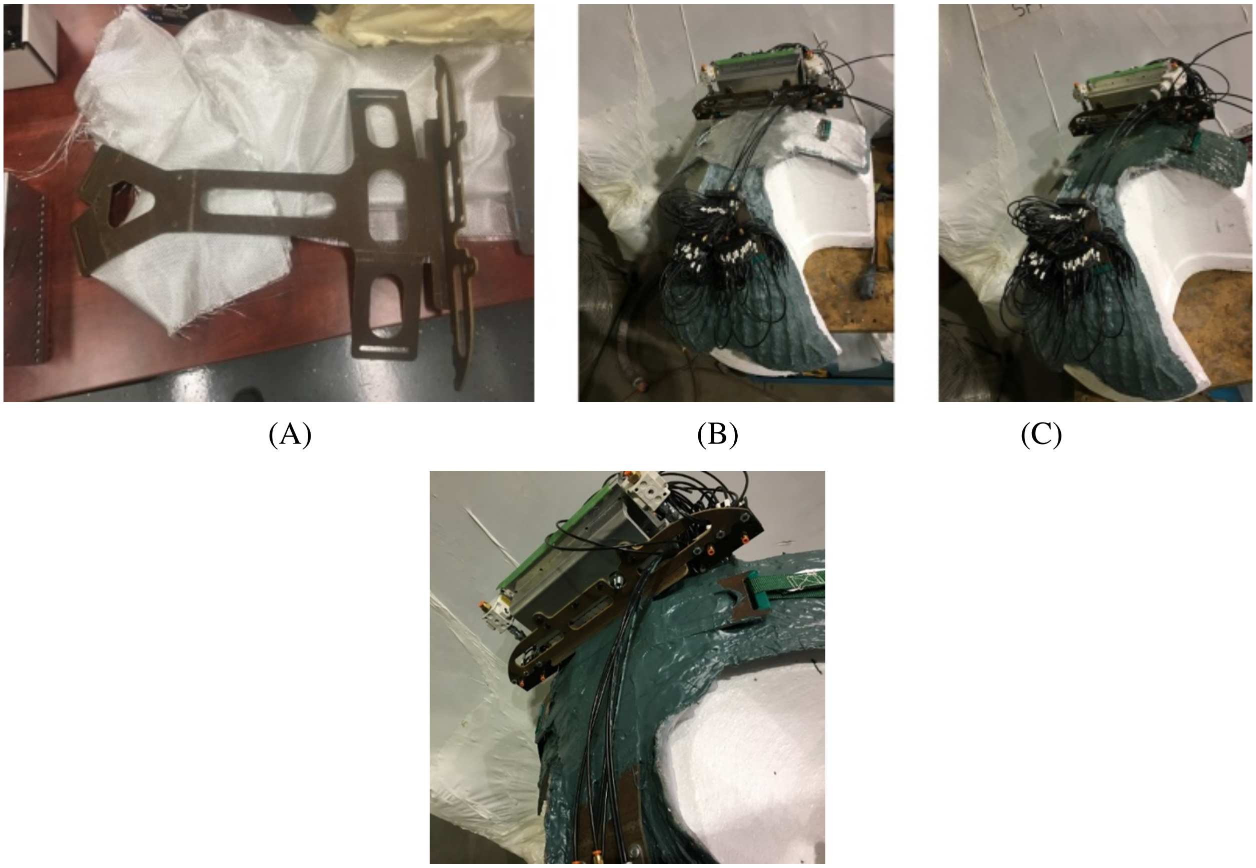


(A) (B)

Figure A.19. Once the radius of the horse's chest and abdomen had been established, a Styrofoam mould was milled, (A) and (B), similar to the mould made of EARL (the Styrofoam horse testing model).

(A) (B)

Figure A.20. The Styrofoam mould was used to shape the fibreglass shell when applying Autobody filler and fibreglass resin. Autobody filler was used to fill in areas between hoses for protection and to avoid crushing of hoses once the weight was applied (A). The manifolds were attached to the steel plate, and the steel plate was fibre-glassed onto the fibreglass shell (B) with the hoses and air pockets using fibreglass resin and mesh.



(A) (B) (C)

(D)

Figure A.21. Application of the steel frame (A) to the breastplate. Applied fibreglass cloth (B) to steel frame on breastplate shell. Fibreglass resin was applied (C) and Autobody filler added on top to further strengthen (D).

All air manifolds were attached to the steel frame. Solenoids, pressure gauges, air hoses and controls were also attached. Further sensors included thermocouple wires attached to 32 air pockets with silicone (Figure A.22, A), for temperature readings, a factor believed to contribute to pressure ulcer development. Two humidity sensors were placed in 3D printed plastic cases (Figure A.22, B), sealed with silicone and connected to the breastplate, with one sensor measuring humidity in the air entering and one measuring the air leaving. The humidity sensors were to detect moisture that is believed to be another factor in pressure ulcer development (Coleman et al., 2014; Mitchell, 2018; Schwartz et al., 2018) and to determine the amount of airflow needed to dry the hair underneath the breastplate. First, the amount of airflow required to dry the hair needed to be determined (through a separate study) and then the proper control could be obtained for that amount of airflow (e.g., an airflow sensor or volume flow meter). Air would be directed overtop of the air pockets, separate from the air within the air pockets providing support. An on-board control system (Arduino) (Figure A.23, A) was attached to the steel plate on the bottom of the breastplate to allow for control of the air pockets via a laptop (i.e., the cycle of the air pockets and the duration of each cycle). Pressure entering the air pockets could be controlled through the pressure gauges attached to the sides of the steel manifold (Figure A.23, B

& C). The amount of pressure for inflation of the air pockets was controlled through a pressure gauge.

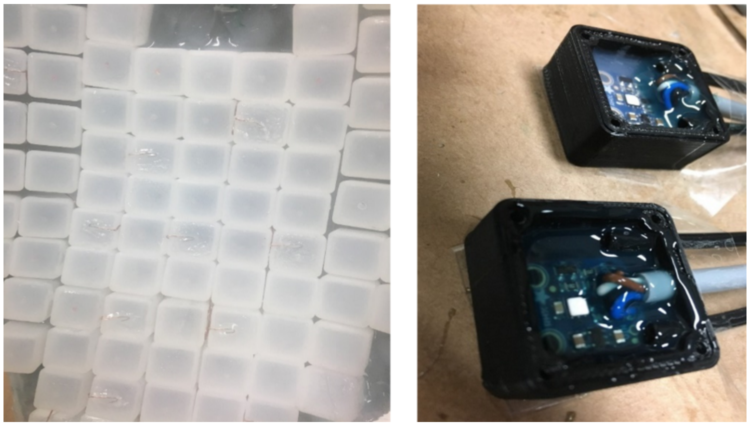
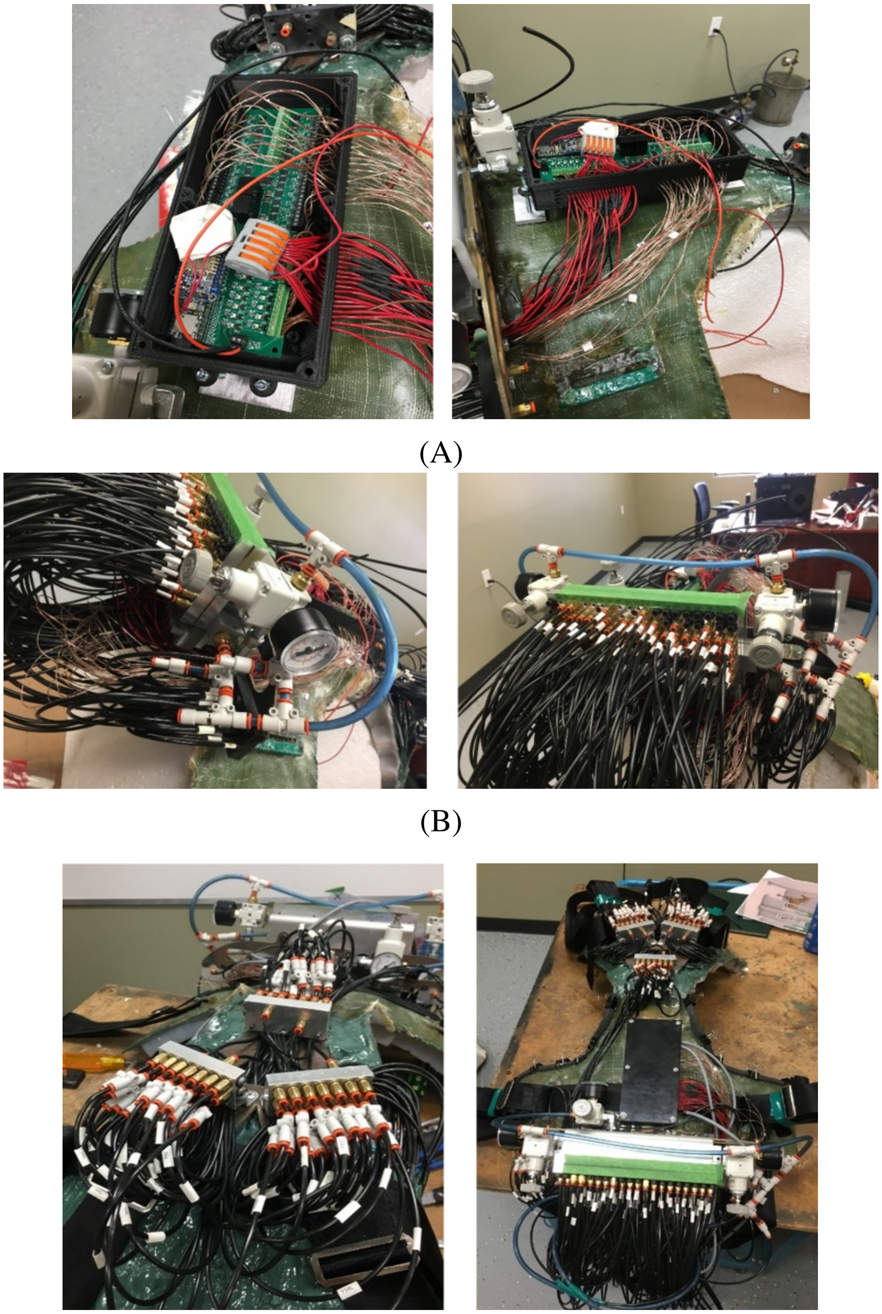

(A) (B)

Figure A.22. Thermocouple wires were attached to the silicone air pockets, using silicone, to allow for skin temperature readings (A). The outside edge of the air pockets was sealed on multiple sides to allow for air to be passed over deflated cubes to dry the skin and hair while the pockets were deflated. Humidity sensors were enclosed in 3D printed boxes and sealed with silicone to protect the circuit board while allowing the sensor to read humidity through air circulation via air hoses (B). The sensors were set up to measure the air before it contacted the horse's skin and hair and after contact to measure the amount of moisture removed from the area.

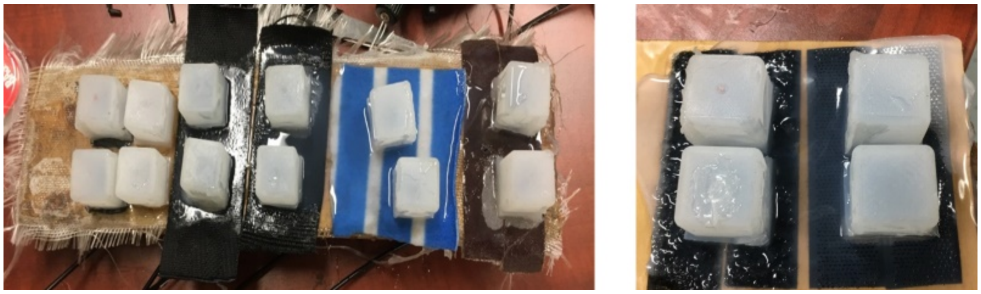


(A)

(B)

(C)

Figure A.23. The circuit board was installed in the protective case (A), which was 3D printed. The thermocouple wires and solenoids were wired to the circuit board. External hoses were connected between fittings (B) to allow for an air and a power source to be attached for operation. The testing of inflation and deflation of the air pockets was successful. The plastic manifolds were leaking and needed to be changed to metal. The new manifolds were made from aluminum (C).



(A) (B)

Figure A.24. Material testing to determine materials able to bond with silicone. (A) includes household silicone, seatbelt webbing, standard webbing, fleece, and Velcro. (B) includes both sides of the Velcro, the hook and the loop.

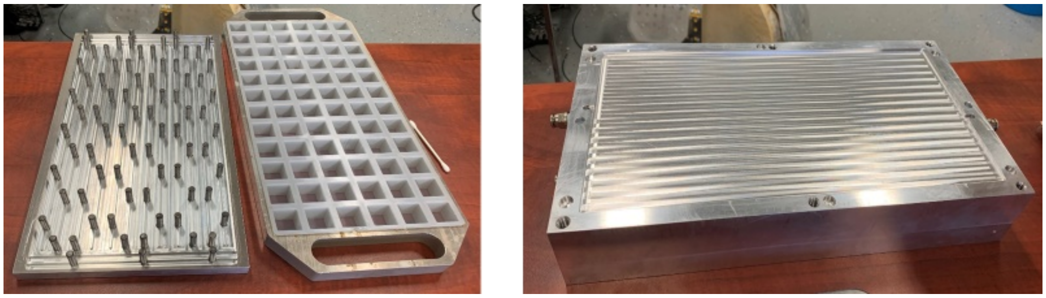
Figure A.25. Removal of silicone air pockets in an attempt to re-bond and seal air pockets. Silicone separated from fibreglass during initial testing.

Figure A.26. Image of the air hoses through the fibreglass that were inserted into each air pocket.

(A) (B)

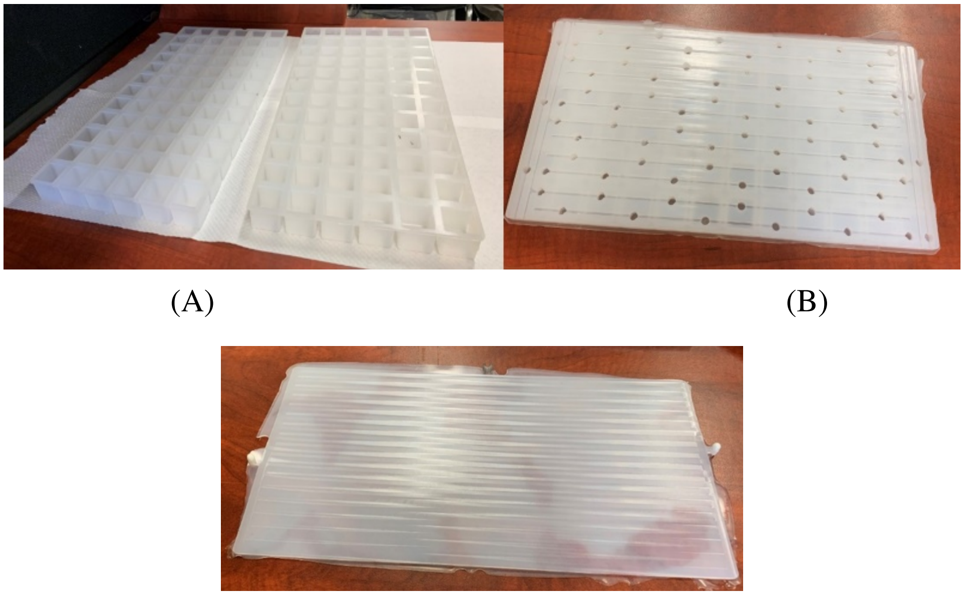
Figure A.27. Application of Velcro to fibreglass [(A) and (B)] in an attempt to re-bond the silicone to the fibreglass. Air pockets were re-attached with silicone, but some leakage was still present.

Prototype II:



(A) (B)

Figure A.28. Moulds used to make air pocket batch. (A) left is the airline mould, right is the air pockets, and (B) is the bottom component sealing in the air pockets. Each section of air pockets contains 72 air pockets in a 1-in-4 cycle, allowing staggered air pockets to be deflated to maximize the contact area.



(A) (B)

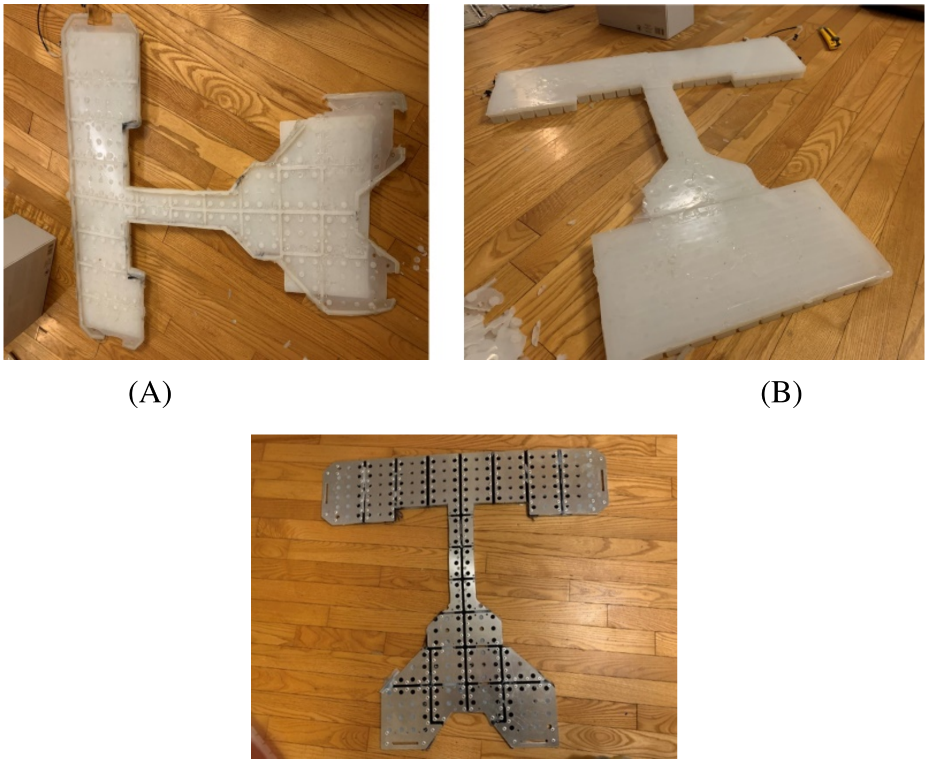
(C)

Figure A.29. The components of each air pocket section. (A) is the silicone air pockets, (B) is the air lines and (C) is the bottom component sealing in the air pockets. All components were glued together with silicone. Each section of air pockets contains 72 air pockets (total 288 air pockets) in a 1-in-4 cycle, allowing staggered air pockets to be deflated to maximize the contact area.

(A) (B)

Figure A.30. The assembling of the air pocket sections onto the breastplate structure (silicone-covered metal plates and seatbelt webbing). Four air pocket sections were used to fill the breastplate. This pouring of air pockets in sections sped up the building and modification of the breastplate. Sections were connected via silicone air lines to create one continuous flow of air throughout all sections. Air pockets were separated into a 1-in-4 cycle to allow for the relief of pressure intermittently.

Prototype III:



(A) (B)

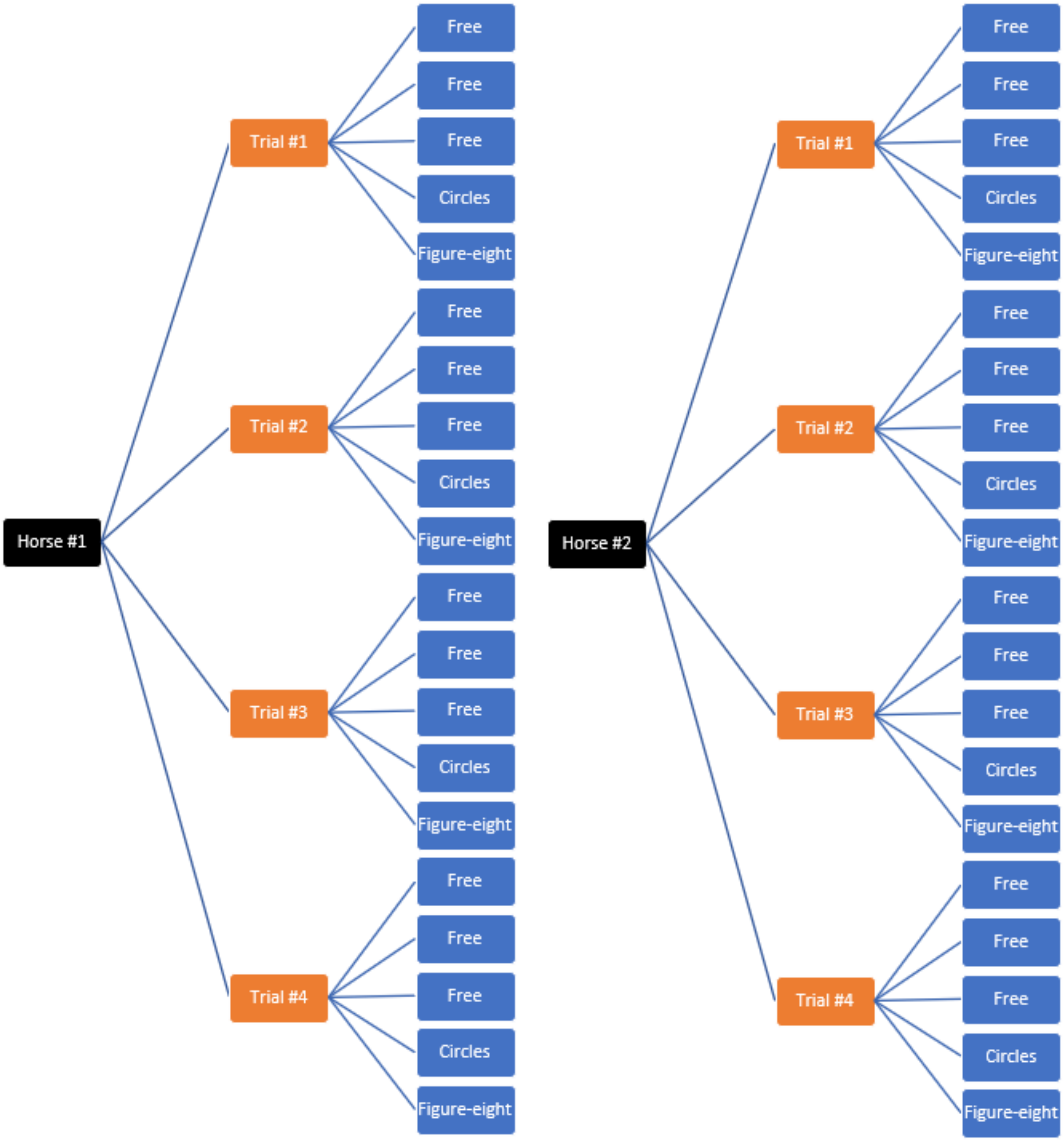
(C)

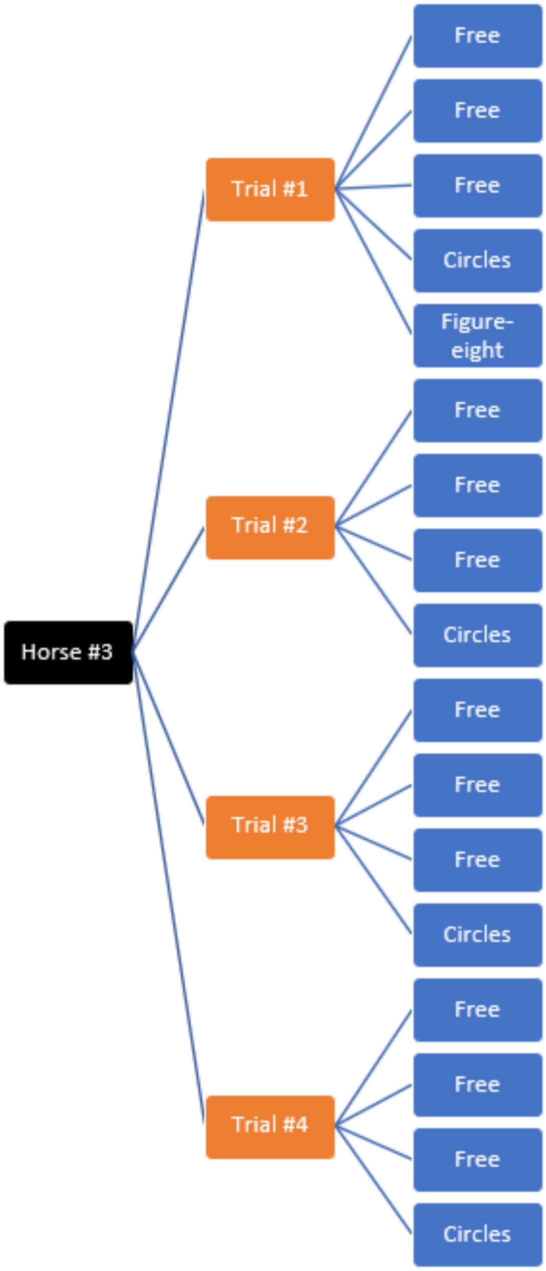
Figure A.31. The silicone air pockets (A) were removed from the metal plates (B). The air pockets were cleaned up, and extra silicone removed (C) to be reattached to different support material. Breastplate silicone was to be incorporated into fibreglass meshing.

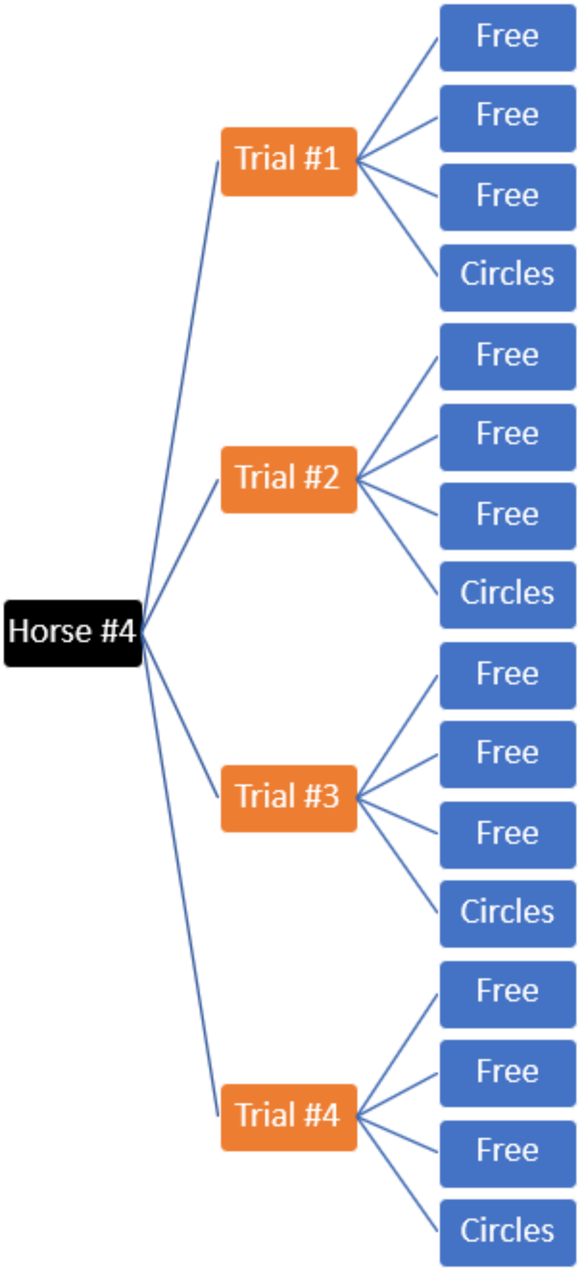
(A) (B)

Figure A.32. The pressure gauge displaying the air pressure of the air pockets at 3 psi (A) and the inflated breastplate air pockets on the horse (B).

Layout of Movement Trials:




Horse #3
Trial #1
Free
Free
Free
Circles
Figure-eight
Trial #2
Free
Free
Free
Circles
Trial #3
Free
Free
Free
Circles
Trial #4
Free
Free
Free
Circles


Horse #4
Trial #1
Free
Free
Free
Circles
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Circles
Trial #3
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Trial #4
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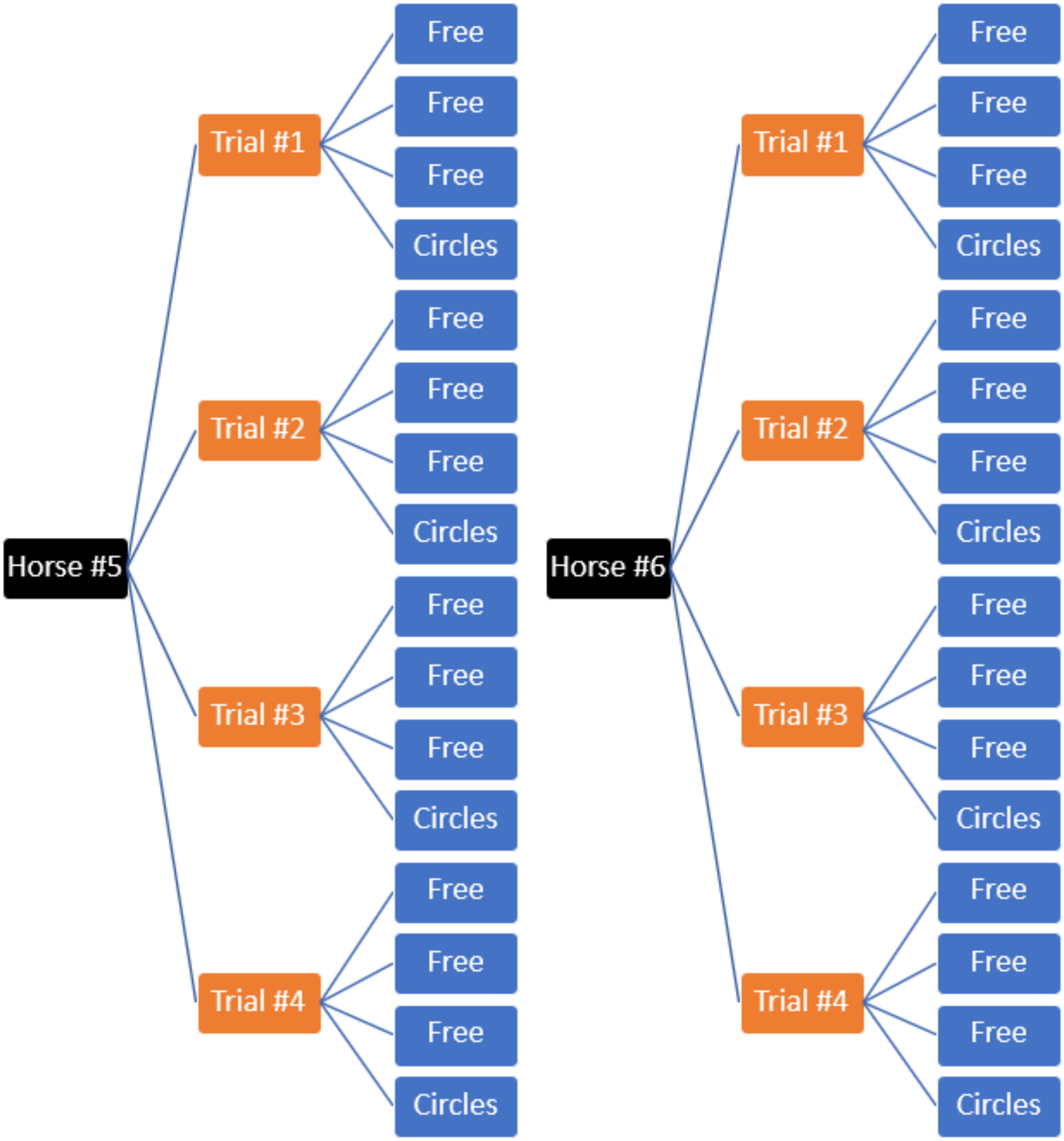

Figure A.33. The layout of testing completed by each horse. Each horse completed four days of testing, and each test consisted of three five-minute free movements, one five-minute circle and, if applicable, one five-minute figure-eight. Three free movements were completed in each test due to some free movements having little to no movement. 24 testing sessions in total were completed, including 72 Free movement trials (3 per test day), 24 circle trials, and nine figure-eight trials (the smallest horse at the personal barn attempted the figure-eights in the first test session with difficulty, due to stall size. Therefore, it was removed from future sessions in this location).

APPENDIX B MATLAB CODES

LPFilt100 CODE

```
%This script lowpass filters accelerometer data that has been
imported as
%follows.

    %Note re: placement and axes. The Apple Watch IMU should be
placed at the withers, right forelimb or hindlimb

    %Import data: To load the data from a .csv file, rename the
file 'Data', then block the 3 data columns to the right,
    %select 'Numeric Matrix' as the output type and then click
'Import data' under 'Import Selection'. Save the variable 'Data'
    % as a Matlab file ('Data.mat'). The data should be
contained in the data file Data.mat.

    %n = the order of the filter (default is 4) Fc = the low
pass cutoff
    %frequency (default is 10 Hz) Fs = the sampling rate
(default
    %is 100 Hz) Wn = the normalized cutoff frequency (this
should be 0.2,
    %regardless of whether the sampling is 100 or 60 Hz (i.e.,
use 10 Hz
    %cutoff for 100 Hz sampling rate and 6 Hz for 60 Hz
sampling; Wn will =
    %0.2 in both cases). b and a = the filter coefficients
    load Data.mat
%Loads the imported data structure file.
    X = Data (2:end, 1); % Creates the variable X for the 1st
column (= the ML accel. data).
    Y = Data (2:end, 2); % Creates the variable Y for the 2nd
column (= the Vertical accel. data)
    Z = Data (2:end, 3); % Creates the variable Z for the 3rd
column (= the AP accel. data)

    n = 4;
    Fc = 10;
    Fs = 100;
    Wn = (Fc*2)/Fs;
    [b,a] = butter(n, Wn, 'low');
    filtx = filtfilt(b, a, X);
    filty = filtfilt(b, a, Y);
    filtz = filtfilt(b, a, Z);
```

STV_X CODE (Limbs)

```
  %This is the PREFERRED routine for processing the vertical
signal.

    %This script finds the time between the LP filtered X-axis
peaks (i.e, the individual Step Times) and removes outliers that
are
    %3 SD above and below the median Step time.

    %findpeaks is the function that finds the peaks of the
signal.
    %pks = the magnitude of the peaks.
    %locs = the location (i.e, the sample number) of the peaks
(i.e., the
    %peak locations).

    [pks, locs] = findpeaks(filtx,'MinPeakDistance',80,
'MinPeakProminence', 0.5); %This command finds the peaks and
    %creates variables for the magnitude (pks) and locations
(locs) of the peaks. The command also specifies that
    %there must be a minimum horizontal distance between each
peak (i.e,. default = 20 samples; i.e., 0.33 s @ 60 Hz)
    %and that the peaks must be 0.30 g higher than the lowest
value.
    SteptimeX = diff(locs) * 1/Fs; %This command finds the
differences between the peak locations (i.e., # of samples)
    %and then multiplies this by the sampling rate time. This
provides the
    %series of individual step times.

    ThreshU = median(SteptimeX) + 3*(std(SteptimeX)); %This
command finds the median value of the SteptimeX variable
    %and then adds 3 standard deviations to it.
    OutliersU = find(SteptimeX > ThreshU); %This creates a
variable that contains the outliers that are greater than the
    %Threshold value.
    SteptimeX(OutliersU) = [median(SteptimeX)]; %This command
replaces the outliers in SteptimeX with the median
    %steptime.
    %The nextseries of commands repeats the above process for
steptimes
    %that are 3 SD's below the median step time.
    ThreshD = median(SteptimeX) - 3*(std(SteptimeX));
    OutliersD = find(SteptimeX < ThreshD);
    SteptimeX(OutliersD) = [median(SteptimeX)];
```

```
    Odd = SteptimeX(1:2:end,:);  %This creates a variable of odd
steptimes.
    Even = SteptimeX(2:2:end,:);  %This creates a variable of
even steptimes.
    SizeO = size (Odd,1); %This provides the number of rows in
the Odd steptime variable.
    SizeE = size (Even,1); %This provides the number of rows in
the Even steptime variable.

    %The "if elseif" statement below says: if the size (i.e., #
of rows) of
    %the Odd and Even variables are the same, then Odd = Odd
(i.e., do
    %nothing). If the size of Odd is greater than Even (which
will occur
    %when you have an odd number of rows) then the last row in
the Odd variable is to be removed (Odd(SizeO(1),:) = [];).

    if SizeO == SizeE
        Odd = Odd;
    elseif SizeO > SizeE;
    Odd(SizeO(1),:) = [];
    end

    StridetimeX = Odd + Even;  %This statement adds each row of
the Odd and Even variables together to provide the series of
    %stride times.
    AsymX = (abs(mean(Odd) - mean(Even))/((mean(Odd) +
mean(Even))/2))*100; %This command finds the asymmetry between
    %the mean of the right and left steps.
    avgStepX = mean(SteptimeX); %This variable finds the mean of
the series of step times.
    avgStrideX = mean(StridetimeX); %This variable find the mean
of the series of stride times.
    COVStepX = (std(SteptimeX)/avgStepX) *100; %This variable
finds the coefficient of variation of the step time series.
    COVStrideX = (std(StridetimeX)/avgStrideX) *100; %This
variable finds the coefficient of variation of the stride time
    %series.
    [CadenceX] = 1/((size(filtx)/size(SteptimeX))/60)*60; %This
variable determines the overall cadence of the series
    %based on the total number of samples (in filtx) and the
total number of
    %steps (SteptimeX).
    StepcountX = SizeE + SizeO;
```

```
    save StepX.txt SteptimeX -ascii %This saves the variable
Steptime (containing the series of step times) to a .txt file.
    save StrideX.txt StridetimeX -ascii %This saves the variable
Stridetime (containing the series of stride times) to
    %a .txt file.
    %The following line saves the output variables to a ascii
.txt file
    %(figure out how to include a column of labels).
    save OutputX.txt StepcountX avgStepX COVStepX CadenceX AsymX
-ascii
```

STV_XW CODE (Withers)

```
%This is an alternative routine for processing the "withers"
mediolateral signal.

    %This script finds the time between the LP filtered X-axis
peaks (i.e, the individual Step Times) and removes outliers that
are
    %3 SD above and below the median Step time.

    %findpeaks is the function that finds the peaks of the
signal.
    %pks = the magnitude of the peaks.
    %locs = the location (i.e, the sample number) of the peaks
(i.e., the
    %peak locations).

    [pks, locs] = findpeaks(filtx,'MinPeakDistance',35,
'MinPeakProminence', 0.3); %This command finds the peaks and
    %creates variables for the magnitude (pks) and locations
(locs) of the peaks. The command also specifies that
    %there must be a minimum horizontal distance between each
peak (i.e,. default = 20 samples; i.e., 0.33 s @ 60 Hz)
    %and that the peaks must be 0.30 g higher than the lowest
value.
    SteptimeX = diff(locs) * 1/Fs; %This command finds the
differences between the peak locations (i.e., # of samples)
    %and then multiplies this by the sampling rate time. This
provides the
    %series of individual step times.

    ThreshU = median(SteptimeX) + 3*(std(SteptimeX)); %This
command finds the median value of the SteptimeX variable
    %and then adds 3 standard deviations to it.
    OutliersU = find(SteptimeX > ThreshU); %This creates a
variable that contains the outliers that are greater than the
```

```
    %Threshold value.
    SteptimeX(OutliersU) = [median(SteptimeX)]; %This command
replaces the outliers in SteptimeX with the median
    %steptime.
    %The nextseries of commands repeats the above process for
steptimes
    %that are 3 SD's below the median step time.
    ThreshD = median(SteptimeX) - 3*(std(SteptimeX));
    OutliersD = find(SteptimeX < ThreshD);
    SteptimeX(OutliersD) = [median(SteptimeX)];

    Odd = SteptimeX(1:2:end,:);  %This creates a variable of odd
steptimes.
    Even = SteptimeX(2:2:end,:);  %This creates a variable of
even steptimes.
    SizeO = size (Odd,1); %This provides the number of rows in
the Odd steptime variable.
    SizeE = size (Even,1); %This provides the number of rows in
the Even steptime variable.

    %The "if elseif" statement below says: if the size (i.e., #
of rows) of
    %the Odd and Even variables are the same, then Odd = Odd
(i.e., do
    %nothing). If the size of Odd is greater than Even (which
will occur
    %when you have an odd number of rows) then the last row in
the Odd variable is to be removed (Odd(SizeO(1),:) = [];).

    if SizeO == SizeE
        Odd = Odd;
    elseif SizeO > SizeE;
    Odd(SizeO(1),:) = [];
    end

    StridetimeX = Odd + Even;  %This statement adds each row of
the Odd and Even variables together to provide the series of
    %stride times.
    AsymX = (abs(mean(Odd) - mean(Even))/((mean(Odd) +
mean(Even))/2))*100; %This command finds the asymmetry between
    %the mean of the right and left steps.
    avgStepX = mean(SteptimeX); %This variable finds the mean of
the series of step times.
    avgStrideX = mean(StridetimeX); %This variable find the mean
of the series of stride times.
    COVStepX = (std(SteptimeX)/avgStepX) *100; %This variable
finds the coefficient of variation of the step time series.
```

```
    COVStrideX = (std(StridetimeX)/avgStrideX) *100; %This
variable finds the coefficient of variation of the stride time
    %series.
    [CadenceX] = 1/((size(filtx)/size(SteptimeX))/60)*60; %This
variable determines the overall cadence of the series
    %based on the total number of samples (in filty) and the
total number of
    %steps (SteptimeX).
    StepcountX = SizeE + SizeO;
    save StepX.txt SteptimeX -ascii %This saves the variable
Steptime (containing the series of step times) to a .txt file.
    save StrideX.txt StridetimeX -ascii %This saves the variable
Stridetime (containing the series of stride times) to
    %a .txt file.
    %The following line saves the output variables to a ascii
.txt file
    %(figure out how to include a column of labels).
    save OutputX.txt StepcountX avgStepX COVStepX CadenceX AsymX
-ascii
```

STV_Y CODE (Limbs)

```
%This is the PREFERRED routine for processing the AP signal.

    %This script finds the time between the LP filtered Y-axis
peaks (i.e, the individual Step Times) and removes outliers that
are
    %3 SD above and below the median Step time.

    %findpeaks is the function that finds the peaks of the
signal.
    %pks = the magnitude of the peaks.
    %locs = the location (i.e, the sample number) of the peaks
(i.e., the
    %peak locations).

    [pks, locs] = findpeaks(filty,'MinPeakDistance',80,
'MinPeakProminence', 0.5); %This command finds the peaks and
    %creates variables for the magnitude (pks) and locations
(locs) of the peaks. The command also specifies that
    %there must be a minimum horizontal distance between each
peak (i.e,. default = 20 samples; i.e., 0.33 s @ 60 Hz)
    %and that the peaks must be 0.30 g higher than the lowest
value.
    SteptimeY = diff(locs) * 1/Fs; %This command finds the
differences between the peak locations (i.e., # of samples)
```

```
    %and then multiplies this by the sampling rate time. This
provides the
    %series of individual step times.

    ThreshU = median(SteptimeY) + 3*(std(SteptimeY)); %This
command finds the median value of the SteptimeY variable
    %and then adds 3 standard deviations to it.
    OutliersU = find(SteptimeY > ThreshU); %This creates a
variable that contains the outliers that are greater than the
    %Threshold value.
    SteptimeY(OutliersU) = [median(SteptimeY)]; %This command
replaces the outliers in SteptimeY with the median
    %steptime.
    %The nextseries of commands repeats the above process for
steptimes
    %that are 3 SD's below the median step time.
    ThreshD = median(SteptimeY) - 3*(std(SteptimeY));
    OutliersD = find(SteptimeY < ThreshD);
    SteptimeY(OutliersD) = [median(SteptimeY)];

    Odd = SteptimeY(1:2:end,:);  %This creates a variable of odd
steptimes.
    Even = SteptimeY(2:2:end,:);  %This creates a variable of
even steptimes.
    SizeO = size (Odd,1); %This provides the number of rows in
the Odd steptime variable.
    SizeE = size (Even,1); %This provides the number of rows in
the Even steptime variable.

    %The "if elseif" statement below says: if the size (i.e., #
of rows) of
    %the Odd and Even variables are the same, then Odd = Odd
(i.e., do
    %nothing). If the size of Odd is greater than Even (which
will occur
    %when you have an odd number of rows) then the last row in
the Odd variable is to be removed (Odd(SizeO(1),:) = [];).

    if SizeO == SizeE
        Odd = Odd;
    elseif SizeO > SizeE;
    Odd(SizeO(1),:) = [];
    end

    StridetimeY = Odd + Even;  %This statement adds each row of
the Odd and Even variables together to provide the series of
    %stride times.
```

```
    AsymY = (abs(mean(Odd) - mean(Even))/((mean(Odd) +
mean(Even))/2))*100; %This command finds the asymmetry between
    %the mean of the right and left steps.
    avgStepY = mean(SteptimeY); %This variable finds the mean of
the series of step times.
    avgStrideY = mean(StridetimeY); %This variable find the mean
of the series of stride times.
    COVStepY = (std(SteptimeY)/avgStepY) *100; %This variable
finds the coefficient of variation of the step time series.
    COVStrideY = (std(StridetimeY)/avgStrideY) *100; %This
variable finds the coefficient of variation of the stride time
    %series.
    [CadenceY] = 1/((size(filty)/size(SteptimeY))/60)*60; %This
variable determines the overall cadence of the series
    %based on the total number of samples (in filty) and the
total number of
    %steps (SteptimeY).
    StepcountY = SizeE + SizeO;
    save StepY.txt SteptimeY -ascii %This saves the variable
Steptime (containing the series of step times) to a .txt file.
    save StrideY.txt StridetimeY -ascii %This saves the variable
Stridetime (containing the series of stride times) to
    %a .txt file.
    %The following line saves the output variables to a ascii
.txt file
    %(figure out how to include a column of labels).
    save OutputY.txt StepcountY avgStepY COVStepY CadenceY AsymY
-ascii
```

STV_YW CODE (Withers)

```
  %This is the PREFERRED routine for processing the AP signal.

    %This script finds the time between the LP filtered Y-axis
peaks (i.e, the individual Step Times) and removes outliers that
are
    %3 SD above and below the median Step time.

    %findpeaks is the function that finds the peaks of the
signal.
    %pks = the magnitude of the peaks.
    %locs = the location (i.e, the sample number) of the peaks
(i.e., the
    %peak locations).

    [pks, locs] = findpeaks(filty,'MinPeakDistance',35,
'MinPeakProminence', 0.3); %This command finds the peaks and
```

```
    %creates variables for the magnitude (pks) and locations
(locs) of the peaks. The command also specifies that
    %there must be a minimum horizontal distance between each
peak (i.e,. default = 20 samples; i.e., 0.33 s @ 60 Hz)
    %and that the peaks must be 0.30 g higher than the lowest
value.
    SteptimeY = diff(locs) * 1/Fs; %This command finds the
differences between the peak locations (i.e., # of samples)
    %and then multiplies this by the sampling rate time. This
provides the
    %series of individual step times.

    ThreshU = median(SteptimeY) + 3*(std(SteptimeY)); %This
command finds the median value of the SteptimeY variable
    %and then adds 3 standard deviations to it.
    OutliersU = find(SteptimeY > ThreshU); %This creates a
variable that contains the outliers that are greater than the
    %Threshold value.
    SteptimeY(OutliersU) = [median(SteptimeY)]; %This command
replaces the outliers in SteptimeY with the median
    %steptime.
    %The nextseries of commands repeats the above process for
steptimes
    %that are 3 SD's below the median step time.
    ThreshD = median(SteptimeY) - 3*(std(SteptimeY));
    OutliersD = find(SteptimeY < ThreshD);
    SteptimeY(OutliersD) = [median(SteptimeY)];

    Odd = SteptimeY(1:2:end,:);  %This creates a variable of odd
steptimes.
    Even = SteptimeY(2:2:end,:);  %This creates a variable of
even steptimes.
    SizeO = size (Odd,1); %This provides the number of rows in
the Odd steptime variable.
    SizeE = size (Even,1); %This provides the number of rows in
the Even steptime variable.

    %The "if elseif" statement below says: if the size (i.e., #
of rows) of
    %the Odd and Even variables are the same, then Odd = Odd
(i.e., do
    %nothing). If the size of Odd is greater than Even (which
will occur
    %when you have an odd number of rows) then the last row in
the Odd variable is to be removed (Odd(SizeO(1),:) = [];).

    if SizeO == SizeE
```

```
        Odd = Odd;
    elseif SizeO > SizeE;
    Odd(SizeO(1),:) = [];
    end

    StridetimeY = Odd + Even;  %This statement adds each row of
the Odd and Even variables together to provide the series of
    %stride times.
    AsymY = (abs(mean(Odd) - mean(Even))/((mean(Odd) +
mean(Even))/2))*100; %This command finds the asymmetry between
    %the mean of the right and left steps.
    avgStepY = mean(SteptimeY); %This variable finds the mean of
the series of step times.
    avgStrideY = mean(StridetimeY); %This variable find the mean
of the series of stride times.
    COVStepY = (std(SteptimeY)/avgStepY) *100; %This variable
finds the coefficient of variation of the step time series.
    COVStrideY = (std(StridetimeY)/avgStrideY) *100; %This
variable finds the coefficient of variation of the stride time
    %series.
    [CadenceY] = 1/((size(filty)/size(SteptimeY))/60)*60; %This
variable determines the overall cadence of the series
    %based on the total number of samples (in filty) and the
total number of
    %steps (SteptimeY).
    StepcountY = SizeE + SizeO;
    save StepY.txt SteptimeY -ascii %This saves the variable
Steptime (containing the series of step times) to a .txt file.
    save StrideY.txt StridetimeY -ascii %This saves the variable
Stridetime (containing the series of stride times) to
    %a .txt file.
    %The following line saves the output variables to a ascii
.txt file
    %(figure out how to include a column of labels).
    save OutputY.txt StepcountY avgStepY COVStepY CadenceY AsymY
-ascii
```

STV_Z CODE (Limbs)

```
  %This is the PREFERRED routine for processing the ML signal.

    %This script finds the time between the LP filtered Z-axis
(AP) peaks (i.e, the individual Step times) and removes outliers
that are
    %3 SD above and below the median Step time.
```

```
    %findpeaks is the function that finds the peaks of the
signal.
    %pks = the magnitude of the peaks.
    %locs = the location (i.e, the sample number) of the peaks
(i.e., the
    %peak locations).

    Negz = filtz * -1; %This command flips the LP filtered Z-
axis signal (so that the peak minimums are now maximums).
    [pks, locs] = findpeaks(Negz,'MinPeakDistance',80,
'MinPeakProminence', 0.50); %This command finds the peaks and
creates variables
    %for the magnitude (pks) and locations (locs) of the peaks.
The command also specifies that there must
    %be a minimum horizontal distance between each peak (i.e,.
20 samples = 0.33 s)
    %and that the peaks must be 0.3 g higher than the lowest
value.
    SteptimeZ = diff(locs) * 1/Fs; %This command finds the
differences between the peak locations (i.e., # of samples)
    %and then multiplies this by the sampling rate time. This
provides the
    %series of individual step times.

    ThreshU = median(SteptimeZ) + 3*(std(SteptimeZ)); %This
command finds the median value of the SteptimeZ variable
    %and then adds 3 standard deviations to it.
    OutliersU = find(SteptimeZ > ThreshU); %This creates a
variable that contains the outliers that are greater than the
    %Threshold value.
    SteptimeZ(OutliersU) = [median(SteptimeZ)]; %This command
replaces the outliers in SteptimeZ with the median
    %steptime.
    %The nextseries of commands repeats the above process for
steptimes
    %that are 3 SD's below the median step time.
    ThreshD = median(SteptimeZ) - 3*(std(SteptimeZ));
    OutliersD = find(SteptimeZ < ThreshD);
    SteptimeZ(OutliersD) = [median(SteptimeZ)];

    Odd = SteptimeZ(1:2:end,:);  %This creates a variable of odd
steptimes.
    Even = SteptimeZ(2:2:end,:);  %This creates a variable of
even steptimes.
    SizeO = size (Odd,1); %This provides the number of rows in
the Odd steptime variable.
```

```
    SizeE = size (Even,1); %This provides the number of rows in
the Even steptime variable.

    %The "if elseif" statement below says: if the size (i.e., #
of rows) of
    %the Odd and Even variables are the same, then Odd = Odd
(i.e., do
    %nothing). If the size of Odd is greater than Even (which
will occur
    %when you have an odd number of rows) then the last row in
the Odd variable is to be removed (Odd(SizeO(1),:) = [];).

    if SizeO == SizeE
        Odd = Odd;
    elseif SizeO > SizeE;
    Odd(SizeO(1),:) = [];
    end

    StridetimeZ = Odd + Even;  %This statement adds each row of
the Odd and Even variables together to provide the series of
    %stride times.

    AsymZ = (abs(mean(Odd) - mean(Even))/((mean(Odd) +
mean(Even))/2))*100; %This command finds the asymmetry between
    %the mean of the right and left steps.
    avgStepZ = mean(SteptimeZ); %This variable finds the mean of
the series of step times.
    avgStrideZ = mean(StridetimeZ); %This variable find the mean
of the series of stride times.
    COVStepZ = (std(SteptimeZ)/avgStepZ) *100; %This variable
finds the coefficient of variation of the step time series.
    COVStrideZ = (std(StridetimeZ)/avgStrideZ) *100; %This
variable finds the coefficient of variation of the stride time
    %series.
    [CadenceZ] = 1/((size(Negz)/size(SteptimeZ))/60)*60; %This
variable determines the overall cadence of the series
    %based on the total number of samples (in Negz) and the
total number of
    %steps (SteptimeZ).
    StepcountZ = SizeE + SizeO;
    save StepZ.txt SteptimeZ -ascii %This saves the variable
Steptime (containing the series of step times) to a .txt file.
    save StrideZ.txt StridetimeZ -ascii %This saves the variable
Stridetime (containing the series of stride times) to
    %a .txt file.
    %The following line saves the output variables to a ascii
.txt file
```

```
    %(figure out how to include a column of labels).
    save OutputZ.txt StepcountZ avgStepZ COVStepZ CadenceZ AsymZ
-ascii
```

STV_ZW CODE (Withers)

```
  %This is the PREFERRED routine for processing the vertical
signal.

    %This script finds the time between the LP filtered Z-axis
(AP) peaks (i.e, the individual Step times) and removes outliers
that are
    %3 SD above and below the median Step time.

    %findpeaks is the function that finds the peaks of the
signal.
    %pks = the magnitude of the peaks.
    %locs = the location (i.e, the sample number) of the peaks
(i.e., the
    %peak locations).

    Negz = filtz * -1; %This command flips the LP filtered Z-
axis signal (so that the peak minimums are now maximums).
    [pks, locs] = findpeaks(Negz,'MinPeakDistance',20,
'MinPeakProminence', 0.25); %This command finds the peaks and
creates variables
    %for the magnitude (pks) and locations (locs) of the peaks.
The command also specifies that there must
    %be a minimum horizontal distance between each peak (i.e,.
20 samples = 0.33 s)
    %and that the peaks must be 0.3 g higher than the lowest
value.
    SteptimeZ = diff(locs) * 1/Fs; %This command finds the
differences between the peak locations (i.e., # of samples)
    %and then multiplies this by the sampling rate time. This
provides the
    %series of individual step times.

    ThreshU = median(SteptimeZ) + 3*(std(SteptimeZ)); %This
command finds the median value of the SteptimeZ variable
    %and then adds 3 standard deviations to it.
    OutliersU = find(SteptimeZ > ThreshU); %This creates a
variable that contains the outliers that are greater than the
    %Threshold value.
    SteptimeZ(OutliersU) = [median(SteptimeZ)]; %This command
replaces the outliers in SteptimeZ with the median
```

```
    %steptime.
    %The nextseries of commands repeats the above process for
steptimes
    %that are 3 SD's below the median step time.
    ThreshD = median(SteptimeZ) - 3*(std(SteptimeZ));
    OutliersD = find(SteptimeZ < ThreshD);
    SteptimeZ(OutliersD) = [median(SteptimeZ)];

    Odd = SteptimeZ(1:2:end,:);  %This creates a variable of odd
steptimes.
    Even = SteptimeZ(2:2:end,:);  %This creates a variable of
even steptimes.
    SizeO = size (Odd,1); %This provides the number of rows in
the Odd steptime variable.
    SizeE = size (Even,1); %This provides the number of rows in
the Even steptime variable.

    %The "if elseif" statement below says: if the size (i.e., #
of rows) of
    %the Odd and Even variables are the same, then Odd = Odd
(i.e., do
    %nothing). If the size of Odd is greater than Even (which
will occur
    %when you have an odd number of rows) then the last row in
the Odd variable is to be removed (Odd(SizeO(1),:) = [];).

    if SizeO == SizeE
        Odd = Odd;
    elseif SizeO > SizeE;
    Odd(SizeO(1),:) = [];
    end

    StridetimeZ = Odd + Even;  %This statement adds each row of
the Odd and Even variables together to provide the series of
    %stride times.

    AsymZ = (abs(mean(Odd) - mean(Even))/((mean(Odd) +
mean(Even))/2))*100; %This command finds the asymmetry between
    %the mean of the right and left steps.
    avgStepZ = mean(SteptimeZ); %This variable finds the mean of
the series of step times.
    avgStrideZ = mean(StridetimeZ); %This variable find the mean
of the series of stride times.
    COVStepZ = (std(SteptimeZ)/avgStepZ) *100; %This variable
finds the coefficient of variation of the step time series.
    COVStrideZ = (std(StridetimeZ)/avgStrideZ) *100; %This
variable finds the coefficient of variation of the stride time
```

```
    %series.
    [CadenceZ] = 1/((size(Negz)/size(SteptimeZ))/60)*60; %This
variable determines the overall cadence of the series
    %based on the total number of samples (in Negz) and the
total number of
    %steps (SteptimeZ).
    StepcountZ = SizeE + SizeO;
    save StepZ.txt SteptimeZ -ascii %This saves the variable
Steptime (containing the series of step times) to a .txt file.
    save StrideZ.txt StridetimeZ -ascii %This saves the variable
Stridetime (containing the series of stride times) to
    %a .txt file.
    %The following line saves the output variables to a ascii
.txt file
    %(figure out how to include a column of labels).
    save OutputZ.txt StepcountZ avgStepZ COVStepZ CadenceZ AsymZ
-ascii
```