Wearable Monitors for Improved Equine Welfare

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SCHOLARLY ABSTRACT

The use of digital technology is becoming increasingly popular in equine research. Current applied technologies for livestock are being used to detect pathogens, observe locomotion patterns, determine estrus periods, and measure vital parameters. These sensors leverage global positioning systems, accelerometers, magnetometers, goniometers, optics, among other emerging sensing technologies. The success of these devices has led to the introduction of various equine wearable sensors into market. These technologies seek to promote mobile devices to be used in equine training, monitoring, and clinical contexts. Therefore, the objective of this research is to characterize advancements, opportunities, and gaps in our existing knowledge of equine wearable sensor technology. Specifically, this research explores two innovative sensors designed for equines and their potential to enhance animal safety and health. The purpose of the research on these sensors is to (1) better contextualize biomechanical data in practically applicable terms and (2) evaluate the accuracy of a photoplethysmography based pulse sensor to detect heart rates of adult horses. In addition, currently marketed equine wearable sensors are reviewed, and their limitations are evaluated. Areas of future research and developments of equine wearable technologies are also explored.

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GENERAL AUDIENCE ABSTRACT

The use of digital technology is becoming increasingly popular in equine research. Several biosensors exist for livestock species which have been successful in helping manage health and wellbeing of these animals. Although commercial development of equine wearable sensors has begun, the success of initial industry prototypes is limited. Commercially available equine wearable sensors currently marketed often seek to provide support in equine training, monitoring, and clinical contexts. Despite several commercially available equine wearable sensors, there has been slow adoption of this type of technology in the industry. Therefore, the objective of this research is to characterize advancements, opportunities, and gaps in our existing knowledge of equine wearable sensor technology. Specifically, it explores two innovative sensors designed for equines and their potential to improve the safety and health these animals. The purpose of these sensors are to (1) better understand factors that influence the safety of equestrian sports with jumping phases and (2) evaluate the accuracy of a sensor to detect heart rates of adult horses. In addition, current marketed equine wearable sensors are reviewed, and their limitations are evaluated. Areas of future research and developments of equine wearable technologies are also explored.

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List of Abbreviations

AQHA- American Quarter Horse Association

ASPCA- American Society for the Preservation of Cruelty to Animals

ANS- Automatic nervous system

AVA- American Vaulting Association

AVMA- American Veterinary Medical Association

AWA- Animal Welfare Act

AHC- American Horse Council

ECG- Electrocardiogram

GPS- Global positioning system

HPA- Horse Protection Act

HR- Heart rate

IMU- Inertial measurement unit

JCF- Jockey Club Foundation

LED- Light-emitting diode

LF- Left forelimb

LH- Left hindlimb

MFHA- Masters of Foxhounds Association

NAHMS- U.S Department of Agriculture's National Animal Health Monitoring System's

NASS- National Agriculture Statistic Service

MRL- Maximum Residue Limits

NHBA- National Barrel Horse Association

PLT- Precision Farming Techniques

RF- Right forelimb

RH- Right hindlimb

RR- Respiratory rate

RMSE- Root-mean square deviation

RMSPE- Root-mean square prediction error

PNS- Para-sympathetic nervous system

PRCA- Professional Rodeo Cowboys Association

PPG- Photoplethysmography

SHRF- Sport Horse Research Foundation

SNS- Sympathetic nervous system

USDA- United States Department of Agriculture

USDA- United States Dressage Federation

USEA- United States Eventing Association

USEF- United States Equestrian

USHJA- United States Hunter/Jumper Association

USPA- United States Polo Association

USPEA- United States Para-Equestrian Association

UKGERF- University of Kentucky Gluck Equine Research Foundation

CHAPTER I

Introduction

Horses were first domesticated 5,500 years ago and their role in society has changed markedly throughout history (Orlando 2020). By providing humans with speed, horses revolutionized transportation and helped to globalize the world by circulating different human cultures and goods across the planet (Forrest 2016). With horses, communication between people also became more efficient which contributed to the stability of countries (Orlando 2020). Horses also changed the way of war and proved to be key military assets up until the mid-twentieth century (Robinson 2016). Although some countries still rely heavily on these animals for transportation and agriculture, the modern use of the horse in the United States has evolved into that of a companion animal (Orlando 2020).

Today, the horse industry's economic contribution to the American economy is unique from other livestock branches because of its broad diversity. Horse owners, racetrack facilities, veterinarians, and shows all generate direct and indirect economic activity that contribute to the success of the U.S. equine industry. Since 2005, the equine industry's total value added to the United States economy has increased by more than $20 billion to reach a current total impact of $122 billion (American Horse Council Foundation 2018). The horse industry also has a notable total employment impact in the U.S. of about 1,800,000 jobs (American Horse Council Foundation 2018).

Horses' new roles as companion animals in the U.S. has put emphasis on equine welfare. Although equine sport is important in terms of economic impact and recreational enjoyment, it can expose horses to physical and psychological harm (Campbell 2016). Because of this, unease about equine welfare and health is growing amongst the pubic, media, and veterinarians

(Campbell 2016). Ultimately, improving welfare and wellbeing not only enhances the life of domesticated horses but allows for them to continually add substantial economic value to the United States.

Given the supposed financial wealth of the equine industry, it not unreasonable to suggest that wearable monitoring systems could be an attractive way to enhance equine welfare and well-being. Using objective systems to analyze equine health and fitness parameters could provide knowledge that humans cannot see subjectively. In other livestock species these technologies have been valuable tools in supplementing traditional management toward better understanding of animal experiences, safety, and wellbeing. For example, lameness in dairy cows can be automatically and accurately detected through accelerometer data from sensor devices fitted to cows legs (Alsaaod, Fadul et al. 2019, Eckelkamp 2019). Additionally, abnormal behavior such as long periods of lying and shorter periods of ruminating can be obtained from wearable sensors (Beer, Alsaaod et al. 2016, Alsaaod, Fadul et al. 2019, Eckelkamp 2019). Sensor technology has also been successful in helping to improve the welfare of poultry, pigs, and sheep (D’Eath, Jack et al. 2018, Zhuang, Bi et al. 2018, McLennan and Mahmoud 2019).

Although wearable sensor technologies for horses exist; they typically are expensive and are focused on sensors attached to equipment leveraged during exercise. For example, EquiMoves, is an equine wearable device that aims to assess lameness and gait performance while a horse is in motion (Bosch, Serra Bragança et al. 2018). Similarly, Lameness Locator, is a system based on three accelerometers that work together to measure the swing phase of the diagonal pair of limbs while a horse is trotting in motion (Bosch, Serra Bragança et al. 2018). Although such sensor systems exist, there is a large gap in continuous monitoring technology for horses, namely, that most existing technologies pose some degree of safety risk if used continuously and without monitoring. For example, most continuous monitors currently available for horses require a halter or headgear to be worn at all times which has been shown to be a dangerous management practice (SAFELY 2009).

Despite the growing number of wearable sensors available for equines, there is limited research investigating if these current technologies are meeting needs for their intended users in the field. This is surprising given that wearable technologies show great potential to prevent injury for horses and riders while providing useful measurement parameters to be used in training, monitoring, and clinical, contexts. One potential challenge with existing technologies is the contextualization or reliability of data. Although sensor systems provide a lot of data, that data is often difficult to interpret, or can suffer from lack of reliability. Evaluating the interpretability and reliability of data obtained from emerging sensor systems may help highlight the degree to which these challenges are present within the precision equine technology field. The purpose of our research was to explore two wearable equine sensors to (1) better contextualize how biomechanical sensing data can be used to understand jump quality and safety and (2) evaluate the reliability of a photoplethysmography based pulse sensor to detect heart rates of adult horses.

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CHAPTER II

Review of Literature

Economic Impact of the Equine Industry in the United States

The American Horse Council (AHC) is a trade organization that advocates for social, economic, and legislative interests of the United States equine industry. Over the past 50 years, the AHC has conducted numerous economic impact studies with the most recent one completed in 2017 (Kline 2021). Unlike consensus studies conducted by the American Veterinary Medical Association (AVMA) and the United States Department of Agriculture (USDA), the AHC is inclusive of all equids. This difference makes their economic data the most comprehensive and representative of the population of horses in the United States.

The AHC describes the economic impact of the horse industry in the United States through six sectors. These include the racing, competition, recreation, hippotherapy, rescue, and working horse sectors. The racing branch has historically been the largest contributor to the United States economy. In 2017, the racing branch had a total economic impact of $63 billion and supported approximately 470,000 jobs. The second largest contributor to the U.S. economy was the competition sector which supported 417,000 jobs and had a total economic impact of $50 billion. The third largest sector recorded in 2017 was recreational riding which contributed $18 billion in total economic impact and generated 270,000 jobs. The working horse sector was the fourth largest contributor. This group supported approximately 70,000 jobs with a total economic impact of $7.9 billion. Hippotherapy, was the fifth largest contributor and supported approximately 9,550 jobs and added $263 million in economic impact. Equine rescue was the smallest contributor and added approximately $42 million in value while supporting 1,370,000 volunteers and workers (American Horse Council Foundation 2018).

Precision technology for horses may influence the economic impact of these industries. The use of precision technology has the potential to improve many aspects of the sport. For instance, continuous devices that diagnose disease quickly could give rise to the horse population, resulting in the need for current equine industries to expand. In addition, autonomous horse trailers could make it possible for owners, trainers, and underaged riders to attend more shows in shorter periods of time. However, the introduction of these technologies could also lower labor demands by making work more automated and less time-consuming to complete. Examples could include automated feeders or manure spreaders.

Demographics of the U.S. Equine Population

The National Agriculture Statistic Service (NASS), American Veterinary Medical Association (AVMA) and AHC all publish studies that assess demographics of the domesticated horse population in the US. However, because these three organizations target different audiences the estimated total number of horses in the United States generated by these groups is different. For instance, the USDA only counts horses on working operations that produce or sell $1,000 in equine products (Kilby 2007). This difference excludes boarding, riding facilities, and "backyard" owners (Kilby 2007). In comparison, the AVMA's focuses on companion animals which may underrepresent horses used for breeding and working purposes (Kilby 2007). Therefore, the most compressive number comes from the AHC which counts 1.1 million horse owners owning or leasing farms housing 7.2 million horses in the United States (American Horse Council Foundation 2018). Among U.S states, the AHC reports that most horses live in Texas, California, and Florida with the fewest in Rhode Island (American Horse Council Foundation 2018).

As part of the U.S Department of Agriculture's National Animal Health Monitoring System's (NAHMS) Equine 2015 study, data was collected regarding equine health and breed popularity. Among 28 states in the United States, Quarter horses represented the highest percentage by breed (United States Department of Agriculture 2017). Aside from Quarter horses, other popular horse breeds found in the United States included Arabians, Drafts, Miniature horses, Morgans, Mustangs, Paints, Saddlebred, Standardbred, Tennessee Walkers, Thoroughbreds, and Warmbloods (United States Department of Agriculture 2017). NAHMS reported that the highest percentage of resident equids in the US ranged between the age distribution of 5 years to less than 20 years of age (United States Department of Agriculture 2017).

Due to discrepancies in demographic data, precision technology for equines could be used to better record and manage the horse population in the United States. For instance, drone technology could be used to gather information about domestic and wild populations in a low-cost and humane manner. Even more, electronic ID tags connected to a nationwide database could be issued for horses in the United States as identification markers. These ID tags could be used to allow for immediate tracking of characteristics like breed, age, or geographic location.

Equine Breed Registries

Most horses in the United States are organized into two major groups: grade horses and registered horses. Grade horses are those whose lineage is unknown, unidentifiable, or of mixed breeding (Ray and Grimes 1991). These horses are not registered with any distinctive breed association. In comparison, registered horses are those whose lineage can be traced and is often recorded within a particular breed registry (Ray and Grimes 1991). Currently, more than a hundred recognized horse breed registries exist in the United States (Kilby 2007).

The primary goal of breed registries or stud books is to advance horse genetics by concentrating desirable breed characteristics (Kilby 2007). Examples of these characteristics include speed, gait type, and coat or marking colors (Lynghaug 2009). Studbooks are categorized as being “closed” or “open”. A closed studbook means that registered animals and all offspring can be traced back to the foundation animals of that breed (Kilby 2007). Although this ensures that the animal is a purebred member, it can put limitations on improving a breed. An example of a “closed” horse studbook is The Thoroughbred Studbook (The Jockey Club) (Kilby 2007). In comparison, “open” studbooks allow for occasional outcrossing to a few identified breeds that introduce new genetics (Kilby 2007). One of the most popular open studbooks in the U.S. today is the American Quarter Horse Association (AQHA) that has permitted mating with other breeds like thoroughbreds (Fletcher 1945) (Kilby 2007). The nine largest U.S horse breed registries include the Quarter horse, Paint, Thoroughbred, Arabian, Appaloosa, Standardbred, Tennessee Walking Horse, Saddlebred, and Morgan registries (Kilby 2007).

Breed registries may be a reason for limitations in the use of precision technology for equines. For instance, some breed registries like The Jockey Club only allow horses to reproduce through “live cover”. Breed registries that follow this rule believe that artificial insemination dilutes the gene pool and diminishes the value of stud fees (Kilby 2007). However, this means that precision technology designed to aid in reproduction would not be allowed.

Role of the Horse in the U.S. & Governing Bodies

Horses serve many roles in the United States and are used for recreational, showing, racing, and working purposes. The United States Equestrian Federation (USEF) is the national governing body for most equestrian sports in the United States. In total, USEF recognizes 18 disciplines on both international and national levels. These disciplines recognized by USEF include Combined Driving, Dressage, Endurance, Eventing, Jumping, Para-Equestrian, Reining, Vaulting, English Pleasure, Carriage Pleasure Driving, Hunter, Hunter/Jumping Seat Equitation, Parade Horse, Roadster, Saddle Seat, Western, Western Dressage, and Western/Reining Seat Equitation. USEF international discipline associations include the American Vaulting Association (AVA), United States Hunter/Jumper Association (USHJA), United States Dressage Federation (USDF), United States Eventing Association (USEA), United States Para-Equestrian Association (USPEA), and USA Reining.

Furthermore, there are also several active National Horse Organizations that focus on lesser-known disciplines and promoting equine research. One of the most popular groups, the Jockey Club Foundation (JCF), is dedicated to the improvement of Thoroughbred breeding and racing. Lesser-known discipline-oriented organizations include the United States Polo Association (USPA), United States Dressage Federation (USDF), National Barrel Horse Association (NHBA), Masters of Foxhounds Association (MFHA), and Professional Rodeo Cowboys Association (PRCA). Some of the largest national groups dedicated to equine research include the University of Kentucky Gluck Equine Research Foundation (UKGERF), Grayson-Jockey Club Research Foundation, and Sport Horse Research Foundation (SHRF).

Advancements in precision technologies depends on the involvement of large organizations like USEF, SHRK, and UKGERF to promote the potential success of these devices. Horses are expensive to utilize in research and without groups like these, funding for equine research would be difficult to obtain (Nielsen 2020). Although USEF provides yearly grants to fund equine research, most of the merit goes to laminitis and colic studies. Though laminitis and colic are large concerns in the equine industry, precision technology could be the gap in knowledge in developing more targeted therapeutic drugs and treatment plans.

Equine Welfare

In 2017, there was an estimated number of 7.2 million horses in the United States (American Horse Council Foundation 2018). This figure represents a major decline in horse population numbers compared to before the industrial revolution, when agricultural practices were far less mechanicalized than today (Leontief 1983). Although the welfare of horses is of global interest, there is particular concern in developed countries where horses are increasingly being kept as pets or companion animals (Waran 2002). Unlike developed nations, developing countries still rely heavily on horses for agriculture and transportation (Pritchard, Lindberg et al. 2005). Therefore, in developing countries the welfare of animals is viewed differently as compared to the United States (Waran 2002). For instance, human needs are placed above that of an animal when resources are limited. Even though the roles of the horse may be different among cultures, the key issues of providing proper housing conditions, nutrition, and health care remain economically important for all.

Currently, there are no universally accepted scientific indicators of welfare because welfare itself cannot be objectively measured (Waran 2002). However, measurements of behavioral and physiological responses have been accepted as the best way to evaluate an animal's state (Waran 2002). These equilibrium changes can occur in response to both immediate and long-term challenges (Budzyńska 2014). Acute indicators of stress in horses have shown to include increases in heart rate (HR) and respiratory rate (RR) (Munsters, Visser et al. 2012) (Budzyńska 2014) (Schmidt, Möstl et al. 2010); however, direct symptoms of mechanical or system breakdown (such as lameness) also can reflect stress incurred by an animal. Similarly, chronic signs of stress in horses have been correlated with reproductive problems, increased incidence of disease or lamenesses, and development of stereotypic behaviors (Budzyńska 2014).

Precision technologies hold promise to help owners better understand the welfare of their horses in “real-time”. Objective measurements could be obtained from wearable technologies and could be used to interpret if a horse is experiencing pain or stress. Even more, continuous sensors could provide owners information about their horse when they are not interacting. While these technologies could be useful in owners understanding the well-being of their horse, these technologies have concurrent application in the monitoring and maintenance of animal health.

Horse Health Monitoring

It is generally accepted that the welfare of a horse influences the animal’s performance and health. Although horses were domesticated over 5,000 years ago, their basic behavioral and physical needs have not changed drastically over time (Budiansky 1997). However, modern horse management practices often deprioritize these basic behavioral and physical needs, which can negatively affect horse welfare (Mills and Clarke 2007). For instance, prior to domestication horses were adapted to live freely in environments that they evolved in (Goodwin 2007). However, as the role of the horse diversified, humans began to manage their environments to maximize performance (Goodwin 2007, Lesimple, Poissonnet et al. 2016) (Huntington, Brown-Douglas et al. 2020). Today, it is common for humans to restrict horses’ freedom to roam, forage, and mate depending on the intended use of the animal (Goodwin 2007).

Research has shown that there have been some attempts to better the welfare of horses over the years (Lesimple 2020). Particularly, there has been interest in how modern management practices like stabling can influence an animal’s wellbeing (McBride and Long 2001) (Visser, Ellis et al. 2008) (McGreevy, Cripps et al. 1995). However, most of these studies rely on subjective questionnaires and do not focus on objective parameters (Lesimple and Hausberger 2014). For one, using subjective surveys relies on the owner’s ability to be able to accurately assess welfare and identify behavioral problems. It also implies the willingness of owners to admit that their horse has behavioral problems (Lesimple and Hausberger 2014) (Hötzel, Vieira et al. 2019). Therefore, assessment and monitoring of health and fitness parameters may be better to help identify welfare problems associated with stress and pain.

Stress

Stress is an everyday occurrence of most horses, and is of particular concern for those who actively compete and travel (Budzyńska 2014) (Foreman and Adrianna Ferlazzo 1996). Stress is defined as a state in which an animal "makes abnormal or extreme adjustments in its physiology or behavior in order to cope with adverse aspects of its environment and management" (Fraser, Fraser et al. 1975). A key part of a horse being able to respond to a stressor is the ability of the central nervous system to perceive threats (Ayala, Martos et al. 2012). Once a threat is perceived, the central nervous system of the animal develops a biological response that reacts to the stimulus or stressor. The biological response(s) of the automatic nervous system (ANS), neuroendocrine system, and behavior work to alleviate the effects of perceived threats (Bartolomé and Cockram 2016).

The first biological response by an animal is the behavior response (Bartolomé and Cockram 2016). Behavior responses are described as reactive or inhibitive (Bartolomé and Cockram 2016). Generally, reactive behavior patterns include fearful or aggressive actions such as pinning ears back, defecating, kicking, or exaggerated movements of the tail (Kaiser, Heleski et al. 2006). Comparatively, inhibitive behavior is indicative of an animal freezing when a threat is identified (Bartolomé and Cockram 2016). The biological response of the ANS is associated with the "fight or flight" phenomenon and helps to upregulate and downregulate various body functions (McCarty 2016). The ANS is categorized into the sympathetic nervous system (SNS) and the para-sympathetic nervous system (PNS). The SNS controls the "fight or flight" response and prepares the body for physical activity while the PNS is activated during rest (McCorry 2007). Lastly, the neuroendocrine biological response is controlled by the hypothalamus-pituitary-adrenal axis (HPA) (Bartolomé and Cockram 2016). The HPA releases cortisol which is known to be the primary stress hormone (Ayala, Martos et al. 2012).

Research programs worldwide are studying these biological responses of stress in animals (Romero, Platts et al. 2015). Knowing how stress works in animals helps us to learn how to become better providers for them. It also helps us understand how to better manage animals on larger scale operations given that those environments come with challenges of monitoring and caring for animals individually. However, what is missing in the field is technology that can detect stress mechanisms and connect them to certain outcomes. Having technology with aims to monitor emotional conditions would allow owners to easily study behavior changes in their animals and make quick adjustments to reduce stress to promote welfare. While equine owners may be open to using this technology, the impact has not been fully explored.

Pain

Recognition and alleviation of pain is critical when evaluating the welfare of horses (Dalla Costa, E. et al. 2014). Because pain can only be experienced by an individual, it can be difficult to quantify. Currently, there is no single method or parameter used to assess pain in small or large animals (Valverde and Gunkel 2005). However, there are some accepted subjective and objective methods that have been researched to help determine pain in horses.

Some objective measurements used to evaluate pain in horses include cardiovascular parameters like heart rate and blood pressure (Valverde and Gunkel 2005). However, these values can vary greatly among individuals which can make applying this method to define pain in horses as a species difficult (Valverde and Gunkel 2005). For example, a horse suffering from a chronic illness does not always present as having an increased heart rate although a horse experiencing acute illness typically would display elevated vital signs (Valverde and Gunkel 2005). Also, cardiovascular parameters can be influenced, or masked, by the administration of drugs such as the use of an anti-inflammatory like phenylbutazone or a mild tranquilizer like acepromazine (Worboys and Toon 2018) (Driessen, Zarucco et al. 2011). Another accepted objective method of determining pain in horses is the use of force plates for gait analysis (Valverde and Gunkel 2005). However, this type of pain detection is limited for disease or illness associated to limbs. As such, although understanding pain response is paramount to maintaining animal wellbeing, the lack of standardized and broadly applicable methodologies for evaluating pain makes use of the metric challenging for understanding continuous variation in animal wellbeing.

Although few objective measurements of animal pain have been pioneered, subjective evaluation of pain is commonly achieved through quantifying or observing behavioral changes in horses (Gleerup and Lindegaard 2016). Behaviors used as sentinels of pain response can be further described as being general or specific. Some examples of general pain behavior include restlessness, decreased physical activity, decreased appetite, and loss of interest in socialization (Gleerup and Lindegaard 2016) (Pritchett, Ulibarri et al. 2003). In comparison, some specific pain behaviors include decreased weightbearing to a specific limb and flank watching or pawing in relation to colic or abdominal pain (Gleerup and Lindegaard 2016). Although it may be several years before commercial systems for monitoring animal stress and pain biomarkers are available, systems for sensing animal behavior are more advanced, meaning that these precision technologies have promise to help improve understanding of animal wellbeing.

Horse behavioral monitoring with visual or motion-based sensing has been conducted in experimental settings. For example, a three-dimensional wireless acceleration measurement system (WAS) was used to analyze the movements of free-moving horses (Scheibe and Gromann 2006). In addition, dual force sensors have been used to characterize the effect of different horse bridles and bits on horse behavior (Cross, Cheung et al. 2017). Although these technologies hold promise to help owners better understand horse behavioral patterns, they are limited in that behavior is a non-specific indicator of stress and pain. For example, a horse which rapidly ceases movement could be doing so because movement has suddenly become painful, or because it is being distracted by a change in the farm environment. As such, more specific sensing technologies are needed to help the equine industry progress toward enhanced understanding and detection of pain and stress in horses.

Wearable Sensor Technology for Animals

A large amount of money is spent on agriculture research each year (Neethirajan 2017). However, this research investment does not always lead to increased animal health or improved production techniques. To meet the current challenges of animal health, a change is needed in how diseases are being diagnosed and managed. Wearable sensors are one emerging technology which may help catalyze that shift through supporting timely diagnosis of disease, potentially decreasing economic loss for owners and producers. Unlike manual measurements where human error is expected, sensor technology can provide reliable, continuous, and real-time data reflecting the physiological condition of an individual (Neethirajan 2017). With potential to outpace humans in detecting abnormalities, wearable sensors could become the most useful and practical tools commercially available for welfare monitoring of animals.

The development and use of wearable sensors designed for companion and livestock species has grown exponentially in the past ten years. Products like tracking collars, ear tags, accelerometers, and “smart” halters are being purchased at high rates with aims to better animal welfare and production (Harrop, Hayward et al. 2015). These technologies are versatile, and recent advancements have made them more affordable for the daily consumer. For instance, a sensor attaching to ears to measure the body temperature of cattle now cost $100,000 for 10,000 cows which is significantly less than in previous years (Harrop, Hayward et al. 2015). Global growth of these wearable sensor technologies is predicted to reach $2.6 billion in the next decade, increasing more than 2 times the current rate (Harrop, Hayward et al. 2015).

Instead of relying on human knowledge, wearable sensors can be used to provide information about an animal's condition through objective and continuous measurements. For example, body temperature and heart rate are important well-being indicators that greatly influence organ function, pregnancy, performance, parturition, and lactation (Neethirajan 2017). An example of how wearable sensors can be used to track health data can be seen through ingestible sensors or "E-pills" designed for bovines. These sensors are designed to stay in the rumen for extended periods of time and transmit data regarding temperature and heart rate of the animal through software (Harrop, Hayward et al. 2015). Similar sensors have been developed for goats (Castro-Costa, Salama et al. 2015) and birds (Wilson, Pütz et al. 1995). Other forms of this technology can be seen in "E-tags" or sensors that monitor temperature change and disease onset from the ear (Neethirajan 2017).

One way that wearable sensors can be used is for behavior classification. Like physiological parameters, behavior can give owners and veterinarians insight into an animal's well-being (Neethirajan 2017). Therefore, the need of advanced in behavior technology to help detect abnormalities due to behavior changes is crucial. Commercial and research-sale advancements in behavioral classification technologies currently exist for birds and sheep. For example, sensors have been developed to help notify farmers of chicken stress levels.

Specifically, this sensor is used to detect sounds emitted by hens and classifies the stress in the sound with 96.2% accuracy (Lee, Noh et al. 2015). Additionally, sensors been developed for sheep that can detect lactate levels which can help notify farmers when their sheep are stressed (Naylor Aillon et al. 2012) (Neethirajan 2017). While equine owners may to open to using behavioral classification technologies, the impact of them has not been fully explored.

Wearable sensors can also be used is for geolocation classification. Several commercial and research-sale advancements in geolocation technologies include developments of GPS and 3D collar and accelerometer-based behavioral classification tools have been successful in identifying abnormal animal behaviors associated with disease states (Spink, Cresswell et al. 2013) accelerometers that monitor for abnormal movement in dairy cattle (Spink, Cresswell et al. 2013). Additionally, there also been developments of sensor technologies in the swine industry with the capacity to analyze motion and detect low weight in pigs without any manual inspection (Sa, Ju et al. 2015). Furthermore, in the beef and dairy industries, similar, commercially available technologies like the “MooMonitor™” have shown promise as a strategy in the cattle industry for heat detection based on animal restlessness and locomotion patterns (Neethirajan 2017). Although strengths of using this technology have been seen in many livestock species, a gap in its usefulness for horses remains.

Event alert technologies are also useful forms of wearable devices in the animal industry. For instance, commercially available event technologies exist for cows to determine real time determination of animal lying time (Darr and Epperson 2009). Additionally, wearable sensor technology has been explored to continuously monitor environmental and body-fluid pH (Murayama and Maruyama 2015). Although event alert technology for horses exists, most are limited to sensors used for parturition (Korosue, Murase et al. 2012). This leaves a major gap in the usefulness of this technology to be applied outside of equine reproduction.

Lastly, biomarker sensing technologies have shown promise to be useful for a wide variety of animals. Currently, antibiotic resistance is a major threat for the animal industry due to the unjustifiable and frequent use of antibiotics (Neethirajan 2017). However, it is almost impossible to ban the use of antibiotics for animals as they help cure the most common illnesses like respiratory infections (Neethirajan 2017). To help combat this, Maximum Residue Limits (MRLs) were implemented to create a maximum allowed concentration of pharmacologically active products in each animal. To help measure MRLs, sensors technology can be used to help warn farmers when antibiotics are close to or exceeding maximum ranges (Mungroo and Neethirajan 2014). Although MRLs are frequency used in the sense of production animals, this type of biosensing technology could be useful in the equine industry to detect illegal substances during competition settings.

Equine Wearable Sensor Technology

Despite the successes in livestock species, wearable technologies for the equine industry are still rather limited, and the translatability of these technologies to horses is largely uninvestigated. This limited progress in the equine wearable sensing field could be due, largely in part, to monetary and resource limitations. For instance, federal agencies often consider horse research as less important because they are viewed as recreational animals rather than food-producing animals (Nielsen 2020). Furthermore, horses are expensive to utilize in research due to their large body sizes and elevated economic value (Nielsen 2020). Therefore, using other animal models for primary research and transposing the technology to horses after-the-fact may be more competitive for federal funding purposes. In addition, collaboration between researchers might make wearable device research for equines in the future more practical by combining funds.

Alternatively, the poor uptake of these technologies could be because horses are still managed as individuals and sensor technologies have not yet outpaced the human in terms of their ability to diagnose health anomalies. For example, lameness and feeding behavior disruptions can be visually observed with near perfect accuracy when horses are handled multiple times daily. However, subtle clinical presentations of lameness or changes in feeding behavior can easily go unnoticed. Therefore, it is reasonable that wearable devices could be used alongside visual aids to provide better continuous monitoring of horses.

Equine Wearable Sensor technologies for horses exist; however, they typically are expensive and are focused on sensors attached to equipment leveraged during exercise. Some examples of this type of technology include the Alogo Move Pro®, Equimetre™, EquiMoves™, and Lameness Locator™. Alogo Move Pro® incorporates GPS-based technology and an inertial measurement unit (IMU) (Montavon, Deillon et al. 2021). These tools allow for the Alogo Move Pro® Sensor to track a horse's movement in 3D space and give the device the ability to measure lateral balance, longitudinal balance, straightness, cadence, velocity, and strike power. However, there are several limitations with the Alogo Move Pro® device. For one, the cost of one sensor is approximately $2,000, and is designed to be used with a girth from Amerigo which is an upscale tack company. This puts limitations on the availability of the product for a wide range of users. Furthermore, the Alogo Move Pro® device uses GPS technology that makes taking measurements in indoor riding facilities difficult. Finally, although marketed for a variety of disciplines, Alogo Move Pro® is most useful for those that involve jumping.

Equimetre™ is another marketed equine wearable sensor designed to be worn during training sessions. Equimetre™ uses a single lead electrocardiogram to track horse fitness parameters for trainers, owners, and riders (Ter Woort, Dubois et al. 2022). Although Equimetre™ has been validated to detect heart beats, the device has some constraints. For instance, single lead electrocardiograms can be unreliable because unlike multi-lead electrocardiograms they do not have other leads to use for diagnostics if one shows artefact (Ter Woort, Dubois et al. 2022). In addition, even though Equimetre™ has 2 custom electrodes designed to reduce motion artefacts, the sensor has shown to have difficulty taking measurements at high intensity speeds (Ter Woort, Dubois et al. 2022).

EquiMoves™ is an equine wearable device that aims in assessing lameness and gait performance while a horse is in motion. Specifically, the system works by capturing movement from eight synchronized inertial measurement units (Bosch, Serra Bragança et al. 2018). Although this system is precise in understanding the horse's motion because it has sensors located on the upper body and legs, there are some limitations. For example, EquiMoves™ is designed for veterinarian professionals and may not be suitable for the average everyday user (Bosch, Serra Bragança et al. 2018). In addition, EquiMoves™, like other exclusively IMU-based systems, is prone to drift errors (Bosch, Serra Bragança et al. 2018)

Another well-known equine commercial system is the Lameness Locator™. This system is based on three sensors which include two accelerometers and one gyroscope. During data collection, the accelerometers are placed on the head and pelvis of the horse while the gyroscope is placed on a forelimb. These tools are aimed to work together to measure the swing phase of the diagonal pair of limbs while a horse is trotting in motion (Bosch, Serra Bragança et al. 2018). Although the Lameness Locator™ device can identify limbs with lameness in nearly the same time as clinicians there are some drawbacks to the system (McCracken, Kramer et al. 2012). For instance, Lameness Locator™ can only be purchased by a licensed veterinarian (McCracken, Kramer et al. 2012). In addition, attachment of the Lameness Locator™ sensor to a horse can be challenging and may require additional adhesive or Velcro to ensure a proper fit (McCracken, Kramer et al. 2012). Although these technologies and sensors work well for exercise investigation, they are not feasible for long-term, continuous monitoring.

Recently, some advancements have been made in continuous wearable sensors for equines. The most well-known include the NIGHTWATCH® Smart Halter™ and Hoofstep®,. The NIGHTWATCH® Smart Halter™ utilizes sensors for 24 hour monitoring and generates automated alerts to users that their horse is in distress (Saxena, Shrivastava et al. 2021). This device has also been widely used as a labor alert device (Ferris 2021). However, there are risks associated with horses wearing halters while in a stall or pasture. For instance, halters left unsupervised on a horse can get easily caught on fences or tree branches. Furthermore, horses use their rear limbs to scratch their heads, and loose-fitting halters could result in a leg getting caught.

Like the NIGHTWATCH® Smart Halter™, Hoofstep®, is another continuous monitoring device that attaches to the horse's head. Hoofstep®, contains a GPS, accelerometer, gyroscope, and radiotransmitter that work together to assign a horse's behavior to one of four categories: "feeding" (time when horse is chewing), "resting" (time when horse is not in motion), "active" (slow locomotion), and "highly active" (fast movement) (Kelemen, Grimm et al. 2021). Although Hoofstep® has been used to show how domestic horse behavior is different than feral horses, there are some limitations with the product (Kelemen, Grimm et al. 2021). For one, this technology only has range for a few kilometers (Klune, Arhant et al. 2021). Additionally, the sensor itself weighs about 148 grams, and may be uncomfortable to the horse and interfere with normal behavior (Klune, Arhant et al. 2021).

Although there are a modest number of commercially available equine wearable technologies available to assist horse owners in monitoring the stress and wellbeing of their animals, these technologies require additional research to more completely contextualize the information sensed and to make better management decisions. As such, future work on wearable sensing technologies for horses should take a focused look at how data can be used more holistically by owners interested in improving capacity to sense, monitor, and ultimately understand the wellbeing of their horse in real-time.

Conclusion

Monitoring equines using sensor technology can provide reliable, continuous, and real-time data reflecting the physiological condition of an individual. Based on advancement of equivalent technologies in the livestock industries, these sensing systems may have the potential to outpace humans in detecting abnormalities and could become the most useful and practical tools commercially available for horses in terms of health and fitness monitoring**.** However, to make these devices more reliable, low-cost, marketable, and usable to the average equine user, more research in needed in product design and data interpretation.

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Chapter III

Photoplethysmography (PPG) Pulse Sensors Designed to Detect Human Heart Rates are Ineffective at Measuring Horse Heart Rates

Abstract

Photoplethysmography (PPG) technology is a popular health monitoring tool used in human medicine to monitor heart rate and oxygen saturation. Unlike electrocardiograms (ECG) that use electrodes on patient chests, PPG sensors are small, non-invasive, and more affordable. Consequently, the interest in using PPG sensors in wearable technology for animal health monitoring has increased as this technology has matured. However, despite the successes of other wearable sensors, particularly for behavioral and health monitoring of livestock species, wearable technologies for the equine industry remain rather limited and the translatability of these existing technologies to horses is unknown. The purpose of the study was to evaluate the accuracy of a wearable PPG-based sensor originally designed to detect human heart rates in monitoring the distal limb pulse of healthy, adult horses. We hypothesize that the PPG-based sensor would be sensitive to placement location and orientation, and that measurement accuracies would depend on sensor placement and orientation on the distal limb. To evaluate this hypothesis, a completely randomized block design with a factorial treatment structure was used. Horses were considered as the block, and limb type (right front, RF; left front, LF; right hind, RH; and left hind, LH) and position of sensor (medial or lateral) were treatments, with levels arranged in a complete (4x2) factorial design. Data was collected by placing the PPG-based sensor on the distal limb of each horse (n=6), with placement location according to the treatment (limb type and location) combination, and collecting sensed pulse readings for 60 seconds. Concurrent with the sensor readings, manual heart rates (ground truth data) were collected by a trained technician using a stethoscope. Data was analyzed by calculating root mean squared prediction errors (RMSPE) for the PPG-based measurements with the manual heart rates as a gold standard. Variation in RMSPE associated with limb and location of sensor were evaluated using a general linear model with fixed effects for limb and location and a random effect for horse. Our results indicated that the PPG-based sensor was ineffective at measuring horse heart rates, and that the device was not sensitive to placement location and orientation. Future work should focus on developing alternative analytics to interpret the data from PPG sensors to better reflect horse heart rates, as most current detection approaches are most appropriately calibrated to human subjects.

Keywords: sensor, heart rate, horses

Introduction

The use of wearable technology is becoming gradually more important for animal health management. These sensor devices, if designed well and used properly, can help provide timely diagnosis of disease, potentially decreasing economic loss for owners and producers. Unlike manual measurements where human error is expected, an ideal sensor technology should provide reliable, continuous, and real-time data reflecting the physiological condition of an individual animal (Neethirajan 2017). Sensor technology has also proven to be successful in helping to improve the welfare of poultry, pigs, and sheep (D'Eath, Jack et al. 2018, Zhuang, Bi et al. 2018, McLennan and Mahmoud 2019), with notable advantages in detecting gait abnormalities (Alsaaod, Fadul et al. 2019, Eckelkamp 2019) and disruptions in eating behavior (Beer, Alsaaod et al. 2016, Alsaaod, Fadul et al. 2019, Eckelkamp 2019). Despite the successes in livestock species, wearable technologies for the equine industry are still comparatively limited. This could be due, in part, to challenges with the practical applicability of sensor technologies, which have problems like low sample sizes, technical or equipment problems, and high sensitivity to external factors (weather, hair, different days, etc) (Egan, Brama et al. 2019). Alternatively, the poor uptake could be because horses are still managed as individuals and sensor technologies have not yet outpaced the human in terms of their ability to diagnose health anomalies like lameness and feeding behavior disruptions because such challenges can be visually observed with near perfect accuracy when horses are handled (typically) twice daily.

One area where sensor technology may be most initially useful to the equine industry is in heart rate detection. This is because heart rates are not easily observed visually, and rapid fluctuation of physiological importance may occur in the short hours between human interaction. Heart rate monitoring technologies for horses exist; however, they typically are focused on core heart rate determination through sensors attached to equipment leveraged during exercise. Although these technologies work well for exercise investigation, they are not feasible for long-term, continuous heart rate monitoring. In other species, photoplethysmography (PPG) technology has been used to create low cost, small, and simple wearable heart rate sensors that are well-suited to this continuous monitoring application. These sensors typically use visual and infrared light to measure blood volume changes in tissue beds to determine heart rate and pulse oximetry (Tamura, Maeda et al. 2014). Unlike electrocardiograms (ECG) that use electrodes on patient chests, PPG technology is non-invasive and low-cost. As such, evaluation of the opportunities to leverage PPG technology for equine heart rate detection is needed to understand how placement and preparation of equine PPG sensors may influence the accuracy of this technology in detecting horse pulse rates.

The objective of the study was to evaluate the accuracy of a wearable PPG-based sensor originally designed to detect human heart rates in monitoring the distal limb pulse of healthy, adult horses. We hypothesized that the PPG sensor would be sensitive to placement location and orientation, and that measurement accuracies would depend on sensor placement and orientation.

Material and Methods

Animals, Treatments, and Facilities

Virginia Polytechnic Institute and State University Institutional Animal Care and Use committee approved all procedures involving the use of animals. Six randomly selected horses were used from the Virginia Tech's collegiate equestrian program herd. Horses ranged in age from 9 to 22. The sample of horses included geldings (n=5) and mares (n=1) of various breeds including two thoroughbreds, two appendix quarter horses, one warmblood, and one morab.

Prior to enrollment, all horses in the study were determined to be clinically healthy with no known or observed signs of cardiac abnormalities. All animals were housed on Virginia Tech barn facilities, were given water ad libitum, and offered diets based on commercial grain mixes, grass hay, and grass pasture that were formulated to meet or exceed requirements (Council 2007).

To maintain consistency, one member of the research team was designated responsible for attaching the PPG-based heart rate sensor on each given test day. Heart rate data were collected between the hours of 9 am and 3 pm in the facility where the horses were housed over a period of 10 days. During data collection each horse was restrained by cross ties to restrict large amounts of movement. Prior to data collection, all horses had an acclamation period of having a fetlock exercise boot placed around their limb. This exercise boot was similar in size and attachment method to the PPG-based heart rate sensor, and was used to discourage the horses from reacting excessively to the PPG-based sensor, allowing for more consistent data collection. The PPG sensor device was positioned just above the fetlock on the lateral or medial sides of each limb for the duration of data collection. Each horse was subjected to a total of 80 readings: 20 readings per limb with 10 readings on each side of the limb. (Figure 1). The heart rate displayed on the HR monitor was compared with that taken manually by a trained technician with a stethoscope at the beginning of each recording.

Sensor Overview

To avoid a rigid structure that could interfere with capillary pressure, our system was constructed using flexible neoprene with Velcro attachments. This made the PPG sensor system lightweight, compact, and sturdy. We used a MAX30101 (Maxim Integrated, San Jose, California) health sensor platform with internal LEDs, photodetectors, optical elements, and low-noise electronics with light rejection for PPG sensing. The signals from this sensor were integrated, analyzed, and displayed using an M5 Stack GRAY kit (M5Stack, Guangdong, China), which has an ESP-32 core and integrated OLED screen used for data integration and visualization, respectively (Figure 1).

Statistical Analysis

The performance of the developed algorithm was evaluated in terms of the accuracy of the heart rate estimation which was assessed using the Root Mean Square Error (RMSE) and RMSE-observations standard deviation ratio (RSR) that are given as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(HR_{\text{!!"}}(k) - HR_{\text{\#\$\%\$\&'\#(')\%}}(k)\right)^{*}}$$

$$RSR = \frac{RMSE}{STDEV_{\text{\#\$\%\$\&'\#(')\%}}}$$

where N is the total number of observations, $HR_{\text{!!"}}(k)$ and $HR_{\text{\#\$\%\$\&'\#(')\%}}(k)$ are the estimated heart rates measured from the heart rate sensor and manually with a stethoscope. Both the overall RMSE and RSR, as well as RMSE and RSR for individual limb and position measurement units were evaluated. Variation in RMSPE associated with limb and location of sensor were evaluated using a general linear model with fixed effects for limb and location and a random effect for horse. Significance was declared at $P < 0.05$.

To better evaluate whether the sensor system was appropriate for classifying horse heart rates (e.g., low, normal, high), we classified both the measured and sensed heart rates based on whether they fell within the normal range (28 to 40 beats per minute), above, or below the normal range. To evaluate these responses a confusion matrix was generated, and five metrics were calculated per class to evaluate the quality of the sensor classification. These metrics are given as follows:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

$$Missclassification = \frac{FP + FN}{TP + TN + FP + FN}$$

$$Percision = \frac{TP}{TP + FP}$$

$$Sensitiviy = \frac{TP}{TP + FN}$$

$$Specificity = \frac{TN}{TN + FP}$$

Where “TP” is the number of true positives, “FP” is the number of false positives, “FN” is the number of false negatives, and “TN” is the number of true negatives.

Results and Discussion

We evaluated the accuracy of a wearable PPG sensor designed to detect human heart rates in terms of its ability to detect heart rates of adult horses. The sensor system leveraged was designed to be non-invasive, compact, and low-cost. The current costs for the MAX30101 health system platform ($5) and M5 Stack GRAY kit used for data integration and visualization ($45) show promise for the future application of these devices to be affordable to a range of consumers.

Despite the potential promise in terms of affordability, the PPG based sensor was ineffective at measuring horse heart rates (Table 1). This demonstrates that although similarly designed PPG HR sensors have been applied in other species like pigs (Youssef, Peña Fernández et al. 2020) and cattle (Jun, Kim et al. 2013), using this technology to the equine industry will require future work. In particular, specific tailoring of the algorithms to interpret voltage readings from the PPG sensor in terms of actual pulses of blood though horse capillary beds will be necessary to enhance the effectiveness of this technology for equine subjects. The poor coherence between the sensor readings and the measured heart rates is underpinned by our global RMSE (69.3 %), which suggested the sensor had high error compared with measured value. In addition to the challenges associated with interpreting sensor-signals in a species-specific manner, some studies indicate that poor accuracy when using PPG sensors on animals could be attributed to the inability to keep good contact between the sensor and animal (Youssef, Peña Fernández et al. 2020). This suggests that improvements on sensor attachment for horses could also be an important future research objective to consider.

In addition to poor overall coherence with measured heart rates, the accuracy of our PPG sensing device was not sensitive to lateral or medial placement on the limb (Table 2). Although we had postulated that PPG sensing would be sensitive to placement, our results suggest that the sensor was ineffective at determining heart rates even when placed in different orientations on the limb. Given that PPG sensors are difficult to apply in environments that are not controlled, it was expected that the sensor readings, and thereby sensor accuracy, would be sensitive to external factors such as placement location and limb type (e.g., front vs hind). However, it is possible that the sensitivity of the sensor to these factors was masked by the poor overall accuracy of the readings and the high variability among sensor measurements. Other studies of the use of PPG sensors on non-anesthetized and anesthetized animals help to further describe this finding. For example, sensors used on anesthetized pigs in controlled environments had less motion artifacts in HR data compared to those not anesthetized (Youssef, Peña Fernández et al. 2020). As such, the high variability among readings observed in this study could be partially due to motion of the non-anesthetized horses, which do fidget frequently, even when calmly standing during restraint. Accounting for variability induced by horse motion is a challenge that must be addressed by further research if PPG technology is going to be used as a viable heart rate monitoring strategy for these animals. Successes in heart rate monitoring during exercise, both in human technologies leveraging PPG sensing, and in existing horse technologies, suggests that with improved data analytics, there will be opportunity to address this challenge (Hebenbrock, Düe et al. 2005, Weiler, Villajuan et al. 2017).

Although prediction of exact heart rates is an ideal goal for PPG sensing, a minimum viable performance level would require ability to identify when a horse's heart rate extends outside the normal range. For example, sensing that the heart rate is 85 beats per minute may be only marginally more useful than being able to determine that the horse's heart rate is elevated. As such, we additionally evaluated whether the heart rate classifications (low, normal, high) by the sensor had improved coherence with measured values. Unfortunately, precision, accuracy, and sensitivity of heart rate classification data were also poor (Table 4). The classification-based analysis suggested that the PPG sensor, in its current form, was not able to realiably classify heart rates as normal, low, or high. This finding further supports the need for more horse-specific analytics to interpret and understand PPG data obtained from equines. PPG sensors for humans are designed to measure through skin layers that average 1.2 mm (SOUTHWOOD 1955). Unlike humans, horse skin layers are much thicker and can be up to 7.0 mm (Wakuri, Mutoh et al. 1995), with an additional 0.19 mm of hair (Yedke, Raut et al. 2013). This increase in thickness, and the addition of a hair layer, may dampen the absorbance of light occurring with capillary bed filling, meaning that the signals obtained by the PPG sensor readings in horses may be dampened compared with humans. Other studies indicating high accuracy with PPG sensor technology on animals may be due to more anatomical and physiological similarities of their subjects to humans. For instance, it has been reported that the orientation, thickness, and distribution of vessels in the dermis of pigs is like that of humans which could contribute to better measurement accuracy in pigs (Nie, Berckmans et al. 2020).

The readings within this study were, on average, higher than those obtained with the stethoscope, suggesting more peaks within the data being identified as heart beats than were actually occurring. This elevated number of peaks could reflect higher variability due to motion, sensor movement/slippage, or variability induced by the thicker skin and hair surface. Future work should isolate these factors and attempt to train better analytics to convert PPG readings to reliable and robust measurement of equine heart rates.

Conclusion

The motivation of this study was to evaluate the opportunity to use a low-cost PPG sensor capable of detecting human heart rates in terms of its ability to detect heart rates of healthy adult horses at rest. Although simplistic, practical, and affordable, the designed sensor was ineffective in accurately determining horse heart rates. This could be due, in part, to challenges with the practical applicability of sensor technologies. For one, PPG sensors are known to be sensitive to environmental noise. Given our readings were not taken in a controlled environment, external factors could have greatly influenced the accuracy of our sensor. Furthermore, misclassifications of measurements could be attributed to voluntary and involuntary bodily functions such as muscle movements, which can disrupt sensor readings. The variation in horse anatomy compared with humans and other similar livestock species could also have contributed to variations in readings. Future implications of designing PPG sensors that can accurately detect horse heart rates should focus on better and more robust data analytics to translate PPG signals obtained from horse measurements to heart rate observations.

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Tables

Table 1. Overall descriptive statistics when evaluating measured heart rates versus those obtained from a heart rate sensor.

Measurement[a]	Overall
N	480
Observed	34.6
Predicted	38.3
RMSE, bpm	19.6
RMSE, %	69.3
Mean Bias, % MSE	10.4
Slope Bias, % MSE	85.5
RSR	4.44

[a] N = number of observations; RMSE = root mean squared error of PPG measurements versus ground truth observations (higher values are undesirable); MSE = mean squared error of PPG measurements versus ground truth observations; and RSR = the RMSE expressed as a ratio of the measurement standard deviation (values > 1 are undesirable)

Table 2. Fit statistics for comparing measured heart rates versus those obtained from a heart rate sensor when stratified by limb and positioning on the limb.

	RMSE (%)[a]		Slope Bias (% of MSE)		Mean Bias (% of MSE)	
Limb[b]	Lateral	Medial	Lateral	Medial	Lateral	Medial
LF	93.1	71.2	58.0	67.8	39.9	30.5
LH	70.1	48.1	69.6	79.3	27.1	17.7
RF	156.8	134.9	44.2	53.9	53.9	44.5
RH	129.8	107.9	49.1	58.8	48.8	39.4
SE	36.4	36.4	40.2	40.2	10.6	10.6
Significance Values						
Limb	0.257		0.245		0.317	
Side	0.505		0.300		0.325	

[a] RMSE = root mean squared error of PPG measurements versus ground truth observations (higher values are undesirable); MSE = mean squared error of PPG measurements versus ground truth observations

[b] LF = left front; LH = left hind; RH = right hind; RF = right front

Table 3. Presents a confusion matrix for classification of heart rate data obtained from a sensor into categorical responses reflecting "Normal", "Low", and "High" heart rates.

Measurement	Prediction			Class Error [a]
	Normal	Low	High	
Normal	135	55	22	0.36
Low	82	43	12	0.68
High	29	11	3	0.93

[a] Class error = percent error of PPG measurements versus ground truth observations

Table 4. confusion matrix metrics summary

	Precision [a]	Sensitivity [b]	Accuracy [c]	Misclassification[d]	Specificity[e]
Normal	54.88	63.68	52.04	47.96	38.33
Low	39.45	35.83	59.18	40.82	74.12
High	6.98	8.10	81.12	18.88	88.73

[a] Precision = proportion of true positives to total predicted positives

[b] Sensitivity = proportion of true positives to total (actual) positives in the data

[c] Accuracy = proportion of correct classifications

[d] Misclassification = proportion of incorrect classifications

[e] Specificity = proportion of true negatives to total negatives in the data

Figures

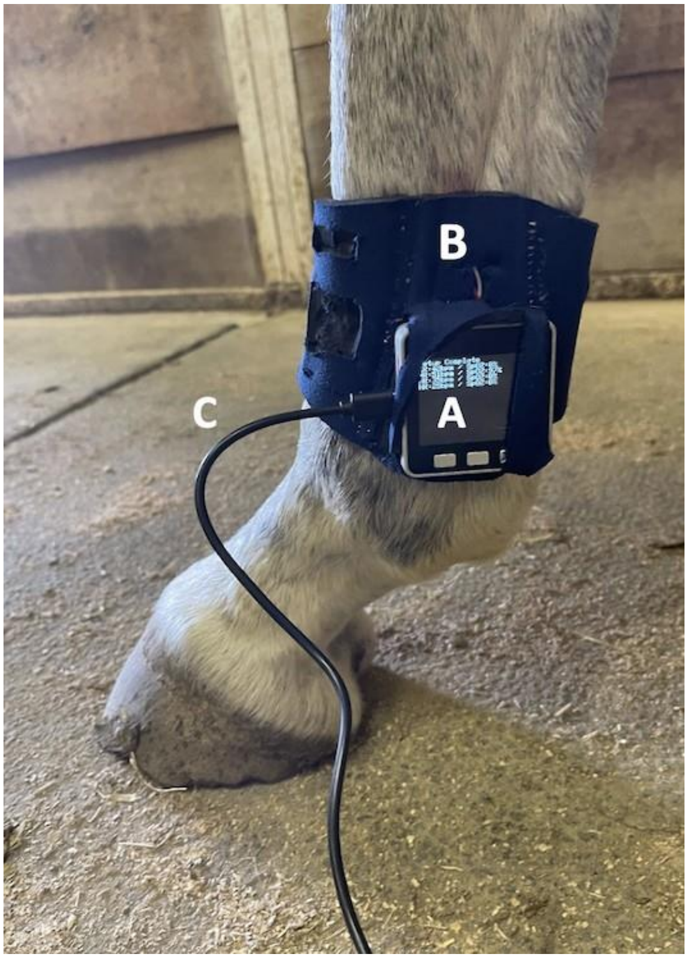

Figure 1. PPG-based Heart Rate Sensor. Figure 1 illustrates the PPG-based heart rate sensor attached to a hind limb during data collection. (A) M5 Stack GRAY kit (M5Stack, Guangdong, China), which has an ESP-32 core and integrated OLED screen used for data integration and visualization. (B) Attachment of the sensor to the horse using flexible neoprene with a Velcro strap. (C) USB charging cable connected to external battery source

Chapter IV

Horse Jump Trajectory Parameters Associated with Horse and Rider Experience Level

Abstract

Equine welfare and the safety of human and horse athletes is of paramount importance to the equestrian community. Particularly, welfare and safety are of great concern in equestrian disciplines that have jumping phases where there is high risk of horse and rider injury. Recent technological advancements have led to devices like Alogo Move Pro that evaluate factors influencing jump quality with aims to improve horse health and performance. The objective of the study was to evaluate lateral balance, longitudinal balance, strike power, jump height, velocity, stride parameters, straightness, and distance of a jump as influenced by rider and horse experience level using the Alogo Move Pro device. The purpose of this evaluation was to better understand how horse and rider experience level pairings create different types of jump biomechanics, and to infer how those differences may help understand what safer and more effective jumping efforts look like, in terms of sensed biomechanical measurements. To accomplish this investigation, we categorized riders and horses as "beginner", "intermediate", or "advanced" based on experience and competing jump height. We hypothesized that advanced riders riding advanced horses would have measurable differences compared with other horse and rider experience level pairings, in terms of the sensed biomechanics. To evaluate this hypothesis, data were collected from a convenience sample of horse and rider pairings (n=24) who agreed to an email request for data collection at their home farm, during regular lesson and exercise activities. Riders were interviewed for demographic and experience data, and asked to ride their horse as they normally would for a lesson or workout while the horse wore the Alogo Move Pro

device. Relationships between sensed biomechanics and horse and rider demographical data were analyzed using a linear mixed-effects model with fixed effects for horse and rider experience level, jump height, and jump type (vertical, oxer, etc.). Random effects for farm, breed, and weather conditions were also included. Most jump biomechanical descriptors were affected by horse and rider experience level or the interaction of these factors, suggesting opportunity to learn from comparison of jump biomechanics among different levels of riders and horses to better design targeted training strategies to address opportunities for improvement of lower-level riders and horses.

Introduction

Equine welfare and the safety of human and horse athletes is of paramount importance to the equestrian community, particularly in sports that have jumping phases where there is high risk of horse and rider injury (Paix 1999, Murray, Singer et al. 2010, Foreman, Engsberg et al. 2019). To date, most assessment of the safety risks of equestrian sports have been based on retrospective data analysis, which is limited in terms of sample size, variation, and capacity to explore interventions. Perhaps most notably, these post-catastrophe studies best answer the question "what happened", and are less sensitive in terms of understanding the nuanced changes in long-term horse/rider interactions which contributed to the single-point-in-time catastrophic event. Although understanding why catastrophic events occur in jumping disciplines is of critical importance, these studies do not allow for exploration of every-day changes or interventions which may support safer and more effective horse/human teams. Movement towards more continuous, biomechanical monitoring of horses during exercise may be a strategy to begin understanding and addressing every-day strategies to enhance the safety of equestrian sports. Although some studies exist describing the biomechanics of horse and rider pairs jumping over obstacles, they are often based on visual sensing and lack the ability to capture parameters like acceleration that new GPS tracking technology can measure (Clayton and Barlow 1989, Meershoek, Schamhardt et al. 2001, Galloux and Barrey 2010, Fercher 2017). Evaluating jump trajectory with GPS based technology may be a flexible and more effective way to provide real-time feedback to riders regarding the biomechanics of their horse's jump, and what aspects of the approach, jump, and departure could be targets for improvement.

Recently, Alogo Move Pro designed a new biomechanical monitoring device for equines. This sensor not only incorporates GPS-based technology, but also contains an accelerometer, magnetometer, gyroscope within a 9 degree-of-freedom inertial measurement unit (IMU) (Montavon, Deillon et al. 2021). These tools allow for the tracking of a horse’s movement in 3D space and give the device the ability to measure lateral balance, longitudinal balance, straightness, cadence, velocity, strike force, and speed for the different phases of a jump. In addition, height and length are measured by the device for each stride and jump. Although these data are extremely useful for continuous, long-term monitoring of horse biomechanics, translating these data into qualitative factors like safety or quality of the jump or gait is challenging and may preclude widespread, practical use of this and similar technologies.

The objective of the study was to evaluate lateral balance, longitudinal balance, strike power, jump height, velocity, stride parameters, straightness, and distance of a jump as influenced by rider and horse experience level using the Alogo Move Pro device. The purpose of this evaluation was to better understand how horse and rider experience level pairings create different types of jump biomechanics, and to infer how those differences may help understand what safer and more effective jumping efforts look like, in terms of sensed biomechanical measurements. To accomplish this investigation, we categorized riders and horses as “beginner”, “intermediate”, or “advanced” based on experience and competing jump height. We hypothesized that advanced riders riding advanced horses would have measurable differences compared with other horse and rider experience level pairings, in terms of the sensed biomechanics.

Materials and Methods

Participant Recruitment

Horse and rider pairs were recruited on a volunteer basis based on convenience sampling. The recruitment process entailed sending emails to equine facilities that advertised jumping lessons in Northern Virginia and Central Virginia. Additional emails were sent to specific facilities in Southwest Virginia, North Carolina and Kentucky, based on individual referrals. Facilities were asked to participate in a research project designed to explore how new sensor technologies could be used to improve the safety of equestrian sports with jumping disciplines. The request specifically asked whether researchers could come to the facility for a day, watch a number of riders in lessons, and collect data during normal business operations. Of the 36 farms that were contacted, 6 farms agreed to participate. Of these, 5 were from Virginia and 1 was from Kentucky. Riders, trainers, and facility owners were not compensated for participation; however, sensor data and insights were shared with participating riders, trainers, and owners individually.

Horses and Riders

From the 6 farms that participated, data were collected on 29 horses of various breeds, including Thoroughbreds, Warmbloods, Hanoverians, Trakehners, Holsteiners, and those of mixed breeding. Horse heights at the withers ranged from 152 cm to 175 cm and ages ranged between 4 to 18 years of age. All horses used were visibility sound, fit to jump at their designated competing level, and had no recent lameness injuries. For our study we categorized horses as either “beginner”, “intermediate”, or “advanced” based on competing jump heights. Horses that were considered beginners had jumped in competition at a height of 0.8m or less while intermediate horses competed over fences 0.8m to1.0m in height, and advanced horses jumped 1.0m and higher in competition. To account for the differences between current and historical maximum jump height in competition, the horses’ highest level competed was used for classifying horse experience level.

Some riders rode multiple horses, meaning that although 29 horses were enrolled in the study, only 22 riders participated. At the time of data collection, riders were given a questionnaire asking about their horse's demographics and individual riding experience. Like the horses in our study, riders were also categorized based on their experience and competing jump heights. To maintain consistency and simplicity, riders were designated in the same beginner, intermediate or advanced categories as the horses, following the above description.

Sensor overview and Attachment

For the duration of data collection, each animal was equipped with a Move Pro sensor (Alogo, Switzerland) that contained a GPS unit and an accelerometer, magnetometer, and gyroscope as a part of a 9 degree of freedom inertial measurement unit. Collectively, these sensors are coupled with analytics to track a horse's movement in 3D space to measure executed stride and jump trajectories. The Alogo Move Pro sensor was attached and detached centrally from the girth used by the rider as a part of their regular tack routine. Prior to the start of our data collection, the positioning of the sensor was checked to ensure it was affixed firmly to the girth and located centrally on the animals body. Sessions were recorded by manually pressing the push button on the sensor and synchronized via Bluetooth using a computer at the end of each farms data collection period. Although not used in the study, the Alogo Move Pro system can also be used with a cell phone if a computer is not available or not feasible for the user.

Jump Sessions

The duration of each jump session was determined by the rider, owner, or trainer. Upon arrival, a designated member of the research team was responsible for recording a diagram of the arena, weather conditions, and jump height. During each jump session, the order of jumps was manually recorded for each rider and horse pairing, to corroborate with the jumps identified by the Alogo sensor. On average, riders rode for 40 minutes, and sessions consisted of 8 to 50 jumping efforts.

Jump Measurements

The sensor data were coupled with could-based analytics to generate a number of summary values regarding horse movement on the flat and over fences. Of those data generated, we elected to analyze a subset of observations reflecting the biomechanics of the canter on average over the jump session, the biomechanics of the canter prior to the jump, and the biomechanics of the jump itself. Biomechanical measurements for each of these workout segments included the balance of the horse (lateral, longitudinal, and straightness), the height and distance of the stride or jump, and the strike force associated with that stride or jump. Lateral balance was determined by the horse leaning to one side or the other (left or right). Longitudinal balance was defined as the distribution of weight between the front and the hindquarters. Straightness was determined for both strides and jumps in relation to the horse's movement. Height of each stride or jump was defined as the maximal distance between the sensor and the ground during a stride or a jumping effort. Distance was defined as the length between the start and end of the stride or jump. Strike power was defined as the maximum vertical propulsion of the horse achieved during a stride or jumping effort.

Statistical Analysis

Statistical analysis was preformed using R statistical software (R Development Core Team 2020). Relationships were analyzed using a linear mixed-effects model with horse breed, farm, and weather conditions as random effects. Horse and rider experience levels, as well as the interaction between horse and rider experience levels were considered fixed effects. Models were derived using the *lme4* package, analysis of variance (ANOVA) was performed on the model using the *lmerTest* package and least-squares means were estimated using the *emmeans* package. Significance was declared at $P < 0.05$ (R Development Core Team 2020).

Due to the correlated nature of biomechanical measurements, we also analyzed the data using a Bayesian learning network to more robustly explore relationships among variables of interest. The Bayesian learning network was derived using the *BNLearn* package in R, and importance of relationships within the network were evaluated by comparing the bootstrapped edge weights (R Development Core Team 2020).

Results and Discussion

We evaluated jump and gait biomechanical parameters against rider and horse experience levels to better contextualize these measurements in terms of horse and rider experience levels and to explore how factors changed as horses and riders differed in experience level. We analyzed observations reflecting the biomechanics of the canter on average over the jump session, the biomechanics of the canter prior to the jump, and the biomechanics of the jump itself from jump session data obtained from 29 horses ridden by 22 riders at 6 different farms from 2 states.

Contextualizing Jump Parameters

A large literature exists which attempts to contextualize traditional biomechanical measurements of horse jumping to provide insight into factors which influence jump kinematics or biomechanics. Historical efforts have unified terminology (Clayton 1989), explored the appropriateness of different modeling strategies for interpreting biomechanical information (Powers and Harrison 1999, Chow and Knudson 2011), and explored how biomechanics differ among horses and exercise situations (Fercher 2017). A common goal of this work has been to contextualize the vast amount of data coming from biomechanical analyses into recommendations, analyses, or evaluations that are more understandable by the broader equestrian community. Although traditional biomechanical investigations, which leverage image- or video-based assessments, have been successful in making that translation to recommendations that can be employed by riders and trainers, the data obtained from new methods of biomechanical assessment create different outcome observations, which will require unique contextualization efforts because they are neither directly translatable to image-based assessments, nor are they directly translatable to easily understood training or riding targets.

Contextualizing traditional image-based biomechanical evaluations based on subjective categorizations like animal skill has been broadly applied to animal jumping evaluations in previous work (Miró, López et al. 2020, Tsuruo, Ringhofer et al. 2020) Furthermore, image-based assessment has also been successful in leveraging data with and without riders to explore the influence of the rider on biomechanics (Powers and Harrison 2002) Unfortunately, IMU-based interactions between horse and rider on the flat are not significantly associated with skill level (Eckardt and Witte 2017), suggesting that contextualizing measurements based on skill level may not be a viable method of making more practical sense of these complex data. However, the interaction of horse and rider skill level may be more sensitive when riders are asked to navigate fences. Indeed, several of the jump biomechanical parameters were significantly influenced by horse skill level (jump velocity, height, and straightness), rider skill level (velocity and straightness), or the interaction of these variables (strike power and longitudinal balance; Table 1). The significance of these jump parameters associated with broadly interpretable categories such as horse and rider experience level suggest opportunity to leverage skill categories as a means to contextualized GPS-informed IMU data to allow for more interpretability of these data by equestrian industry stakeholders. As more data on individuals falling into these skill level categories becomes available, it will be more viable to reliably create context for IMU-based measurements based on horse and rider skill categories.

Biomechanical Trends of Jumps

Beginner horses tended to be the most volatile, or the most influenced by rider experience level, when comparing changes in strike power and jump height. Significant interactions between horse experience level and rider experience level were identified when evaluating strike power, with the greatest individual treatment differences being associated with inexperienced horses being ridden by advanced riders (Figure 1.(A)). Although not statistically significant, the jump height data followed the same numerical trends (Figure 1.(B)). Differences among treatments for strike power suggested that inexperienced horses had the greatest variation in strike power across rider experience levels, with those horses using the lowest strike power when being ridden by beginner riders and the greatest strike power when being ridden by advanced riders (Figure 1.(A)). Interestingly, the remaining horse/rider experience level pairings were fairly similar in strike power suggesting that variability in strike power may be most reflective of inexperienced horses learning the appropriate force to apply on a jump. These same general trends were observed with the resulting height of the jump achieved by the horse, with inexperienced horses being more variable with rider experience level than were more experienced horses. This result agrees with previous literature which identified that untrained horses could be classified into jumping skill groups which differed significantly in terms of jump height and takeoff angle (Powers and Harrison 2000) indicating these parameters are among the biomechanical adaptations that untrained horses use in navigating fences, and that there is substantial variability in how untrained horses navigate fences.

For both strike power and height, the elevated values associated with advanced riders suggest that more advanced riders produce more dramatic jumping efforts on inexperienced horses, which could reflect those horses having greater confidence around the fence or having greater uncertainty surrounding the task requested. Further evaluation of the behavior of inexperienced horses being ridden by a variety of riders is likely required to better contextualize this result. Biomechanical assessment and mathematical modeling clearly demonstrate that the rider influences the biomechanics of the horse jump (Powers and Harrison 2004, Nemecek, Cabell et al. 2018, Tsuruo, Ringhofer et al. 2020). As such, it is plausible that advanced riders may have greater capacity to influence the jump parameters than do less skilled riders. Further evaluation of the interaction between horse and rider skill level, augmented by traditional video-based assessment, would be helpful in contextualizing whether the differences in strike force and height observed are beneficial or detrimental to the safety and success of the jumping effort.

The strike power and jump height largely reflect the bascule of the horse achieved over the fence, as does the longitudinal balance. The data on longitudinal balance also suggested a significant interaction between horse and rider experience levels (Figure 1.(D)); however, the differences among treatments were less systematic than those observed with strike power and height. Within the beginning rider category, inexperienced horses had the lowest longitudinal balance, reflecting flatter jumps, while intermediate horses had elevated longitudinal balance. Advanced horses being ridden by intermediate riders were numerically intermediate between inexperienced horses and intermediate horses, but this group also had the greatest variation; perhaps suggesting a heterogeneous response in jumping efforts made by advanced horses being ridden by inexperienced riders. Intermediate riders on advanced horses had the greatest longitudinal balance, which could be reflective of these riders learning the appropriate balance to encourage in the horse over the fence, and could be indicative of getting the horse too close to the base of the fence, which anecdotally is a common rider error when moving between 0.8 m fences and fences closer to 1 m in height. Advanced riders had uniform longitudinal balance among horse experience levels, perhaps indicating that these experienced riders had greater skill in maintaining appropriate balance in their horses and helping the horse find a good spot to the fence. Although these results are sensible given anecdotal influence of riders of different experience levels riding horses of varying experience, they are contrary to those observations of one previous study which compared jumping kinematics when horses were jumped by riders of different skill levels (Nemecek, Cabell et al. 2018). Future exploration of how horse and rider experience levels interact under a broader array on jumping contexts are needed to better characterize the potential effects of the rider on horse balance, bascule, and jump quality.

Biomechanical Trends of Approach Strides

The approach strides leading up to the jump are supported both by anecdote and biomechanical research as paramount to execute a successful jump (Williams 2013). Analyses of the biomechanical data observed by the IMU-based sensor 2 strides before the fence showed similar significance patterns and directionality of influence as the jump parameters (Figure 2). For example, much like the jump parameters, the inexperienced horses appeared to be most influenced by rider experience level in terms of strike force and stride height (Figure 2 (A) (B)). The similarity in directionality and consistency of patterns between the jump data and the data obtained for the jump approach is supported by previous literature (Powers and Harrison 1999, Galloux and Barrey 2010).

The height of the canter stride 2 strides before the jump was the only parameter significantly influenced by the type of the fence (vertical vs oxer or spread fence) (Figure 2. (B)).

Although somewhat counterintuitive, the lack of effect of fence type on jump descriptors was also identified in other work (Clayton, George et al. 2021). Fercher (Fercher 2017) also found minimal influence of the jump type on parameters like those measured by the IMU-based sensor used in the present work. Interestingly, Fercher found that the approach distance and velocity were primarily influenced by fence type (Fercher 2017). Although the IMU system is not capable of measuring the distance from the obstacle upon takeoff, the change in height of the stride before the fence may reflect shifting of takeoff distance to accommodate difference fence dimensions.

Biomechanical Observation of the Canter

All biomechanical parameters of the canter were significantly influenced by the interaction of horse and rider experience level (Figure 1). This was somewhat unexpected because previous work was unable to identify significant effects of riders of different skills on horse-rider interactions during flatwork (Eckardt and Witte 2017). The trends among horse and rider groups in terms of canter biomechanics did not convey consistently to those observed for the approach or jump phases. For example, the strike power data showed that beginning riders did not induce different canter strike force across horse experience levels. Intermediate riders produced greater strike force on less experienced horses; but the opposite was true of advanced riders. Although these results may be indicative of the learning curve associated with producing a quality canter, which can anecdotally be a challenge for intermediate riders, further research better contextualizing these differences is likely required to make robust conclusions.

Other biomechanical observations of the canter were sensible given common differences between horse and rider experience levels observable within equestrian industries. For example, advanced riders, particularly when riding advanced horses, were able to produce a slower canter. Slower canters have, in previous works, been indicative of greater quality jumping efforts (Powers and Harrison 2000) suggesting those riders were able to produce a velocity which allowed the horse to perform better than did other rider levels. Advanced riders, again, particularly on advanced horses, were able to produce much greater longitudinal balance compared with other horse and rider level combinations. This contextualization is sensible given that an uphill canter (i.e., one with a greater longitudinal balance) is theorized as preferable to support jumping efforts of the horse. The advanced horse and rider combinations were better able to produce such efforts.

Although some biomechanical data showed interpretable and sensible differences when comparing canter observations among horse and rider groups, other data were not easily interpretable. For example, the straightness data suggested green riders were able to produce a straighter canter, particularly on green horses, than other rider groups. Developing straightness in the canter is often a focus of more advanced lessons, and therefore this skill would not be expected in less advanced riders. Similarly, the height of canter strides produced by green riders on intermediate horses was greatest. We were unable to identify a plausible explanation for this finding, and believe it may most represent noise within a fairly limited dataset. Further work exploring the consistency of these relationships across broader datasets with greater industry participation would help advance understanding of how to interpret these results.

Associations Among Biomechanical Parameters

The IMU-based sensor data has the advantage of simultaneously measuring a number of parameters; however, interpreting the relationships among these parameters can be a challenge.

Through network analysis, we can attempt to better contextualize how these different exercise parameters are related to one another, for the purpose of defining training, education, or breeding objectives. Three nodes were identified as highly central within the network, meaning that they are intermediates which help relate other factors. These were the approach balance and velocity, as well as the jump height. The jump power, angle, approach power, and jump velocity were end products of the network. The jump power and angle are most indicative of the horse's ability to raise center mass, which has been used as an indicator of jump quality in the past (Powers and Harrison 2002). The horse and rider experience levels both directly influenced jump power and angle, as well as indirectly influenced these outcomes through the association with jump height. Jump height and angle were also influenced by canter height and velocity. One of the strongest associations within the network existed between the approach balance and jump angle, which is sensible given the industry focus on an uphill balance to achieve good jump form. There were also strong associations between approach and jump velocity, which is sensible given the momentum involved in jumping, and between horse/rider experience levels and jump height, which is also sensible given that more experienced pairs would be used to jumping taller obstacles. Collectively the network analysis helps contextualize the meaning of these biomechanical measures by simplifying the associations among parameters and identifying indicators of system function.

Limitations

This research, however, is subject to several limitations. For one, our sample size was low. This is especially true in comparison to other horse biomechanical monitoring studies. The low sample size may partly be due to time and monetary constraints of this study. Additionally, due to poor measurement quality, lateral balance was not included in our analysis. The poor measurement quality could be due to the sensor shifting too far from its original position during the jump sessions. Velocity, straightness, and longitudinal balance canter quality parameters from 2 strides before the jump were also omitted from analysis due to missing data from software malfunctions.

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Figures

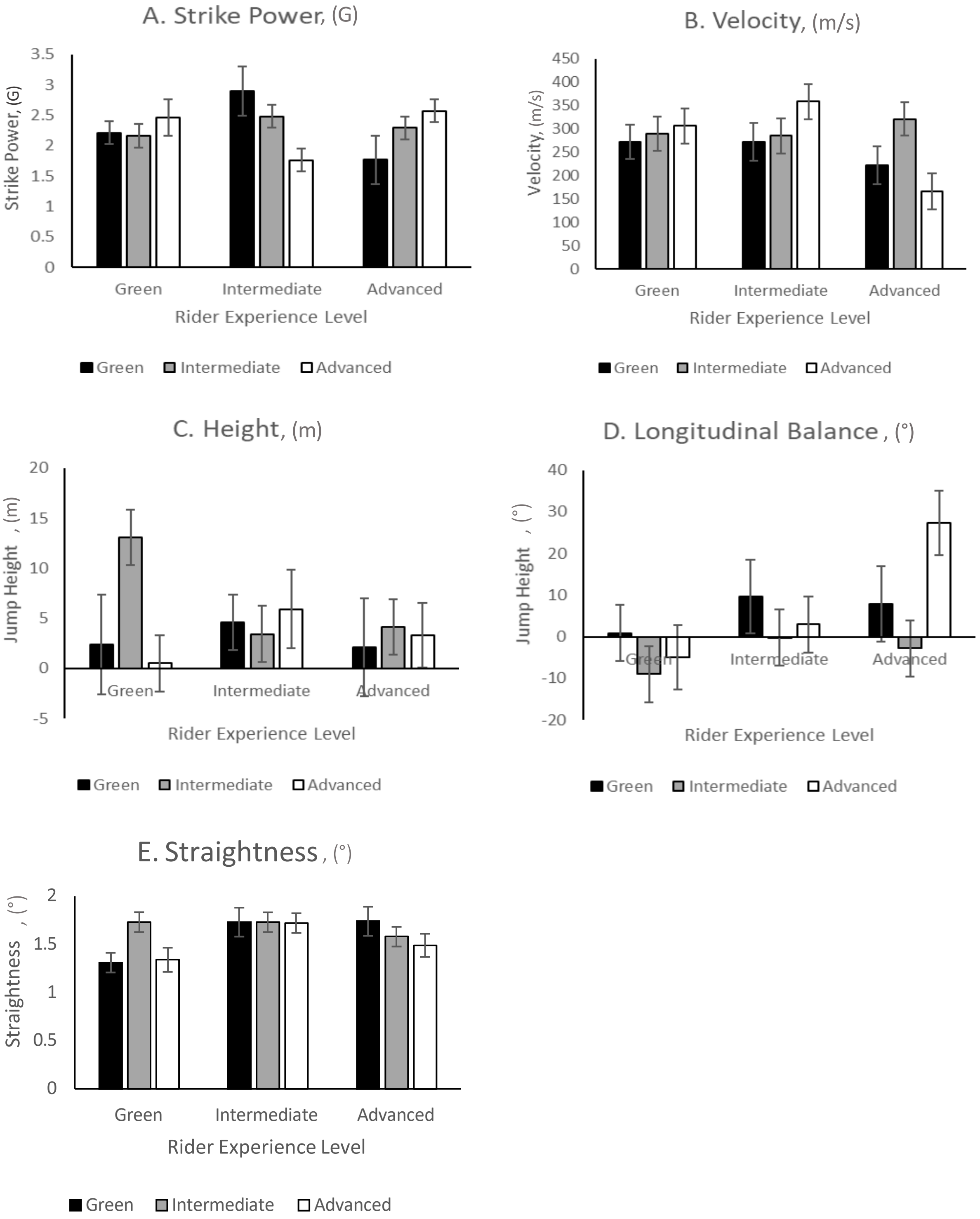

Figure 1. Biomechanical observations associated with canter stride Strike Power (A), Velocity (B), Height (C), Longitudinal Balance (D), and Straightness (E). Horses and riders that were considered beginners had jumped in competition at a height of 0.8m or less while intermediate

horses and riders competed over fences 0.8m to1.0m in height, and advanced horses and riders jumped 1.0m and higher in competition.

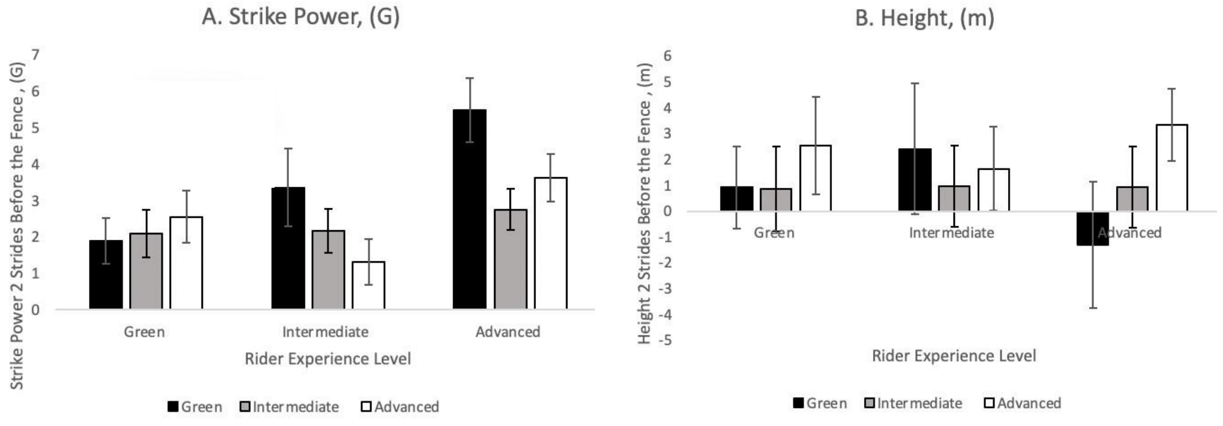

Figure 2. Biomechanical observations associated with canter stride strike power (A), height (B) 2 strides before the fence. Horses and riders that were considered beginners had jumped in competition at a height of 0.8m or less while intermediate horses and riders competed over fences 0.8m to1.0m in height, and advanced horses and riders jumped 1.0m and higher in competition.

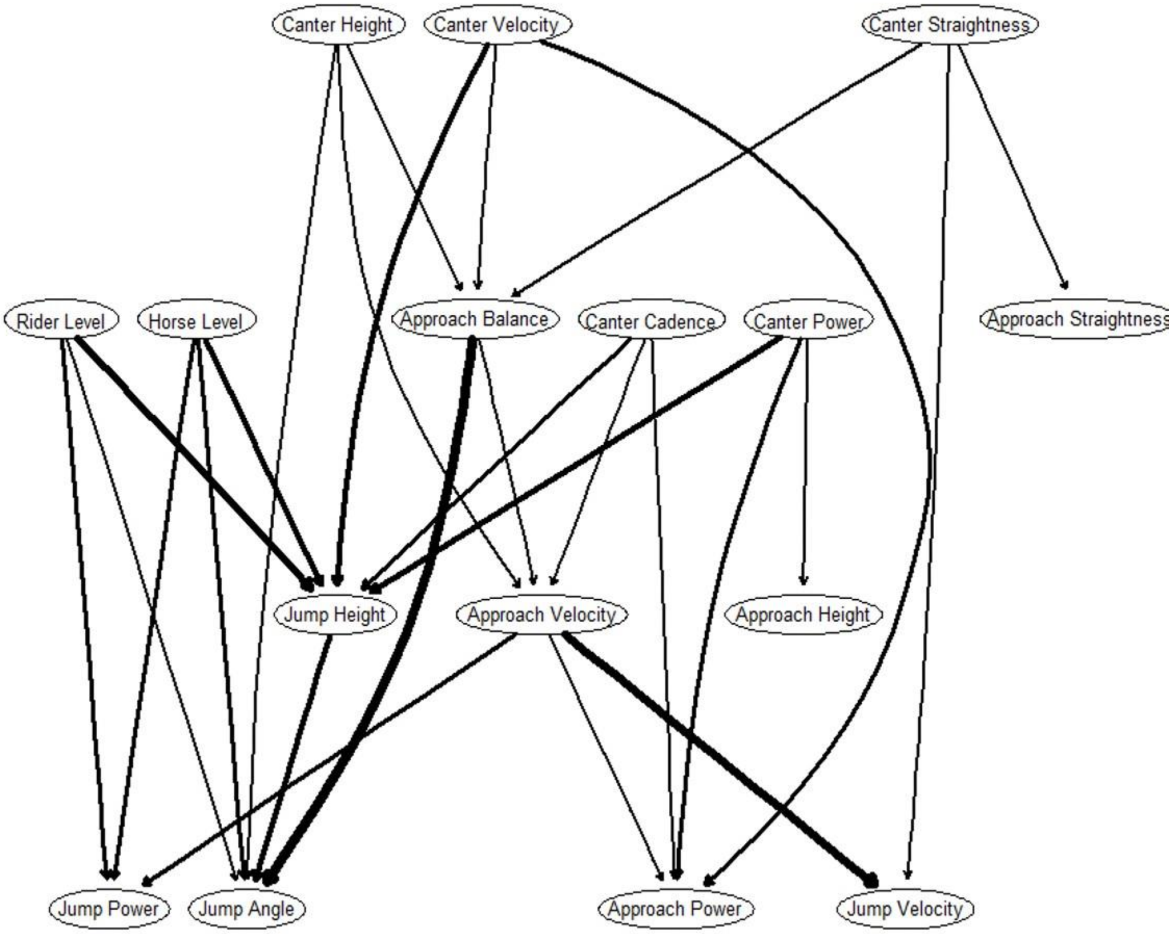

Figure 3: Bayesian Learning Network of Motion Parameters. The above Bayesian Learning Network of Motion Parameters describing the average canter, the canter 2 strides from the fence, and the jump kinetics over the fence, as associated with horse and rider experience level.

Conclusion

Through the research efforts presented in this work, numerous advantages, opportunities, and limitations of wearable equine technologies have been identified. Monitoring equines using sensor technology has the potential to outpace human skill in detecting abnormalities by providing reliable, continuous, and real-time data reflecting the physiological condition of an individual. Ultimately, wearable equine sensors could help in disease detection and decrease economic loss. If achieving sufficient design specifications, wearable sensors for equines are useful to a wide variety of users like owners, veterinarians, and managers of farm operations. Previous research using wearables in livestock species shows the potential of these technologies to become the most practical tools commercially available for health and fitness monitoring. To explore limitations and opportunities in equine wearable technologies surrounding the interpretability and reliability of sensed data, we evaluated two innovate sensor devices to assess reliability of heart rate monitoring and interpretability of biomechanical sensing.

In the first experiment, a low-cost, lightweight, and simple PPG-based monitoring system capable of evaluating heart rate in humans was evaluated for accuracy in estimating horse distal pulse. Although the sensor failed to perform reliably, PPG-based heart rate sensing in horses has tremendous capacity to improve management because heart rates are not easily observed visually in horses, and fluctuation of heart rates may occur in periods of time without human interaction. Without knowing the details of those fluctuations, it is hard to determine the importance of that physiological change. Furthermore, previous research as indicated that heart rates are a useful indicator of an animal’s overall wellbeing. However, the lack of coherence between PPG-sensed heart rates and those measured manually suggest that more research is needed to create data analytics that reliably translate PPG readings to estimates of equine heart rate. These analytics must have capacity to deal with the thicker skin of horses, the hair of these animals, the inevitable motion of the horse, and other environmental factors which may cause variation. A number of approaches could be used to address these challenges.

For instance, one of the major challenges we faced was designing a product that could fit a variety of horse limbs. Due to monetary limitations, we could only create one sensor. Therefore, we used neoprene and Velcro as our sensor attachment pieces with thought of these parts being the most interchangeable among various breeds and their different limb sizes. Although the neoprene and Velcro were flexible, we struggled to attach our device on horses with larger limbs. Also, the sensor could easily move from original placement position on the limb when the horse changed or shifted weight between limbs causing external noise in our data. We believe a more structured PPG-sensor design will give the ability to adjust the sensor to fit a larger variety of horses without losing device integrity. For future research, we recommend using multiple elastic closures should be explored with different levels of adjustability for each strap.

Another challenge we faced with our heart rate monitor sensor was its inability to determine if a heart rate was out of the potential range of a horse. For instance, from previous research we know that a horse’s horse rate at rest ranges between 28-48 beats per minute. However, at times our heart rate sensor would obtain readings that were far into the hundreds which theoretically should not happen while a healthy horse is at rest. Therefore, for analysis we used human logic to categorize measurements as too low or too high. This could partly, be due to attachment issues or the inability of our sensor to read through fur and a thick dermis layer. However, future work could include data analytics which better translate the PPG sensor readings into equine-relevant heart rate estimates is necessary.

Because equine welfare and the safety of equestrian sports is of global importance, the second sensor researched was the Alogo Move Pro device. This sensor is made up of technology that can evaluate lateral balance, longitudinal balance, strike power, jump height, velocity, strides, straightness, and distance of a jump. To contextualize the data obtained from this device in a manner more easily understandable to horse owners, we categorized riders and horses as "beginner", "intermediate", or "advanced" based on experience and explored the relationships of their jump trajectory values. However, we faced some limitations with our study design and the Alogo Move Pro device itself that indicated the need for further research in this area.

For one, due to funding and time constraints we were only able to sample two states. This limited our study to be applicable to horses and rider levels outside of our researched area. Furthermore, because our study was strictly volunteer based, we struggled to obtain a large sample of participants. For future research, we believe finding better ways to supplement participants time with something of high value would create more willingness to participate. An example of this could include monetary supplementation. In addition, future work should involve more colleague collaboration from other universities. By doing this, analysis could be extended across both the United States and international levels.

We also faced some difficulties with our Algo Move Pro system itself. Unfortunately, there were multiple occasions where our sensor lost GPS connection. When this occurred, we lost valuable data that we had to exclude from our overall analysis. The loss of connection could partly, be due to poor GPS signal in indoor facilities. It is not uncommon for GPS systems to face signal blockades depending on atmospheric conditions, particularly when being used under large metal roofs. Therefore, I believe that future work should include expanding the utility of the Alogo sensor to operate independent of GPS signal as signal reliability was clearly a challenge within our dataset.

Lastly, we believe that future work should also include longitudinal studies using the Alogo Move Pro sensor. From previous studies, we know that many sport horses face long-term ailments associated with jumping. By using the Alogo Move Pro sensor, work could be explored in finding ways to better determine disease onset based on differences in jump trajectory values over time. Also, longitudinal studies could help show the potential of the Alogo Move Pro device to be used as a diagnostic tool or rehabilitation device for equines.

From our research, wearable sensor technologies show promise in being able to improve equine health and well-being. Wearable sensors for horses could be used to detect early disease onset and help better reform treatment monitoring. This could be especially useful for laminitis and colic, which are two of the large health concerns domesticated horses face. Our two sensors gave direct insight in how precision technology can be used for horses in exercise and continuous monitoring contexts. Although our sensors were thoughtfully designed, our results indicate that more research in this area in needed to improve accuracy and reliability of measurements.