Genetic parameter estimates for feet and leg traits in Red Angus cattle

by

Brady Robert Jensen

A.S., Butler Community College, 2013
B.S., Kansas State University, 2015

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Animal Science and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Approved by:

Co-Major Professor
Dr. Jennifer Bormann

Approved by:

Co-Major Professor
Dr. Robert Weaber

Copyright

Abstract

The objective of this study was to investigate the parameter estimates for feet and leg traits, relationships within feet and leg traits, and between feet and leg traits and production traits in Red Angus cattle. Subjective scores for 14 traits including: Body Condition Score (BCS), Front Hoof Angle (FHA), Front Heel Depth (FHD), Front Claw Shape (FCS), Rear Hoof Angle (RHA), Rear Heel Depth (RHD), Rear Claw Shape (RCS), Size of Hoof (Size), Front Side View (FSV), Knee Orientation (KNEE), Front Hoof Orientation (FHO), Rear Side View (RSV), Rear View (RV), and a Composite Score (COMP) were collected by trained evaluators on 1885 Red Angus cattle at different ranches across the United States. A three-generation pedigree file was obtained from the Red Angus Association of America (RAAA) that contained 13,306 animals, and EPDs on all animals with feet and leg scores were obtained. All traits except COMP were scored as intermediate optimum traits. Data were modeled using a linear bivariate animal model with random additive genetic and residual effects, and fixed effects of age and contemporary group (herd-year). Variances were estimated with ASREML 3.0 and 4.0. Heritability estimates of BCS, FHA, FHD, FCS, RHA, RHD, RCS, Size, FSV, Knee, FHO, RSV, RV, and COMP were 0.11, 0.20, 0.17, 0.09, 0.19, 0.25, 0.17, 0.36, 0.16, 0.17, 0.17, 0.30, 0.14, and 0.12, respectively. These results showed feet and leg traits were lowly to moderately heritable. Strong, positive genetic correlations were found between FHA and FHD (0.89), FHA and RHA (0.88), FHD and RHA (0.85), FHA and RHD (0.85), FHD and RHD (0.94), and FHO and Knee (0.95), indicating these traits may be highly related to one another. Strong negative correlations were found between Knee and FSV (-0.59) and FHO and FSV (-0.75). The strongest correlation was between front limb traits (FHA, FHD, FSV, FHO, Knee, and Comp) and the Stayability EPD (STAY) was FSV (r =0.16; r_s =0.20) and for rear limb traits (RHA, RHD, RCS, RSV, RV, and

Comp) and STAY was RCS (r = -0.12; r_s=-0.14). This indicates that cattle with more slope to the angle of the shoulder stay in the herd longer and cattle with less curl to the inside of the claw tend to stay in the herd longer. Further studies with more data could help validate the relationship between feet and leg traits and production traits.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I truly appreciate the funding and support from the Red Angus Association of America and Kansas State University Global Food Systems initiative. Also, a special thank you to all the Red Angus breeders that allowed for the research to take place on their cattle and in their operations. Working through this research project was an opportunity I will appreciate for my entirety and I truly enjoyed traveling the countryside, looking at good Red Angus cattle, and meeting new people.

A very special thank you goes out to Lane Giess, who worked alongside myself throughout this process. The long days in the extreme heat or cold while collecting data built a lot of character and great memories that are unforgettable.

Thank you to my advisors, Dr. Robert Weaber and Dr. Jennifer Bormann for granting me the opportunity to work on this project and for always being a resource that continually helped me down the right path throughout this process. Thank you to Dr. Megan Rolf, for allowing me to pop to her office at any time to decipher the myth of Microsoft Access.

No question, I wouldn't be in the spot I am today without the guidance and support of my parents. They have laid a great foundation and opportunity as a person and a cowman and I truly appreciate all they have sacrificed for my sake.

Finally, thank you to my wife, Allie, for the time, support, and patience that she has granted to me throughout my masters degree process. I am very excited to see where the path leads us and know that this research will always hold a special place with us.

Chapter 1 - Literature Review

Importance of Longevity, Feet, and Legs in Beef Cattle

As input costs continue to rise in beef cattle production, increased longevity becomes a more desirable and economically relevant trait. Increasing the longevity of a beef cow can reduce the costs of replacement females by balancing the costs of maintaining a mature cow over a larger number of calves (Cundiff et al, 1992). Increasing the productive life of a beef cow allows a producer to be more selective of replacement females, putting fewer heifers back into the herd. This allows the producer to market a higher percentage of the heifer crop for additional revenue or purchase fewer replacement females.

Feet and leg structure is frequently anecdotally associated with the longevity of beef cattle, both male and female. For instance, “The major factors affecting longevity of cows are infertility, unsoundness of feet and legs, udder troubles, and unsound mouth” (Gadberry et al., 2015). Gadberry et al., (2015) also stated “Sound hips, hocks, shoulders, and feet are valuable for longevity in the herd.” Daniel and Kreise-Anderson (2013) stated “In regard, to reproduction, bulls that are post legged can face issues when it comes to breeding due to the extreme angle of their hind legs and the fact that these legs support the bull’s weight during the act of breeding. These bulls may also face issues when it comes to traveling the distances associated with covering large groups of females in larger pasture settings.” These statements are based off little research and more information regarding feet and leg structure and its association with longevity needs to be investigated among the beef cattle population in the United States.

Feet and leg structure contributes to the likelihood of being culled, but is less important than age at first calving and muscle traits (Forabosco et al., 2004). Intermediate optimum scores were collect on a scale of 1-5, where 3 is most ideal, were assigned to five structure traits including rump angle, top line, fore legs-front view, fore legs-side view, and hind legs-side view in Italian Chianina cattle. Cattle ranking in category 4 or more post legged for hind legs-side view had a 59% greater probability of being culled than cows with an ideal score of 3, whereas, females ranking in category 2 or more sickle-hocked were only 3% more likely to be culled versus an animal ranking in the ideal category (Forabosco et al., 2004). Productions systems are different between the United States and Italy, as a result muscularity traits are a higher priority in the breeding objectives in Italy due to a primarily yield based meat industry. Regardless, feet and leg structure should maintain importance in production systems that vary in nature.

Importance of Longevity, Feet, and Legs in Dairy Cattle

Dairy cows with clinical lameness are an economic burden to producers. Approximately 25% of dairy cows are treated for foot disorders each year and expenses accrue due to direct and indirect costs (Politiek et al., 1986).) Kossaibati et al. (1999) reported “Lameness affects the economic performance of dairy cows in various ways, such as: reduced milk yield due to stress, lower food intake and extended calving interval, increased costs of veterinary treatments, discarded milk due to treatment with antibiotics, higher herd culling rate and hence higher replacement costs, lower value of a culled cow, due to reduced body weight, higher fertility cost, due to the cost of extra services, increased labor cost, due to time spent on treatment and attention by the herdsman, and increased risk of other diseases.” If costs of treatment and care of feet and legs is held as low as possible, the producer’s income can benefit. For instance, average losses due to feet and leg structure issues range from $40 to $75 per cow per year and producers who are more proactive in the treatment of foot issues tend to be more profitable. (Kossaivati et al. 1999; Bruijnis et al., 2010). Ultimately, losses due to feet and leg issues can total 4-5% of the income of a dairy produce, which ranks ranked third behind mastitis and infertility (Enting et al., 1997).

Culling records in dairy cattle are typically broken into two categories; voluntary and involuntary culling. Voluntary culling occurs when a cow is disposed of because of poor performance or an economic incentive, for example, a lower producing female leaves the herd, to be replaced by a higher producing female. Involuntary culling happens when an animal is disposed of for a reason out of the producer's control, such as death, lameness, mastitis, disease, or reproductive issues. Clinical lameness ranked fourth in a dairy culling survey done by the USDA (2007) at a prevalence rate of 16.0%, placing behind infertility or reproductive problems at 26.3%, mastitis at 23.0%, and poor production or performance charting slightly higher at 16.1%. If feet and leg issues are minimized, then involuntary culling should decrease. Reducing the involuntary culling rate less than the voluntary culling rate allows a dairy producer to be more profitable by eliminating a higher percentage of lower producing females and placing higher producing females into the herd (Allaire and Cunningham, 1980).

Measuring Feet and Leg Structure in Beef and Dairy Cattle

The Australian Angus Association (AAA) has been a pioneer in creating genetic selection tools for feet and leg structure in the beef industry. Jeyaruban et al. (2012) evaluated six structural traits from scores derived from AAA accredited technicians. The traits included in the evaluation were front feet angle, rear feet angle, front feet claw set, rear feet claw set, rear leg hind view, and rear leg side view. All the traits are subjectively scored on an intermediate optimum scale ranging from 1-9, where scores 5 and 6 are the most ideal scores. The scoring system for the traits measured is displayed in Figure 1.1 (Jeyaruban et al. 2012).

American Angus Association (2015) has not released any genetic selection tools, but is gathering data from producers on feet and leg traits including foot angle and claw score. The traits are being collected on a scale of 1-9, where 5 is ideal. This scoring system is shown in Figure 1.2 (American Angus Association, 2015).

Holstein Association USA, Inc. (2016) has trained evaluators that score cows on 17 different traits relating to udder, feet and legs, front end and capacity, dairy strength, and rump, which ultimately make up a final score out of 100. Twenty percent of the final score is comprised of traits related to conformation of the feet and legs, which is a subjective measurement assessed by the evaluator and scored on rear legs rear view, locomotion, rear legs side view, feet, thurl position, hocks, bone, and pasterns (Holstein Association USA, Inc. 2016). Linear type trait scores are also recorded by the evaluator for rear legs side view, rear leg rear view, and foot angle and can be seen in Figure 1.3 (Holstein Association USA, Inc. 2016). Rear legs side view and foot angle are 1-50 scores, where an intermediate optimum exists at 25 and foot angle is scored 1-50, where 50 is the most ideal (Holstein Association USA, Inc. 2016). Many other dairy breed associations have programs that collect similar type traits to utilize in genetic evaluations.

Genetic and Phenotypic Parameters

Heritability

Phenotype is the combination of additive genetics, gene combination value, genetic and environmental interaction, and environment. Heritability is an estimate of the variation explained within the phenotype by the additive genetic component. Heritability is a key factor in the response to selection on a trait because a greater heritability estimate or a higher proportion of additive genetic variation results in a greater response to selection. The heritability equation is as follows:

$$h^2 = \frac{\sigma_a^2}{\sigma_p^2}$$

where $\boldsymbol{h^2}$ is heritability, $\boldsymbol{\sigma_a^2}$ is the variance of additive genetics, and $\boldsymbol{\sigma_p^2}$ is the variance of the phenotype.

Most of the research in feet and leg structure originates in the dairy industry due to genetic evaluation tools for type traits. Little research has focused on feet and legs in the beef industry. Table 1.1 lists the heritability estimates of feet and leg structure traits in both beef and dairy cattle populations. The following discussion will further cover the heritability estimates from prior research.

Feet and Leg Score

Feet and leg scores (FLS) are subjective measurements used to evaluate of feet and leg structure. Perez-Cabal et al. (2006) broke subjective FLS's down to 6 categories: poor, fair, good, good plus, very good, and excellent and found a heritability of 0.14. Onyiro and Brotherstone (2008) reported a FLS heritability of 0.18 in Holstein-Friesians, where the scale of the scoring system was from 65 (poor) to 95 (excellent). Vollema and Groen (1997) found a higher heritability of 0.41 on a scale of 65 (poor) to 89 (excellent) in a crossbred population of Dutch Friesian and Holstein-Friesian population. A heritability estimate of 0.24 was recorded in a population with approximately 75% Friesian-Holstein genes on a scale of 70 (poor) to 89 (very good) (Van Der Waaij et al., 2005). Differences between scoring systems seem to play a role in varying degrees of heritability between populations. Fatehi et al. (2003) published heritabilities for FLS to be 0.13, 0.17, 0.17, and 0.15 for solid flooring, slatted flooring, tie stall and free-stall, respectively, which reveals in similar populations differences in environment appear to have little to no effect on heritability.

Mobility and Locomotion

Wright et al. (2013) reported a heritability for mobility of 0.21, which is a score based on a cumulative subjective appearance on actual movement, track and set of the legs and hocks, foot angle, thurl position, and pasterns. Locomotion is a subjective measurement specifically analyzing solely the gait and length of stride. Van Der Waaij et al. (2005) and Onyiro and Brotherstone (2008) reported a 0.10 and 0.18 heritability respectively for locomotion, where the scoring system was 1 (poor) to 9 (even gait, long strides). Van Dorp (2004) published a range of heritabilities for locomotion of 0.05 to 0.07, where the scoring system is 1 (correct) to 5 (severely lame). The differences in the granularity of the scoring systems between the research on mobility and locomotion suggest higher heritabilities are a result of more specific scoring systems.

Foot Angle

Van Dorp et al. (2004), Perez-Cabal et al. (2006), Onyiro and Brotherstone (2008), and Laursen et al. (2009) found heritability estimates of foot angle (FA) based on a 1 to 9 intermediate optimum scale to be 0.10, 0.12, 0.11, and 0.13. In Brown Swiss cattle, a heritability estimate of 0.09 was found for FA (Wright et al., 2013). Heritability estimates for Brown Swiss and Guernsey cattle were 0.13 and 0.10 according to Wiggans et al. (2006). In a study with approximately 75% Holstein-Friesian cows a FA heritability of 0.18 was noted (Van Der Waaij et al., 2005). Fatehi et al. (2003) researched heritabilities depending on housing and flooring differences for foot angle and found a range from 0.09-0.12. In dairy populations, heritability estimates of FA seem to be very similar among subjective scoring systems however, Hahn et al. (1984) found the heritabilities of FA for the inside front toe, outside front toe, inside rear toe, and outside rear toe to be 0.38, 0.40, 0.55, and 0.85, respectively, indicating higher heritability estimates are calculated if the hooves are physically measured with a ruler versus a subjective score by a trained evaluator. Jeyaruban et al. (2012) investigated heritability in Australian Angus cattle utilizing a linear and threshold model with a 1 to 9 intermediate optimum scale and regrouped the scores to a 1 to 3 scale. The linear and threshold animal model posted heritabilities ranging from 0.17 to 0.32 and 0.26 to 0.50, where the lower measurements come from the 1 to 3 grouped scores (Jeyaruban, et al., 2012). The lower heritabilities from regrouping the scores or reducing the granularity of the scoring system indicates a greater percentage of the additive genetic variance is realized with a more granular or more descriptive scoring system.

Rear Leg Set- Side View

Rear leg set side view (RLSV) heritability estimates are 0.19, 0.15, and 0.19 (Perez-Cabal et al., 2006, Onyiro and Brotherstone, 2008, and Laursen et al., 2009) on a 1 (sickle-hocked) to 9 (post-legged) intermediate optimum scale. Van Dorp et al. (2004) found heritability to be 0.23 for RLSV. In the Brown Swiss breed a heritability estimate of 0.14 for RLSV was found (Wright et al., 2013). In Guernsey and Brown Swiss cattle heritability estimates have been reported at 0.16 and 0.18 (Wiggans et al., 2006). Vollema and Groen (1997) found a heritability of 0.17 for RLSV in a crossbred population of Dutch Friesian and Holstein-Friesian population. Cows with approximately 75% Holstein-Friesian breed composition had a RLSV heritability of 0.22 (Van Der Waaij et al., 2005). A heritability range of 0.17 to 0.21 for RLSV in a purebred Holstein population was published by Faheti et al (2003). In the beef industry, Jeyaruban et al. (2012) reported heritabilities of 0.10 to 0.22 for RLSV and noted that threshold models equated to a higher genetic variance. The heritability estimates for RLSV in beef and dairy populations were extremely similar regardless of the scoring system, yet slighter differences were revealed when RLSV was analyzed as a threshold trait versus a linear trait.

Rear Leg Set- Rear View

Rear leg side view (RV) was measured in Brown Swiss cattle by Wright et al. (2013) and reported a heritability of 0.06. Van Der Waaij et al. (2005) researched heritability for RV in crossbred dairy cows and published an estimate of 0.11. Laursen et al. (2009) found a heritability of 0.14 in Holstein cattle. Faheti et al. (2003) found heritability to be low at 0.07 to 0.11 for RV depending on environments. Australian Angus RV heritability ranged from 0.16 to 0.32, where a 1 to 9 intermediate optimum scoring system utilizing a threshold animal model equated the highest heritability. The Australian Angus population appears to have a higher heritability for RV versus the dairy cattle populations analyzed, however more research is needed to validate this difference.

Heel Depth

The measure of heel depth is from the hairline on the back of the foot to the ground. Heel depth heritabilities ranged from 0.06 to 0.09 depending on the surface the Holstein cow was housed on in a study done by Fatehi et al. (2003), where the scorers evaluated the trait subjectively. Hahn et al. (1984) found front hoof and back hoof heel depth heritabilities to be 0.58 and 0.19, respectively, when the scores were taken as a physical measurement in centimeters. Research regarding heel depth is sparse, but past research indicates a physical measurement explains a greater proportion of the variance versus a subjective scoring system.

Hoof Area

Hahn et al. (1984) physically measured the area of the front and rear hooves in centimeters and found the heritabilities to be 0.46 and 0.34.

Claw Shape

In Australia, Jeyaruban et al. (2012) focused on claw structure of Angus cattle for front and rear feet. Heritability estimates of 0.33, 0.18, 0.46, and 0.36 for claw shape on front feet derived from an ungrouped (1 to 9) scoring system linear animal model, grouped (1 to 3) scoring system linear animal model, ungrouped scoring system threshold animal model, and grouped scoring system threshold animal model were reported. For rear foot claw shape, linear animal models and threshold animal model heritabilities ranged from 0.16 to 0.29 and 0.40 to 0.44, where the lower measurements were from the less descriptive scoring system (Jeyaruban, et al., 2012).

Repeatability

Repeatability describes the correlation between repeated records for a trait. A high repeatability indicates the first record is highly predictive of future performance, versus a lowly repeatable trait where a first record is a poor predictor of future performance. The repeatability equation is as follows:

$$\boldsymbol{R = \frac{\sigma_a^2 + \sigma_{pe}^2}{\sigma_p^2}}$$

Where R is repeatability, $\boldsymbol{\sigma_a^2}$ is additive genetic variance, $\boldsymbol{\sigma_{pe}^2}$ is permanent environment variance, and $\boldsymbol{\sigma_p^2}$ is phenotypic variance. Hahn et al. (1984) reported that as cows aged, hoof angle decreased and found repeatability over 4 parities to be 0.44-0.45 for rear hoof angle. In a Brown Swiss population repeatability estimates for FA and RLSV were 0.21 and 0.29 (Wright et al. 2013). Literature contains few estimates on repeatability, however, FA and RLSV appear to be moderately repeatable.

Genetic and Phenotypic correlations

Genetic correlations are important in selection of breeding stock because selection of one trait can have a favorable or unfavorable impact on another important trait. Understanding which traits are related to each other allows producers to make more informed breeding decisions. Refer to Table 1.2 for literature estimates of genetic and phenotypic correlations between structural traits and longevity traits and within structural traits.

Feet and Leg Traits and Longevity

A subjective measurement of the overall quality of feet and legs and FA have positive genetic correlations with longevity traits like productive life and functional herd life (r = 0.03 to 0.32; Dekkers et al., 1994, Vollema and Groen, 1997, and Perez-Cabal et al., 2006). Therefore, dairy cattle with better feet and legs and steeper hoof angles live longer and more productive lives. Dekkers et al. (1994) and Vollema and Groen (1997) reported a negative genetic relationship with productive life and functional herd life with RLSV, so, cattle with a straighter angle to their hock live less productive and shorter lives (r = -0.21 to -0.01).

Genetic Correlations Between Structural Traits

Several studies in the dairy industry have focused on structural traits. Correlations have been mostly positive within feet and leg traits. Genetic correlations for FA and FLS range from 0.51 to 0.73 (phenotypic correlation = 0.42), which indicates that cattle with steeper foot angles have more favorable FLS (Van Der Waaij et al., 2005; Perez-Cabal et al., 2006). A negative genetic correlation between FLS and RLSV suggests cattle with a straighter hock tend to have poor FLS (r = -0.36 to -0.52; Vollema and Groen, 1997; Van Der Waaij et al., 2005; Perez-Cabal et al., 2006). Feet and Legs score and locomotion seem to be influenced by very similar genes because genetic correlations are 0.98 and phenotypic correlations range from 0.78 to 0.85 (Van Der Waaij et al., 2005 and Onyiro and Brotherstone, 2008).

Jeyaruban et al. (2012) reported all positive genetic (r = 0.19 to 0.86) and phenotypic correlations (r = 0.19 to 0.45) for FA with RLSV, however Perez-Cabal et al. (2006) reported a strong negative genetic correlation of -0.44 for RLSV and FA, but scoring systems were reverse for FA in the previously mentioned studies, therefore the correlations indicate cattle with genetics for a steeper hoof angle tend to have genetics for a straighter angle to the hock. In Angus cattle, Jeyaruban et al. (2012) found that both front and rear FA were positively correlated with front and rear claw shape (r = 0.27 to 0.83), indicating cattle with genetics for longer hooves are more likely to possess genetics for a more scissor-like claw shape to the hoof.

Rear leg side view and RV have genetic correlations of 0.27 to 0.67 and phenotypic correlations of 0.08 to 0.41 (Jeyaruban et al. 2012), however Wiggans et al. (2006) reported negative genetic correlations (r = -0.11 to -0.46) and phenotypic correlations (r = -0.19 to -0.16) for RLSV and RV. Yet, the interpretation of the previously mentioned correlations is the same between RLSV and RV because the scoring system for RV is reverse, therefore cattle with more set to the hock from the side view tend to be more hocked in and toed out from behind on the hind leg.

Rear leg side view with both locomotion and mobility have negative and positive genetic correlations ranging from -0.26 to 0.81, yet the scoring systems are different, so the interpretation is that dairy cattle with better locomotion and mobility have a straighter angle to their hock (Van Dorp et al., 2004; Onyiro and Brotherstone, 2008; Wright et al., 2013). Most traits possess similar correlations between dairy and beef research.

Genetic Evaluations

Type trait evaluations have been performed by the dairy industry for many years. In the United States, Jersey cattle were the first to include type traits into genetic evaluations in 1978, and the Holstein breed followed in 1979 (Wiggans 1991). In 1996, Holstein Association USA, Inc. (2017) released an improved feet and leg composite (FLC) Standard Transmitting Ability (STA) index, which is calculated by the equation:

FLC = .5 (linear traits) + .5 (Feet and Legs Score)

Where the linear traits are a weighted index derived from the FA, RLSV, and RV STA's, and the other portion of the FLC is from the STA of FLS. Holstein Association USA, Inc. (2017) reports that for every 1.0 increase in the FLC STA you should expect an increase of 0.3 for the STA productive life. Holstein Association USA, Inc (2017) stated "Selecting animals that transmit superior mobility, steeper foot angle, wider rear leg stance with little or no hock-in, and slightly straight rear legs (side view) will result in animals capable of longer productive life." Selection for feet and leg structure traits that are quantified through whole breed genetic evaluations are commonplace in the dairy industry.

In the United States beef industry, there is presently no genetic evaluation tools published by a breed association, though data is currently being collected by American Angus Association members (American Angus Association, 2017). However, the Australian Angus Association (2017) currently publishes five structural soundness Estimated Breeding Values (EBV) including front FA, rear FA, front claw shape, RLSV, and RV (Australian Angus Association 2017).

Conclusion

Feet and leg structure traits are economically relevant traits in cattle production because of the costs associated with involuntary culling as it relates to longevity. Heritability estimates and correlations demonstrate opportunity for improvement of feet and leg structure in the population. The US dairy industry and international beef breed associations are utilizing genetic selection tools to improve feet and leg structure. Therefore, investigation of genetic parameter estimates for feet and leg structure traits for beef cattle is needed to see if beef breed associations in the United States could incorporate feet and leg structure into their genetic evaluations and publish selection tools to improve feet and leg structure in American beef cattle.

Figure 1.1 Foot scoring system from Australian Angus Association (Jeyaruban et al., 2011)

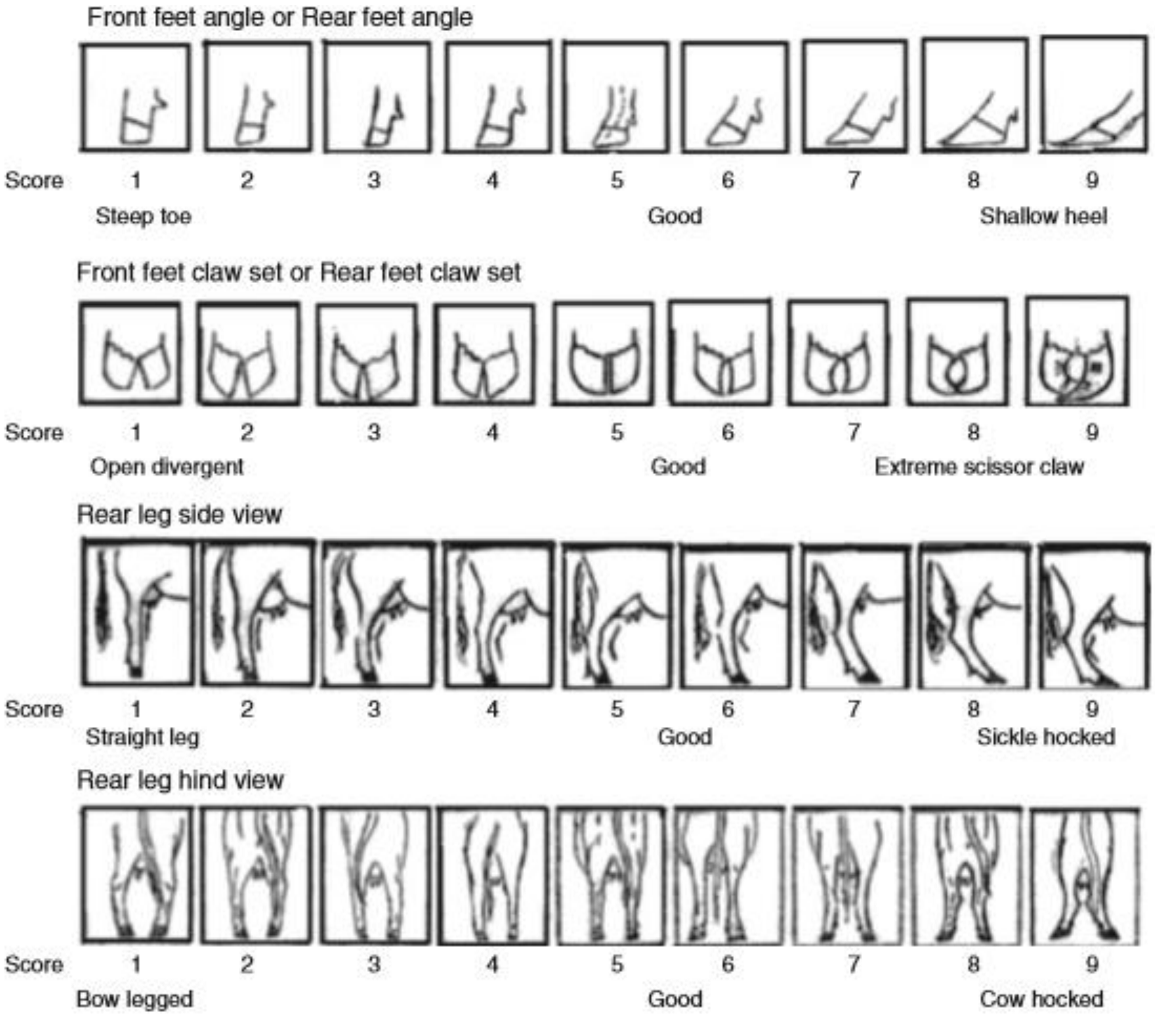

Figure 1.2 Foot angle and claw set scoring system (American Angus Association, 2015)

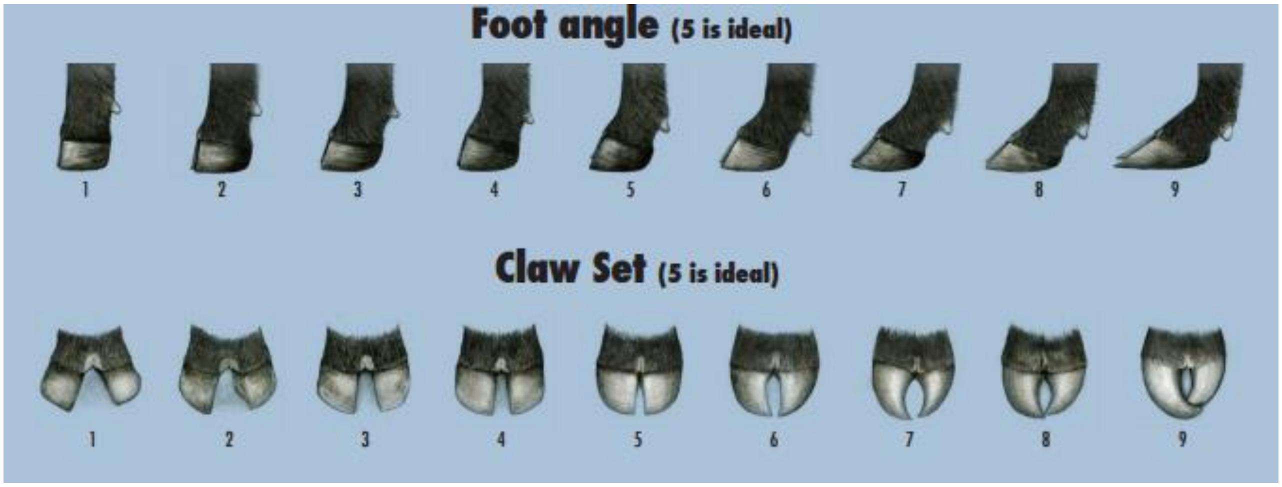

Figure 1.3 Feet and leg scoring system (Holstein Association USA, Inc., 2016)

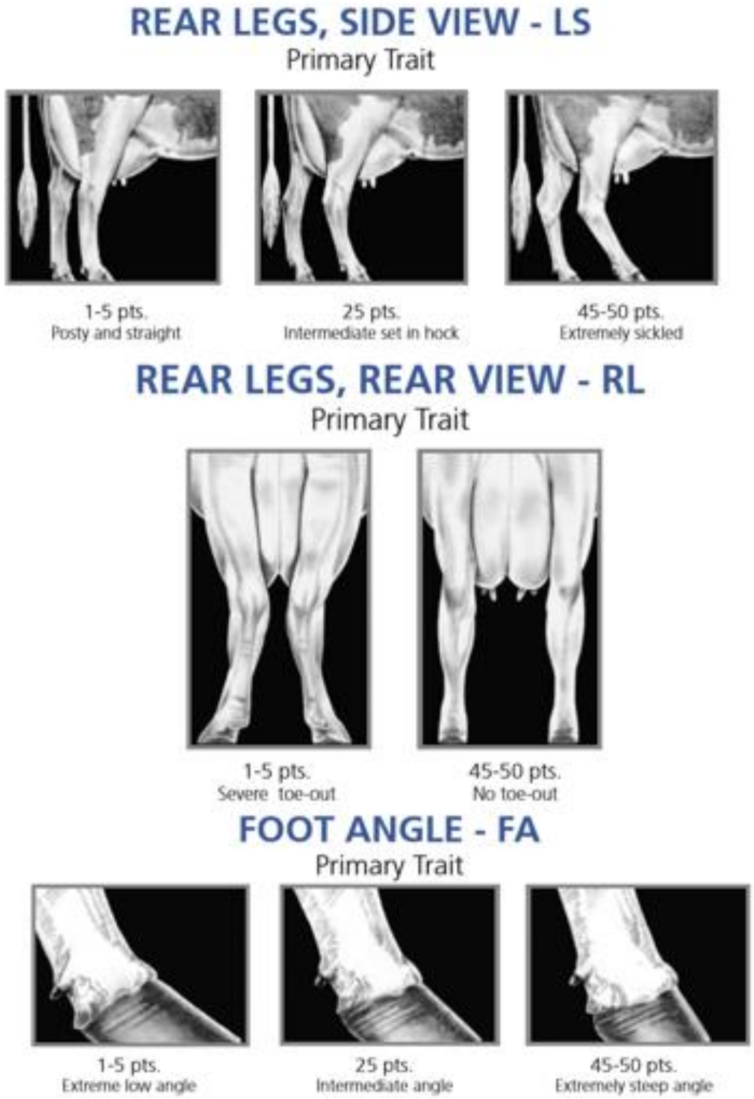

Table 1.1 Heritability estimates for structural traits

Trait	Breed	Model	Reference	Heritability
Feet and Legs	Dutch Friesian and Holstein-Friesian	Linear Sire Model	Vollema and Groen (1997)	0.41
Feet and Legs	Holstein	Linear Animal Model	Fatehi et al. (2004)	0.13-0.17
Feet and Legs	Crossbred Holstein-Friesian	Linear Sire Model	Van Der Waaij et al. (2005)	0.24
Feet and Legs	Holstein	Linear Animal Model	Perez-Cabal et al. (2006)	0.14
Feet and Legs	Holstein	Linear Animal Model	Onyiro and Brotherstone (2008)	0.18
Foot Angle	Holstein	Linear Sire Model	Hahn et al. (1984)	0.38-0.85
Foot Angle	Holstein	Linear Animal Model	Fatehi et al. (2003)	0.09-0.12
Foot Angle	Holstein	Linear Animal Model	Van Dorp et al. (2004)	0.10
Foot Angle	Crossbred Holstein-Friesian	Linear Sire Model	Van Der Waaij et al. (2005)	0.18
Foot Angle	Brown Swiss	Linear Animal Model	Wiggans et al. (2006)	0.13
Foot Angle	Guernsey	Linear Animal Model	Wiggans et al. (2006)	0.10
Foot Angle	Holstein	Linear Animal Model	Perez-Cabal et al. (2006)	0.12
Foot Angle	Holstein	Linear Animal Model	Onyiro and Brotherstone (2008)	0.11
Foot Angle	Holstein	Linear Sire Model	Laursen et al. (2009)	0.13
Foot Angle	Angus	Linear Animal Model	Jeyaruban et al. (2012)	0.17-0.32
Foot Angle	Angus	Threshold Animal Model	Jeyaruban et al. (2012)	0.41-0.50
Foot Angle	Brown Swiss	Linear Animal Model	Wright et al. (2013)	0.09
Rear Legs Side View	Dutch Friesian and Holstein-Friesian	Linear Sire Model	Vollema and Groen (1997)	0.17
Rear Legs Side View	Holsteins	Linear Animal Model	Fatehi et al. (2004)	0.17-0.21
Rear Leg Side View	Holstein	Linear Sire Model	Van Dorp et al. (2004)	0.23
Rear Leg Side View	Crossbred Holstein-Friesian	Linear Sire Model	Van Der Waaij et al. (2005)	0.22
Rear Legs Side View	Holstein	Linear Animal Model	Perez-Cabal et al. (2006)	0.19
Rear Legs Side View	Brown Swiss	Linear Animal Model	Wiggans et al. (2006)	0.18
Rear Legs Side View	Guernsey	Linear Animal Model	Wiggans et al. (2006)	0.16
Rear Leg Side View	Holstein	Linear Animal Model	Onyiro and Brotherstone (2008)	0.15
Rear Leg Side View	Holstein	Linear Sire Model	Laursen et al. (2009)	0.19
Rear Leg Side View	Angus	Linear Animal Model	Jeyaruban et al. (2012)	0.10-0.21
Rear Leg Side View	Angus	Threshold Animal Model	Jeyaruban et al. (2012)	0.16-0.22
Rear Leg Set-Side View	Brown Swiss	Linear Animal Model	Wright et al. (2013)	0.14
Rear Leg Rear View	Holstein	Linear Animal Model	Fatehi et al. (2003)	0.07-0.11
Rear Leg Rear View	Crossbred Holstein-Friesian	Linear Sire Model	Van Der Waaij et al. (2005)	0.11

Rear Leg Rear View	Holstein	Linear Sire Model	Laursen et al. (2009)	0.14
Rear Leg Rear View	Angus	Linear Animal Model	Jeyaruban et al. (2012)	0.16-0.17
Rear Leg Rear View	Angus	Threshold Animal Model	Jeyaruban et al. (2012)	0.12-0.32
Rear Leg Rear View	Brown Swiss	Linear Animal Model	Wright et al. (2013)	0.06
Heel Depth	Holstein	Linear Sire Model	Hahn et al. (1984)	0.19-0.58
Heel Depth	Holstein	Linear Animal Model	Fatehi et al. (2003)	0.06-0.09
Locomotion	Crossbred Holstein-Friesian	Linear Sire Model	Van Der Waaij et al. (2005)	0.10
Locomotion	Holstein	Linear Animal Model	Van Dorp et al. (2004)	0.05-0.07
Locomotion	Holstein	Linear Animal Model	Onyiro and Brotherstone (2008)	0.11
Mobility	Brown Swiss	Linear Animal Model	Wright et al. (2013)	0.21
Hoof Area	Holstein	Linear Sire Model	Hahn et al. (1984)	0.34-0.46
Claw Shape	Angus	Linear Animal Model	Jeyaruban et al. (2012)	0.16-0.33
Claw Shape	Angus	Threshold Animal Model	Jeyaruban et al. (2012)	0.36-0.44

Table 1.2 Genetic and phenotypic correlations between feet and leg traits and feet and leg traits and longevity

Traits	Reference	Genetic Correlation	Phenotypic Correlation
Feet and Legs Foot Angle	Perez-Cabal et al. (2006)	0.73	
Feet and Legs Foot Angle	Van Der Waaij et al. (2005)	0.51	0.42
Feet and Legs Rear Leg Side View	Vollema and Groen (1997)	-0.52	
Feet and Legs Rear Leg Side View	Van Der Waaij et al. (2005)	-0.36	-0.31
Feet and Legs Rear Leg Side View	Perez-Cabal et al. (2006)	-0.39	
Feet and Legs Rear Leg Rear View	Van Der Waaij et al. (2005)	0.79	0.56
Feet and Legs Locomotion	Van Der Waaij et al. (2005)	0.98	0.85
Feet and Legs Locomotion	Onyiro and Brotherstone (2008)	0.98	0.78
Feet and Legs Profit	Perez-Cabal et al. (2006)	0.10	
Feet and Legs Productive Life	Perez-Cabal et al. (2006)	0.05	
Feet and Legs Functional Herd Life	Dekkers et al. (1994)	0.27	
Feet and Legs Functional Herd Life	Vollema and Groen (1997)	0.24 to 0.32	
Feet and Legs Functional Herd Life	Perez-Cabal et al. (2006)	0.05	
Foot Angle Laminitis	Rogers (1993)	-0.50	
Foot Angle Rear Leg Side View	Perez-Cabal et al. (2006)	-0.44	
Front Foot Angle Rear Leg Side View	Jeyaruban et al. (2012)	0.19 to 0.48	0.17 to 0.33
Rear Foot Angle Rear Leg Side View	Jeyaruban et al. (2012)	0.23 to 0.86	0.25 to 0.45
Foot Angle Rear Leg Rear View	Wiggans et al. (2006)	0.19 to 0.31	0.19 to 0.21
Front Foot Angle Rear Leg Rear View	Jeyaruban et al. (2012)	0.02 to 0.31	0.08 to 0.14
Rear Hoof Angle Rear Leg Rear View	Jeyaruban et al. (2012)	0.21 to 0.39	0.11 to 0.26
Front Foot Angle Rear Foot Angle	Jeyaruban et al. (2012)	0.50 to 0.87	0.35 to 0.65
Front Foot Angle Front Claw	Jeyaruban et al. (2012)	0.41 to 0.83	0.23 to 0.43
Front Foot Angle Rear Claw	Jeyaruban et al. (2012)	0.27 to 0.63	0.20 to 0.38
Rear Foot Angle Front Claw	Jeyaruban et al. (2012)	0.29 to 0.40	0.14 to 0.37
Rear Foot Angle Rear Claw	Jeyaruban et al. (2012)	0.30 to 0.82	0.33 to 0.53
Foot Angle	Perez-Cabal et al. (2006)	0.05	

Profit			
Foot Angle Productive Life	Perez-Cabal et al. (2006)	0.03	
Foot Angle Functional Herd Life	Perez-Cabal et al. (2006)	0.03	
Foot Angle Locomotion	Van Dorp et al. (2004)	-0.84	0.07
Foot Angle Locomotion	Onyiro and Brotherstone (2008)	0.30	0.20
Foot Angle Mobility	Wright et al. (2013)	0.47	0.30
Rear Leg Side View Rear Leg Rear View	Wiggans et al. (2006)	-0.11 to -0.46	-0.19 to -0.16
Rear Leg Side View Rear Leg Rear View	Jeyaruban et al. (2012)	0.27 to 0.67	0.08 to 0.41
Rear Leg Side View Front Claw	Jeyaruban et al. (2012)	0.08 to 0.24	0.05 to 0.30
Rear Leg Side View Rear Claw	Jeyaruban et al. (2012)	0.17 to 0.62	0.12 to 0.32
Rear Leg Side View Locomotion	Van Dorp et al. (2004)	0.81	0.09
Rear Leg Side View Locomotion	Onyiro and Brotherstone (2008)	-0.26	-0.16
Rear Leg Side View Mobility	Wright et al. (2013)	-0.10	-0.10
Rear Leg Side View Profit	Perez-Cabal et al. (2006)	0.04	
Rear Leg Side View Productive Life	Perez-Cabal et al. (2006)	-0.09	
Rear Leg Side View Functional Herd Life	Vollema and Groen (1997)	-0.21 to -0.01	
Rear Leg Side View Functional Herd Life	Perez-Cabal et al. (2006)	-0.10	
Rear Leg Rear View Front Claw	Jeyaruban et al. (2012)	-0.14 to 0.16	0.05 to0.22
Rear Leg Rear View Rear Claw	Jeyaruban et al. (2012)	0.07-0.21	0.06-0.15
Rear Leg Rear View Mobility	Wright et al. (2013)	0.72	0.38
Front Claw Rear Claw	Jeyaruban et al. (2012)	0.27-0.81	0.21-0.44

References

Allaire, F. R. and Cunningham, E. P. 1980. Culling on low milk yield and its economic consequences for the dairy herd. Livest. Prod. Sci. 7: 349–359.

American Angus Association. 2015. Foot score guidelines. http://www.angus.org/performance/footscore/footscoreposter.pdf. (Accessed May 16, 2017.)

Australian Angus Association. 2017. Understanding EBVs. https://www.angusaustralia.com.au/breedplan/understanding-angus-breedplan/understanding-ebvs/. (Accessed May 22, 2017.)

Bruijnis, M. R. N., H. Hogeveen, and E. N. Stassen. 2010 Assessing economic consequences of foot disorders in dairy cattle using a dynamic stochastic simulation model. J. Dairy Sci. 93:2419-2432.

Burke, B. P. and D. A. Funk. 1993. Relationship of linear type traits and herd life under different management systems. J. Dairy. Sci. 76:2773-2782.

Cundiff, L. V., R. Nunez-Dominguez, G. E. Dickerson, K. E. Gregory, and R. M. Koch. 1992. Heterosis for lifetime production in Hereford, Angus, Shorthorn, and Crossbred cows. J. Anim. Sci. 70: 2397-2410.

Daniel Jr., D. L., and L. A. Kriese-Anderson. 2013. Beef conformation basics. http://www.aces.edu/pubs/docs/A/ANR-1452/ANR-1452.pdf. (Accessed May 15, 2016)

Dekkers, J. C. M., L. K. Jairath, and B. H. Lawrence. 1994. Relationships between sire genetic evaluations for conformation and functional herd life of daughters. J. Dairy. Sci. 77:844-854.

Enting, H., D. Kooij, A. A. Dijkhuizen, R. B. M. Huirne, and E. N. Noordhuizen-Stassen. 1997. Economic losses due to clinical lameness in dairy cattle. Livest. Prod. Sci. 49:259-267.

Faheti, J., A. Stella, J.J. Shannon, and P. J. Boettcher. 2003. Genetic parameters for feet and leg traits evaluated in different environments. J. Dairy. Sci. 86:661-666.

Forabosco, F., A. F. Groen, R. Bozzi, J. A. M. Van Arendonk, F. Filippini, P. Boettcher, and P. Bijma. 2004. Phenotypic relationships between longevity, type traits, and production in Chinana beef cattle. J. Anim. Sci. 82: 1572-1580.

Gadberry, S., J. Jennings, H. Ward, P. Beck, B. Kutz, and T. Troxel. 2016. Beef cattle production. https://www.uaex.edu/publications/pdf/mp184/MP184.pdf. (Accessed May 15, 2017.)

Hahn, M. V., B. T. McDaniel, and J. C. Wilk. 1984. Genetic and environmental variation of hoof characteristics of Holstein cattle. J. Dairy Sci. 67:2986-2998.

Holstein Association USA, Inc. 2016. Linear descriptive traits. http://www.holsteinusa.com/pdf/print_material/linear_traits.pdf. (Accessed May 16, 2017.)

Holstein Association USA, Inc. 2017. Linear type evaluations. http://www.holsteinusa.com/genetic_evaluations/ss_linear.html. (Accessed May 22, 2017.)

Jeyaruban, G. B. Tier, D. Johnston, and H. Graser. 2012. Genetic analysis of feet and leg traits of Australian Angus cattle using linear and threshold models. Anim. Prod. Sci. 52:1-10.

Kossaibati, M. A., R. J. Esslemont, and C. Watson. 1999. The costs of lameness in dairy herds. In Proceedings of the National Cattle Lameness Conference p. 2.

Laursen, M. V., D. Boelling, and T. Mark. 2008. Genetic Parameters for claw and leg health, foot and leg conformation, and locomotion in Danish Holsteins. J. Dairy Sci. 92:1770-1777.

Onyiro, O. M., and S. Brotherstone. 2008. Genetic analysis of locomotion and associated conformation traits of Holstein-Friesian dairy cows managed in different housing systems. J. Dairy Sci. 91:322-328.

Perez-Cabal, M. A., C. Garcia, O. Gonzalez-Recio, R. Alenda. 2005. Genetic and phenotypic relationships among locomotion type traits, profit, production, longevity, fertility in Spanish dairy cows. J. Dairy. Sci. 89: 1776-1783.

Politiek, R. D., O. Distl, T. Fjeldaas, J. Heeres, B. T. McDaniel, E Nielsen, D. J. Peterse, A. Reurink, and P. Strandberg. 1986. Importance of claw quality in cattle: review and recommendation to achieve genetic improvement. Rep. E.A.A.P Working Group on “claw quality in cattle”. Livest. Prod. Sci. 15:133-152.

Rogers, G. W. 1993. Index selection using milk yield, somatic cell score, udder depth, teat placement, and foot angle. J. Dairy. Sci. 76:664-1992.

USDA. 2007. Dairy 2007. Part I: Reference of Dairy Cattle Health and Management Practices in the United States, 2007 USDA-APHIS-VS, CEAH. Fort Collins, CO.

Van Der Waiij, E. H., M. Holzhauer, E. Ellen, C. Kamphuis, and G. de Jong. 2005. Genetic parameters for claw disorders in Dutch dairy cattle and correlations with conformation traits. J. Dairy Sci. 88:3672-3678.

Van Dorp, T. E., P. Boettcher, L. R. Schaeffer. 2004. Genetics of locomotion. Livest. Prod. Sci. 90:247-253.

Vollema, A. R., Groen, A. F. 1997. Genetic correlations between longevity and conformation traits in an upgrading dairy cattle population. J. Dairy. Sci. 80:3006-3014.

Wiggans, G. R. 1991. National genetic improvement programs for dairy cattle in the United States. J. Anim. Sci. 69: 3853-3860.

Wiggans, G. R., L. L. M. Thornton, R. R. Neitzel, and N. Gengler. 2006. Genetic parameters for Brown Swiss and Guernseys. J. Diary. Sci. 89:4895-4900.

Wright, J. R., G. R. Wiggins, C. J. Muenzenberger, and R. R. Neitzel. 2013. Short communication: genetic evaluation of mobility for Brown Swiss dairy cattle. J. Dairy. Sci. 96:2657-2660.

Chapter 2 - Estimation of Genetic Parameters for Feet and Leg Structure Traits in Beef Cattle

Introduction

Feet and leg structure is frequently discussed as having an impact on the longevity of beef cattle. Industry rhetoric is plentiful with statements linking feet and leg structure traits with associations with longevity and breeding soundness in beef cattle, yet literature is sparse regarding the subject matter (Daniel and Kreise-Anderson, 2013; Gadberry et al., 2015). Yet, research in Italy with Chianina cattle found cattle with a straighter angle to the hock are 59% more likely to be culled than an animal with an ideal set to the hind leg (Forabosco et al., 2004). Increasing longevity can reduce costs associated with beef production, specifically input costs related to replacement heifer development (Cundiff et al., 1992). A low to moderate heritability for feet and leg traits have been found in Angus cattle in Australia (h^2= 0.10 to 0.40) (Jeyaruban et al., 2012). Currently, the Australian Angus Association (2017) is utilizing genetic selection tools for feet and leg structure traits.

Issues related to feet and leg structure are well-studied in the dairy industry. Nearly 25% of dairy cows are treated for foot disorders every year, therefore costs and economic losses accrue because of medication and veterinary expenses, reduced milk yield, suppressed feed intake, and increased labor (Politiek et al., 1986; Kossaivati et al., 1999). Therefore, producers cull cattle with lameness and foot issues frequently and culling due to lameness ranks 4th in terms of prevalence rate behind infertility, mastitis, and poor performance (USDA, 2007).

Jersey cattle were the first dairy breed to include type traits, which included feet and leg traits, into genetic evaluations in 1978 and Holstein followed in 1979 (Wiggans, 1991). Holstein

Association USA, Inc (2017) identified that for every 1.0 increase in Feet and Leg Composite Standard Transmitting Ability (STA) you should expect an increase of 0.3 productive life STA.

Ultimately, improved feet and legs may improve the longevity and profit of beef cattle. The objective of this research is to estimate the genetic parameters of feet and leg traits, identify relationships within feet and leg traits, and between production traits and feet and leg traits in Red Angus cattle.

Materials and Methods

Data were obtained on 1885 cattle from August 2015 through April 2017 on purebred Red Angus cattle at operations located in the Midwestern United States by trained observers from Kansas State University. Data was collected using a protocol (#3635) approved by the Institutional Animal Care and Use Committee at Kansas State University. The traits observed were body condition score (BCS), front hoof angle (FHA), front heel depth (FHD), front claw shape (FCS), rear hoof angle (RHA), rear heel depth (RHD), rear claw shape (RCS), size of hoof (Size), front side view (FSV), front view knee orientation (Knee), front view hoof orientation (FHO), rear leg side view (RSV), rear leg rear view (RV), and composite feet and legs rank (Comp). All scores were assigned subjectively and each animal was scored once by at least two observers. Body condition score was ranked 1 to 9 (BIF, 2016). Front hoof angle, FHD, FCS, RHA, RHD, RCS, Size, FSV, Knee, FHO, RSV, and RV were scored as intermediate optimum traits on a scale of 0 to 100. The Comp score was ranked 0 to 50, where 0 is unsound feet and legs and 50 is the most ideal feet and legs. See Figure 2.1 to 2.11 for examples of the scoring system utilized for each trait.

The Red Angus Association of America provided a three-generation pedigree of each animal scored. In the pedigree file, there was 13,306 animals including: 3157 sires, 1282 sire of sires, 2249 dam of sires, 8724 dams, 2467 sire of dams, and 5913 dam of dams. Contemporary group (n=48) was defined as herd in which the animal was scored and birth year. Records were removed if they were only scored by one observer or did not have a corresponding registration number to match the identification number. The final dataset used for data analysis consisted of 1720 Red Angus animals.

A bivariate animal model was utilized with additive genetic and residual effects fit as random. Fixed effects included contemporary group and a covariate for age in months. The bivariate animal model was:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} X_1\beta_1 \\ X_2\beta_2 \end{bmatrix} + \begin{bmatrix} Z_1u_1 \\ Z_2u_2 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$$

where Y_i was a vector of observations for trait 1 and trait 2, X_i as an incidence matrix relating observations to the fixed effects, β_i was a vector of fixed effects for contemporary group and age, Z_i was an incidence matrix relating observations to additive genetic effects, u_i was a vector of additive genetic effects, and e_i was a vector of random residuals. Ideally all 14 traits would be fit in the linear model, however, the model was too large and not computationally feasible for the memory available. Therefore, the feet and leg traits were evaluated against one another in 169 bivariate analyses. The calculation of heritability is derived from the average of the 13 additive variances and 13 phenotypic variances that resulted from each individual bivariate analysis.

The structure for residual (co)variances was:

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} I\sigma_{e1}^2 & I\sigma_{e1,e2} \\ I\sigma_{e2,e1} & I\sigma_{e2}^2 \end{bmatrix}$$

the matrix I represents an identity matrix with dimensions equal to the number of records for each trait. Error covariances between trait one and trait two can be calculated because every trait was measured on every animal. The structure for genetic (co)variances was:

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} A\sigma_{u1}^2 & A\sigma_{u1,u2} \\ A\sigma_{u2,u1} & A\sigma_{u2}^2 \end{bmatrix}$$

the matrix A is the relationship matrix accounting for the pedigree relationships. Variances were estimated using ASREML (Ver 3.0 and Ver 4.0, VSN International, Ltd., Hemel Hempstead, UK).

Pearson Correlation Coefficients and Spearmans Correlation Coeffecients between breeding values of the feet and leg traits and EPD's from the Red Angus Association of America (RAAA) were calculated utilizing SAS 9.2 (SAS Institute Inc., Cary, NC). Breeding values were grouped into 3 groups of traits, front limb traits (FHA, FHD, FSV, KNEE, FHO, and COMP), rear limb traits (RHA, RHD, RCS, RSV, RV, and COMP), and the final group that included BCS, FCS, SIZE, and COMP. The front limb and rear limb traits were fit in a linear model where each significant correlation between the traits within the model were fixed and the final group was fit without any correlations to find the respective breeding values to be evaluated against the breeding values released from the RAAA. Ideally, the traits would be evaluated in one model, however, only groups of 6 or less were computationally feasible, and the traits with the strongest correlations were grouped together.

Results and Discussion

Mean, standard deviation, minimum, and maximum for each trait scored is displayed in Table 2.1. A total of 1,217 females and 503 males were scored and the distribution of age on all animals, females, and males is described in Figures 2.12, 2.13, and 2.14. Only males 2 years old and younger were scored, because few production systems would possess large contemporary groups of bulls over 24 months. Females scored ranged from less than 1 year to 18 years old. Most scores on females were recorded on heifers or young cows with the number of scores decreasing with increasing age. Figure 2.15 to 2.28 illustrates the distribution of the scores on all 14 traits. Most scores on each trait are centered around the mean.

A range and average of estimates, which are calculated from multiple bivariate analyses, of additive genetic variance are displayed in Table 2.2. Body Condition Scores appear to have the lowest average additive genetic variance at 0.016 and RSV has the highest at 7.71. Estimates for residual variance are located in Table 2.3, where BCS possessed the lowest average residual variance at 0.129 and FCS displayed the highest at 23.84.

Heritability

An average and range of the heritabilities for the 14 traits scored are found in Table 2.4. In most cases the average heritabilities are similar to those previously reported in the literature.

Heritability estimates for FHA and RHA are 0.20 and 0.19, respectively. Jeyaruban et al. (2012) found slightly higher estimates using a similar scoring system and a linear animal model (FHA= 0.32 and RHA= 0.29). Jeyaruban et al. (2012) regrouped the scores by condensing scores, 1 to 9, into scores 1 to 3, and found similar estimates (FHA = 0.17 and RHA = 0.26). Therefore, the larger or more granular scoring system appears to better describe the additive genetic variance versus a less granular scale. A threshold animal model run by Jeyaruban et al. (2012) reported heritabilities ranging from 0.35 to 0.50. The estimates of FHA and RHA heritability are higher versus estimates in dairy cattle populations which ranged from 0.09 to 0.13 (Fatehi et al., 2003; Van Dorp et al., 2004; Wiggans et al., 2006; Perez-Cabal et al., 2006; Onyiro and Brotherstone, 2008; Laursen et al., 2009; Wright et al., 2013). The most similar heritability estimate found in the literature was a study performed in crossbred Holstein cattle (0.18; Van Der Waaij et al. 2005).

Front heel depth and RHD had heritabilities of 0.17 and 0.25. Fatehi et al. (2003) reported a single score for front and rear hooves, which has lower heritability estimates ranging from 0.06 to 0.09. Hahn et al. (1984) found the heritability of FHD and RHD to be 0.58 and 0.19, respectively. However, Hahn et al. (1984) physically measured the heel depth with a ruler and didn’t subjectively appraise the trait and it appears the physical measurements described more additive genetic variance versus the subjective measurements.

Heritability estimates in our study were 0.09 and 0.17 for FCS and RCS, respectively. Jeyaruban et al. (2012) found higher heritability estimates in Australian Angus using a linear model (FCS = 0.33 and RCS = 0.29) and a threshold model (FCS = 0.46 and 0.44). When Jeyaruban et al. (2012) regrouped the scores into a 1 to 3 scoring scale versus 1 to 9 and analyzed the data using a linear animal model, the heritability estimates were more similar (FCS = 0.22 and RCS = 0.16). Estimates in the current study are on the most granular scale and are the lowest, this may be due to the limited amount of phenotypic measurements.

Size of hoof was found to be the most heritable (0.36) in this Red Angus population. Hahn et al. (1984) found similar heritability estimates in Holstein cattle which ranged from 0.16 to 0.33. Even though our estimate was subjective it is similar to the heritability found in research where the area of the hoof was calculated and physically measured.

Front side view, Knee, and FHO reported very similar estimates and appeared to be moderately heritable with estimates at 0.16, 0.17, and 0.17, respectively. Body condition score appeared to be lowly heritable at 0.11.

The heritability for RSV in this population of Red Angus cattle was 0.30. In Australian Angus, much lower estimates for heritability of RSV were reported and ranged from 0.10 to 0.22 (Jeyaruban et al., 2012). Reports of heritability for RSV in dairy cattle appear to be lower at 0.14 to 0.21 (Vollema and Groen, 1997; Fatehi et al., 2004; Van Dorp et al., 2004; Van Der Waiij et al, 2005; Perez-Cabal et al., 2006; Wiggans et al., 2006; Onyiro and Brotherstone, 2008; Laursen et al., 2009; Wright et al., 2014). There is no clear explanation as to why the heritability measurement from the current study is higher than previous research in beef and dairy cattle, however it may be due the difference in the granularity of the scoring system because the current scoring system for this study is 0 to 100 and more descriptive than the other studies, but more phenotypic measurements are needed to further validate this difference.

The RV heritability estimate is 0.14 in this population. Estimates for RV in dairy and beef cattle are similar, and range from 0.11 to 0.17 (Fatehi et al., 2003; Van Der Waiij et al., 2005; Laursen et al., 2009; Jeyaruban et al., 2012). The only literature estimate available which utilized a threshold animal model reported a higher heritability for RV (0.32; Jeyaruban et al., 2012). Wright et al. (2013) reported a low heritability at 0.06 for RV in Brown Swiss cattle. Our heritability estimate for RV is similar to other estimates when calculated on a linear model, however a threshold model in Jeyaruban et al. (2012) research appears to better describe the data from the scores of RV and calculates a higher heritability versus analysis on a linear model.

Estimated heritability for COMP was 0.12. Locomotion is a similar trait that is subjectively scored and the heritability range in the literature is 0.05 to 0.11 (Van Dorp et al., 2004; Onyiro and Brotherstone, 2008).

Genetic and Phenotypic Correlations between Feet and Leg Traits

Table 2.5 contains genetic and phenotypic covariances, and Table 2.6 contains the genetic and phenotypic correlations between all 14 traits measured. Front hoof angle, FHD, RHA, and RHD were all highly genetically correlated (r = 0.85 to 0.94). Front hoof angle and FHD had a strong phenotypic relationship (r = 0.82), as did RHA and RHD (r = 0.83). A strong genetic relationship between FHA and RHA has been reported in Australian Angus cattle using a linear animal model (r = 0.87; Jeyaruban et al., 2012). The strong genetic relationships between FHA, FHD, RHA, and RHD would indicate similar genes control these traits. However, the strength of the relationship of the phenotypic scores between FHA and FHD and RHA and RHD might indicate the scorers need to better differentiate the traits or that the traits are similar and do not need to be scored separately.

Front claw shape and RCS had a genetic correlation of 0.75 and had a phenotypic correlation of 0.38. Genetic relationships with FCS and RCS with FHA, FHD, RHA, and RHD were not significant, indicating in the current population the data suggests FCS and RCS are not controlled by the same genes as FHA, FHD, RHA, and RHD. Jeyaruban et al. (2012) found a genetic correlation of 0.69 between FCS and RCS utilizing a linear animal model analysis. However, Jeyaruban et al. (2012) found stronger relationships between FHA and RHA with FCS and RCS ranging from 0.40 to 0.79. Factors including the number of animals in the genetic evaluation, scale of phenotypic measurements, and breed type may play a role in the differences between the two studies.

Front side view is correlated with FHA, FHD, Knee, and FHO (r = 0.46, 0.45, -0.59 and -0.75, respectively) Knee and FHO have a high phenotypic (r = 0.73) and genetic correlation (r = 0.95), which signifies the traits are controlled by similar genes and cattle who toe out are in at the knee. The negative phenotypic relationship (r = -0.13 and -0.24) between FSV with Knee and FHO indicates that cattle with less angle in their shoulder tend to be in at the knee with front feet toeing out. Front limb traits including FHA, FHD, FSV, Knee, and FHO appear to be genetically related, and selection on one trait should result in a change in the other traits. No previous research has focused on FSV, Knee, or FHO.

Body condition score had strong significant correlations with Size, Knee, and FHO at 0.40, -0.68, and -0.70, respectively. Literature is sparse in research regarding relationships between body condition score and feet and leg traits.

Rear leg side view has positive genetic correlations with FHA, FHD, RHA, and RHD (r = 0.51 to 0.72) and negative genetic correlations with RCS, Knee, and FHO (r = -0.36 to -0.46). Therefore, cattle with genetics for a straighter angle to the hock tended to have genetics for steeper hoof angles, deeper heel depths, more claw like shape to the hoof, in at the knee, toed out up front. Jeyaruban et al. (2012) found positive genetic correlations with FHA and RHA with RSV at 0.32 and 0.68, respectively. In literature from the dairy industry, Perez-Cabal et al. (2006) reported a strong, negative genetic correlation between FA and RLSV (-0.44); however, the interpretation would be similar because our scoring system was reverse of Perez-Cabal et al. (2006).

Rear leg rear view has positive genetic relationships (r = 0.51, 0.51, and 0.63) and positive phenotypic relationships (r = 0.21, 0.23, and 0.32) with FHD, RHA, and RHD, respectively. Jeyaruban et al. (2012) found that positive genetic and phenotypic relationships existed between RV with FHA and RHA (r = 0.02 to 0.39) in Australian Angus cattle. Wiggans et al. (2006) found a positive genetic and phenotypic relationship between foot angle and RV (r =

0.19 to 0.31) in Brown Swiss and Guernsey cattle. Therefore, cattle with more depth to their front and rear heel depth and more angle to their hoof tend to be more cow-hocked.

Studies in beef and dairy cattle suggest a genetic relationship exists between RSV and RV (Wiggans et al., 2006; Jeyaruban et al., 2012). This study did find a genetic correlation of 0.31, but it was not significant. Yet a significant phenotypic correlation was found between RSV and RV at 0.32, indicating cattle with more set to the hind leg were more cow-hocked.

The only traits exhibiting a significant genetic correlation with Comp score were RHA, RHD, FSV and RV at -0.44, -0.57, 0.87, and -0.64, respectively. Strong genetic correlations were found between foot angle and feet and legs score in dairy research ranging from 0.51 to 0.73 (Perez-Cabal et al., 2006; Van Der Waaij et al., 2005). Van der Waaij et al. (2005) found a positive phenotypic correlation between feet and legs and foot angle at 0.42. The scoring system for foot angle in dairy cattle is reversed compared to the ranking utilized in the current research, therefore the interpretation is similar. Thus, cattle with a steeper hoof angle tend to have a better Comp score. Rear leg rear view was positively correlated to the feet and legs score reported by Van Der Waaij et al., (2005) both genetically and phenotypically (r = 0.79 and 0.56). Again, differences in the scoring system result in opposite signs, however, both can be interpreted as cattle with sickled hind legs have poorer scores for overall feet leg structure subjective evaluation. Literature from dairy industry reports negative correlations exist between feet and leg scores and RLSV (r = -0.36 to -0.52; Vollema and Groen, 1997; Van Der Waaij et al.). This study found a negative genetic correlation (0.40), however the value is not statistically significant and a larger data set might assist with validating the correlation.

Correlations between Feet and Legs and Production Traits

Correlations of feet and leg traits with production traits and EPD's including adjusted birth weight (BWADJ), adjusted weaning weight (WWADJ), adjusted yearling weight (YWADJ), post weaning gain (PWG), birth weight EPD, (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughters milk EPD (Milk), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), maternal calving ease EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID) were calculated.

Table 2.7 and 2.8 contain the Pearson correlation coefficients (r) and Spearman (r_s) correlation coefficients between front limb traits (FHA, FHD, FSV, KNEE, FHO, and Comp), productions traits, and EPD's. Front hoof traits had little to no association with production traits and EPD's. The ME EPD showed slightly negative relationships with FSV, KNEE, and FHV (r = -0.15, -0.19, and -0.21; r_s = -0.12, -0.19, and -0.21) and positive relationships with FHA, FHD, and Comp (r = 0.10, 0.14, and 0.26; r_s = 0.11, 0.15, and 0.23). A slight positive relationship with STAY and FSV, Knee, and FHV was found (r = 0.16, 0.11, and 0.12; r_s= 0.20, 0.09, and 0.11) and a slight negative relationship with Comp and STAY at r = -0.11. FHD appeared to have a slight negative relationship with BW, WW, and YW (r = -0.18, -0.11, and -0.15; r_s= -0.17, -0.12, and -0.17). Front Side View exhibited a positive relationship with WW and YW (r = 0.10 and 0.13; r_s= 0.12 and 0.17). Also, the ranking relationship between FSV and STAY, HERD, and GRID were slightly positive (r_s= 0.20, 0.23, and 0.16). The relationship between FSV was the strongest with STAY (r = 0.16; r_s= 0.20) versus all other traits and indicates cattle who possess the genetics for greater angle of the shoulder tend to have a higher STAY.

Table 2.9 and 2.10 show the relationships between rear limb traits (RHA, RHD, RCS, RSV, RV, and Comp), production traits and EPD's. Rear leg traits showed very little to no association with the production traits and EPD's analyzed. The strongest positive relationships found were between RSV and STAY and HERD (r = 0.11 and 0.12; r_s= 0.12 and 0.15, respectively). The strongest negative relationship was between RCS with STAY and HERD (r = -0.12 and -0.11; r_s= -0.14 and -0.11). The lack of strong correlations between rear leg traits, production traits, and EPD's indicates a producer can improve feet and leg traits, while selecting for desirable production traits and EPD's with little consequence. The correlations with EPD's does not represent a true genetic correlation, rather these correlations describe the strength of the linear relationship of the EPD's between the two traits evaluated

Dairy industry literature features slight negative correlations between RSV with productive life and functional herd life (r = -0.01 to -0.21; Vollema and Groen, 1997; Perez-Cabal et al, 2006), indicating cattle with straighter rear legs tend to live longer and more productive lives. The current study found a positive correlation between RSV and STAY (r = 0.11 and r_s= 0.12), indicating cattle with more angle to the hock and hind should remain in the herd longer. Forabosco et al. (2004) found that Italian Chianina cattle with a straighter hind leg are 59% more likely to be culled versus an ideal set to the hind leg. Cattle with a slightly more sickled hock are only 3% more likely to be culled versus an ideal set to the hind leg. The correlations reveal only slight associations between RSV and Stay, however the differences in sign may be due to differences in environment and management practices between the beef and dairy industry. Since the correlations are modest, they may reinforce the idea that RSV is an intermediate optimum trait because either extreme could result in culling from the herd, and the differences in environment and the surface the animal lives on may explain the slight associations with length of life.

In Table 2.7 and 2.9 FHA and RHA have a correlation with STAY at -0.04 and 0.004, respectively. This is similar to the results of Perez-Cabal et al. (2006), which reported low correlations between foot angle and productive life and functional herd life (0.03 and 0.03, respectively). This could indicate that selection on foot angle should have little to no influence on STAY.

Table 2.11 and 2.12 reveal the correlations between BCS, FCS, Size, and Comp with production traits and EPD's. Body condition score appears to be slightly correlated with WWADJ, YWADJ, PWG, BW, WW, YW, HPG, CEM, STAY, and HERD (r = 0.09, 0.19, 0.20, 0.10, 0.18, 0.14, -0.14, -0.20, -0.13, and -0.13; r_s= 0.10, 0.19, 0.22, 0.11, 0.20, 0.16, -0.13, -0.18, -0.14, and -0.12, respectively). Therefore, cattle who have more genetic potential for increased weaning weights and yearling weights tend to have a higher BCS. More genetic potential for BCS was associated with poorer CEM, less STAY, and lower HERD. Front claw shape had slight correlations with BW, WW, YW, ME, HPG, and GRID (r = -0.08, 0.14, 0.16, 0.21, 0.10, and 0.20; r_s= -0.10, 0.12, 0.14, 0.22, 0.10 and 0.19). The strongest relationships found between all feet and leg traits, production traits, and EPD's was between Size with BWADJ, WWADJ, YWADJ, PWG, BW, WW, YW, ME, and GRID (r = 0.24, 0.30, 0.32, 0.23, 0.19, 0.36, 0.37, 0.16, and 0.24; r_s= 0.24, 0.30, 0.34, 0.27, 0.17, 0.36, 0.38, 0.14, and 0.25). Cattle with a larger circumference of hoof tend to have heavier weights and require more energy for maintenance.

When Comp was evaluated as an uncorrelated trait, relationships with production traits and EPD's ranged from r = -0.11 to 0.19 and r_s = -0.10 to 0.18. The Comp score correlations with production traits and EPD's differed depending on how it was evaluated. Composite score was evaluated with correlations between front limb traits, rear limb traits, and as an uncorrelated trait. In dairy literature feet and legs composite score has shown positive relationship with herd life (r = 0.05 to 0.32; Dekkers et al., 1994; Vollema and Groen, 1997; Perez-Cabal et al., 2006). In the current study, Comp score showed slightly positive correlations with STAY when evaluated with correlations on rear limb traits and as an uncorrelated trait (r = 0.06 to 0.08), yet when Comp is evaluated with correlated front limb traits a negative relationship is found between Comp and STAY (r = -0.11).

Moderate to low correlations between most feet and leg EPD’s, production traits, and EPD’s, simultaneous selection can occur for both feet and leg traits, production traits, and EPD’s.

Age Effects on Feet and Leg Traits

Listed on Tables 2.13 to 2.15 are the covariates for age in months for the feet and leg traits. When Comp score was evaluated as a front limb trait to find the appropriate breeding value and EPD, it was the only trait that was significantly affected by age, this could be due to that fact fewer older cows were foot scored versus younger cows with the assumption that poorer structured cows may have been culled or selected against. Age appears to have a significant effect on RHA, RCS, RSV, RV, and Comp (0.26, 0.16, 0.25, -0.18, and 0.20), meaning as the animal ages RHA becomes more open, RCS is more curled, the shoulder set is more sloping, the rear view is more bow legged, and Comp improve with age. Body Condition score appears to decrease with age (-0.03) and the size of the hoof appears to grow as the cow gets older (0.22). A larger data set could further validate these age effects because fewer older cows were scored versus younger cows.

Conclusion

Feet and legs traits were estimated to be lowly to moderately heritable in this population of Red Angus cattle. Thus, producers can select for these traits and realize genetic change. Some genetic correlations are extremely strong between feet and leg traits and may be influenced by many of the same genes, however it could be important to better train evaluators to understand the differences between the traits. There was little to no correlation between growth traits and rear limb traits, which indicate simultaneous selection may occur. Front side view, KNEE, FCS and SIZE reveal that a slight relationship exists with growth traits. EPD’s including STAY and ME have slight relationships with feet and leg traits (RCS, FSV, FHO, and RSV) and selection for one may result in genetic change on another. Further investigation the relationships between feet and leg traits with stayability and longevity is recommended.

References

Australian Angus Association. 2017. Understanding EBVs. https://www.angusaustralia.com.au/breedplan/understanding-angus-breedplan/understanding-ebvs/. (Accessed May 22, 2017.)

Beef Improvement Federation. 2016. Guidelines for uniform beef improvement programs. 9th ed. BIF, Prairie, MS.

Cundiff, L. V., R. Nunez-Dominguez, G. E. Dickerson, K. E. Gregory, and R. M. Koch. 1992. Heterosis for lifetime production in Hereford, Angus, Shorthorn, and Crossbred cows. J. Anim. Sci. 70: 2397-2410.

Daniel Jr., D. L., and L. A. Kriese-Anderson. 2013. Beef conformation basics. http://www.aces.edu/pubs/docs/A/ANR-1452/ANR-1452.pdf. (Accessed May 15, 2016).

Dekkers, J. C. M., L. K. Jairath, and B. H. Lawrence. 1994. Relationships between sire genetic evaluations for conformation and functional herd life of daughters. J. Dairy. Sci. 77:844-854.

Faheti, J., A. Stella, J.J. Shannon, and P. J. Boettcher. 2003. Genetic parameters for feet and leg traits evaluated in different environments. J. Dairy. Sci. 86:661-666.

Forabosco, F., A. F. Groen, R. Bozzi, J. A. M. Van Arendonk, F. Filippini, P. Boettcher, and P. Bijma. 2004. Phenotypic relationships between longevity, type traits, and production in Chinana beef cattle. J. Anim. Sci. 82: 1572-1580.

Gadberry, S., J. Jennings, H. Ward, P. Beck, B. Kutz, and T. Troxel. 2016. Beef cattle production. https://www.uaex.edu/publications/pdf/mp184/MP184.pdf. (Accessed May 15, 2017.)

Hahn, M. V., B. T. McDaniel, and J. C. Wilk. 1984. Genetic and environmental variation of hoof characteristics of Holstein cattle. J. Dairy Sci. 67:2986-2998.

Holstein Association USA, Inc. 2017. Linear type evaluations. http://www.holsteinusa.com/genetic_evaluations/ss_linear.html. (Accessed May 22, 2017.)

Jeyaruban, G. B. Tier, D. Johnston, and H. Graser. 2012. Genetic analysis of feet and leg traits of Australian Angus cattle using linear and threshold models. Anim. Prod. Sci. 52:1-10.

Kossaibati, M. A., R. J. Esslemont, and C. Watson. 1999. The costs of lameness in dairy herds. In Proceedings of the National Cattle Lameness Conference p. 2.

Laursen, M. V., D. Boelling, and T. Mark. 2008. Genetic Parameters for claw and leg health, foot and leg conformation, and locomotion in Danish Holsteins. J. Dairy Sci. 92:1770-1777.

Onyiro, O. M., and S. Brotherstone. 2008. Genetic analysis of locomotion and associated conformation traits of Holstein-Friesian dairy cows managed in different housing systems. J. Dairy Sci. 91:322-328.

Perez-Cabal, M. A., C. Garcia, O. Gonzalez-Recio, R. Alenda. 2005. Genetic and phenotypic relationships among locomotion type traits, profit, production, longevity, fertility in Spanish dairy cows. J. Dairy. Sci. 89: 1776-1783.

Politiek, R. D., O. Distl, T. Fjeldaas, J. Heeres, B. T. McDaniel, E Nielsen, D. J. Peterse, A. Reurink, and P. Strandberg. 1986. Importance of claw quality in cattle: review and recommendation to achieve genetic improvement. Rep. E.A.A.P Working Group on “claw quality in cattle” Livest. Prod. Sci. 15:133-152.

USDA. 2007. Dairy 2007. Part I: Reference of Dairy Cattle Health and Management Practices in the United States, 2007 USDA-APHIS-VS, CEAH. Fort Collins, CO.

Van Der Waiij, E. H., M. Holzhauer, E. Ellen, C. Kamphuis, and G. de Jong. 2005. Genetic parameters for claw disorders in Dutch dairy cattle and correlations with conformation traits. J. Dairy Sci. 88:3672-3678.

Van Dorp, T. E., P. Boettcher, L. R. Schaeffer. 2004. Genetics of locomotion. Livest. Prod. Sci. 90:247-253.

Vollema, A. R., Groen, A. F. 1997. Genetic correlations between longevity and conformation traits in an upgrading dairy cattle population. J. Dairy. Sci. 80:3006-3014.

Wiggans, G. R. 1991. National genetic improvement programs for dairy cattle in the United States. J. Anim. Sci. 69: 3853-3860.

Wiggans, G. R., L. L. M. Thornton, R. R. Neitzel, and N. Gengler. 2006. Genetic parameters for Brown Swiss and Guernseys. J. Diary. Sci. 89:4895-4900.

Wright, J. R., G. R. Wiggins, C. J. Muenzenberger, and R. R. Neitzel. 2013. Short communication: genetic evaluation of mobility for Brown Swiss dairy cattle. J. Dairy. Sci. 96:2657-2660.

Figure 2.1 Body condition score scoring system

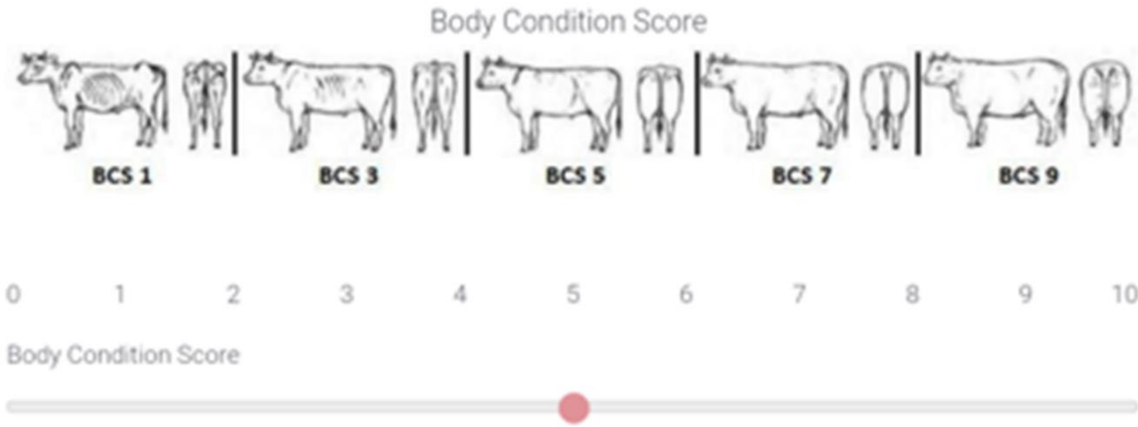

Figure 2.2 Front hoof angle (FHA) and front heel depth (FHD) scoring system

Figure 2.3 Front feet claw shape scoring system

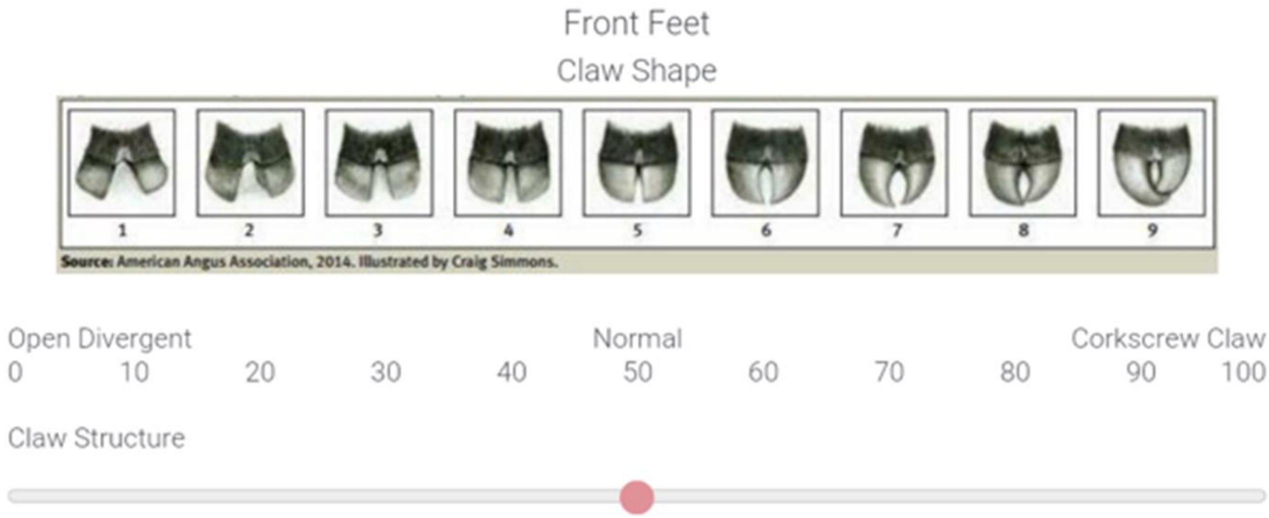

Figure 2.4 Rear hoof angle and rear hoof depth scoring system

Figure 2.5 Rear hoof claw shape scoring system

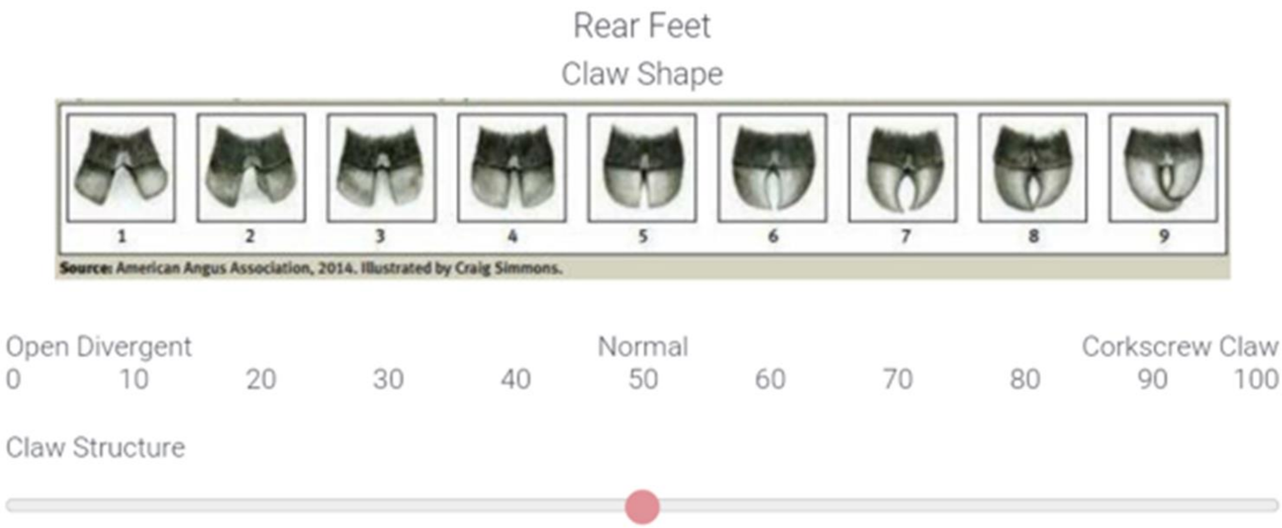

Figure 2.6 Size of hoof scoring system

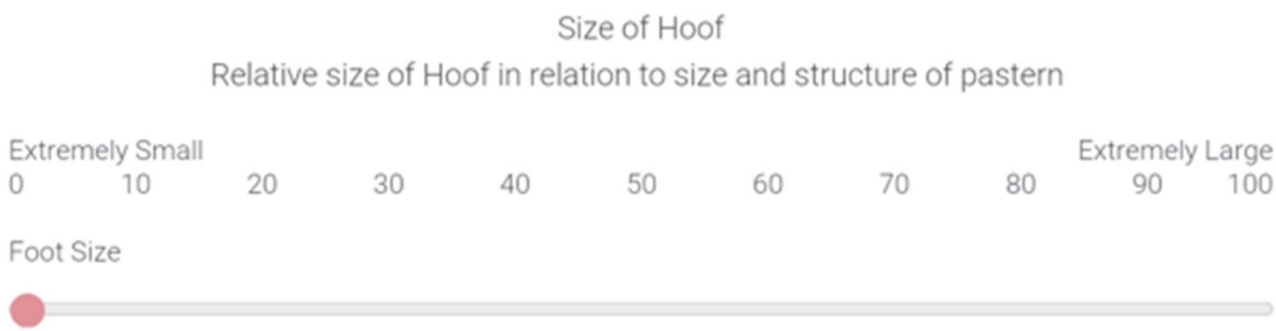

Figure 2.7 Front side view scoring system

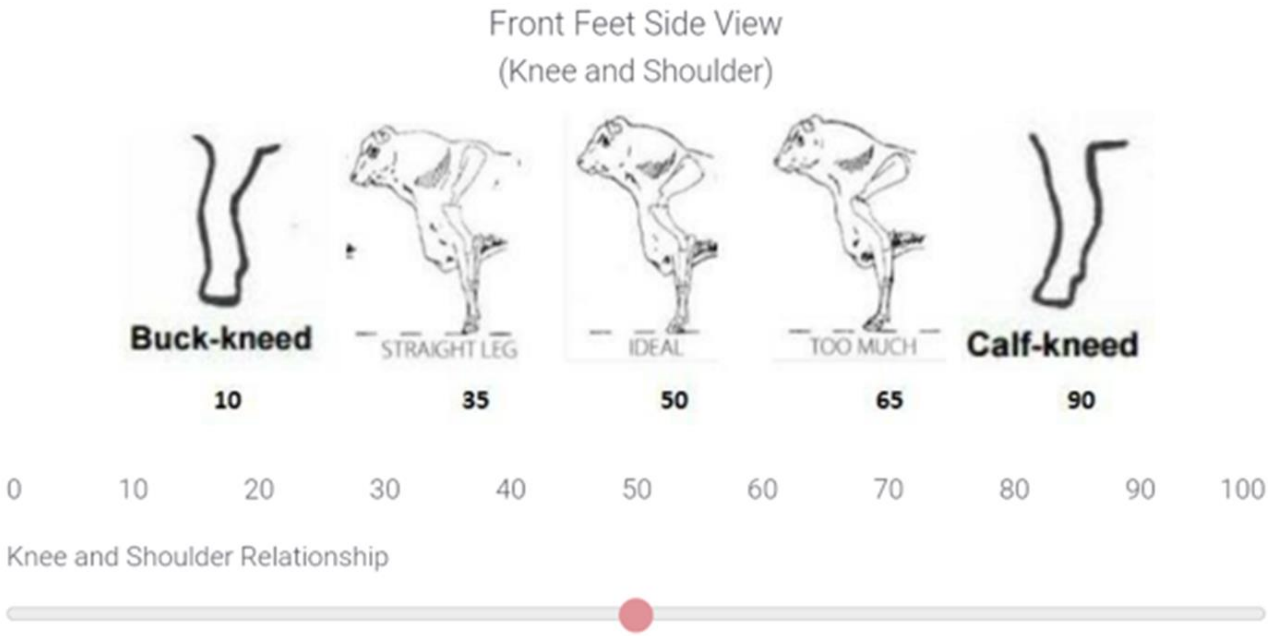

Figure 2.8 Front knee orientation and front hoof orientation scoring system

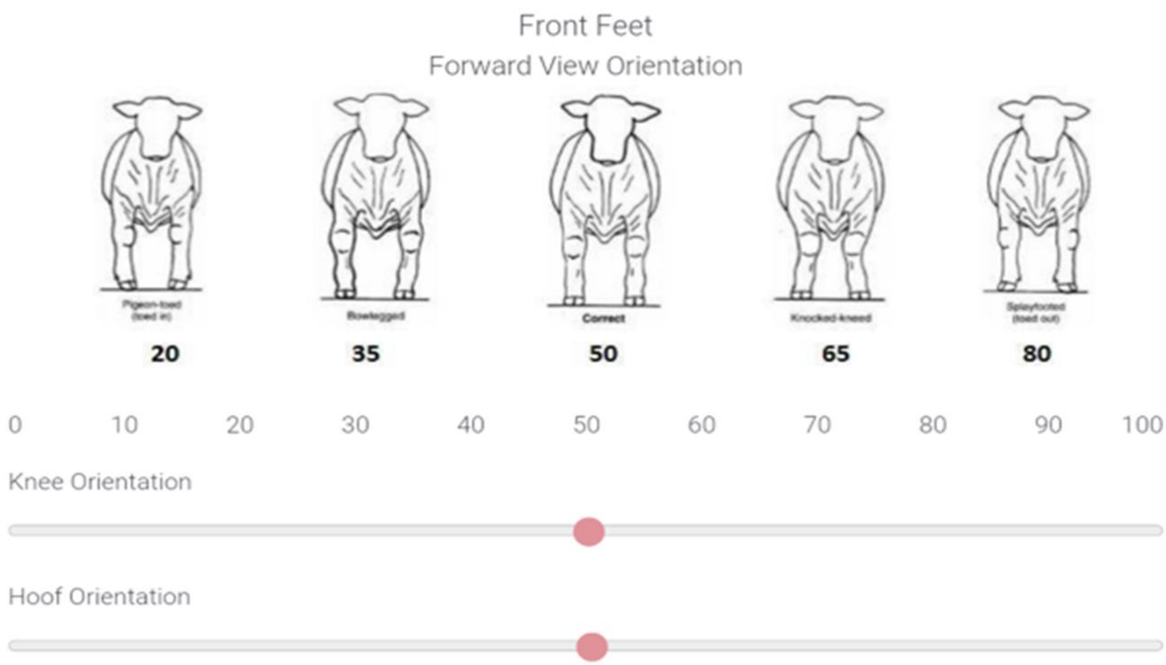

Figure 2.9 Rear leg side view scoring system

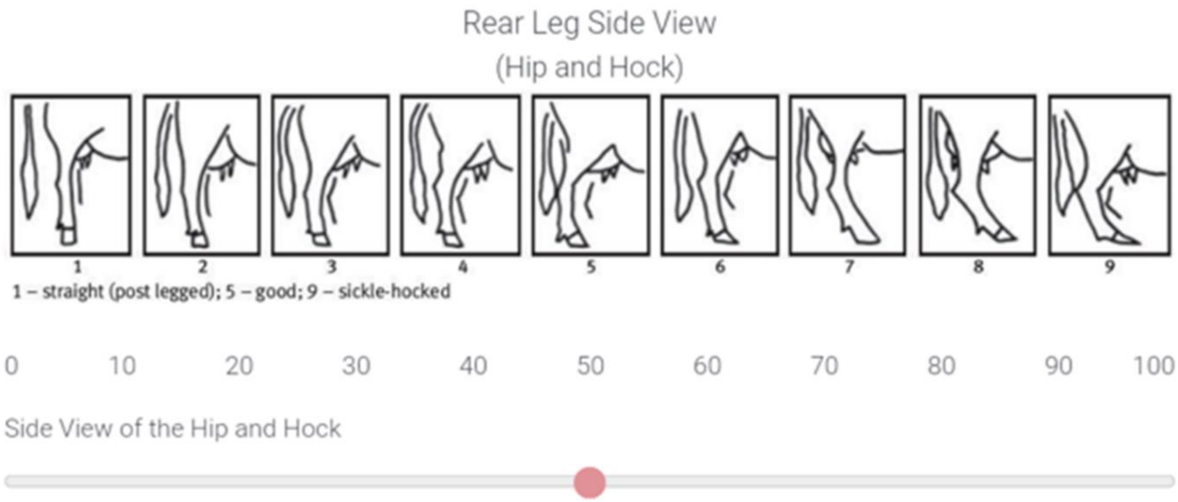

Figure 2.10 Rear leg rear view scoring system

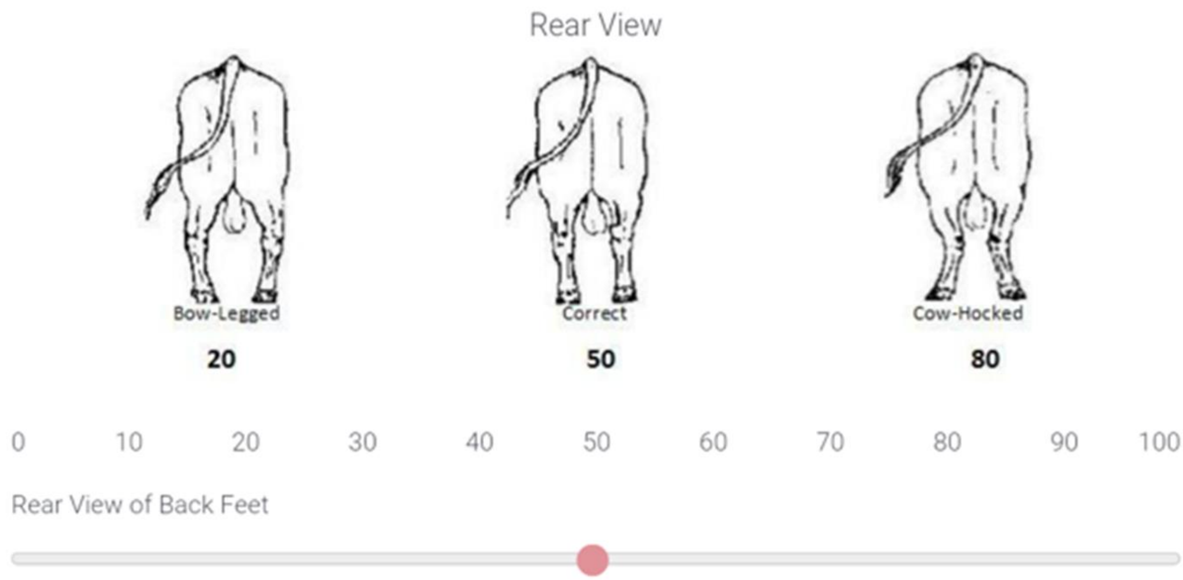

Figure 2.11 Composite feet and leg rank scoring system

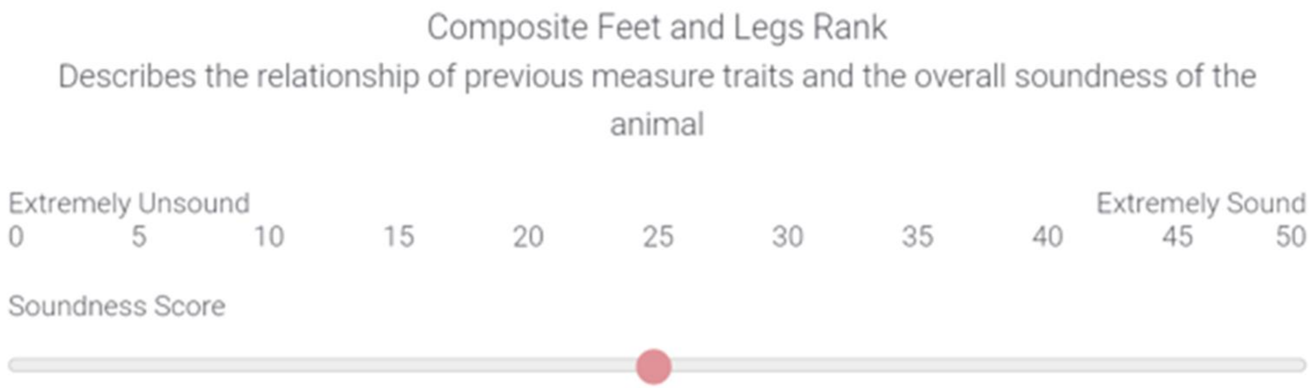

Figure 2.12 Distribution of age in years for feet and leg data for all animals

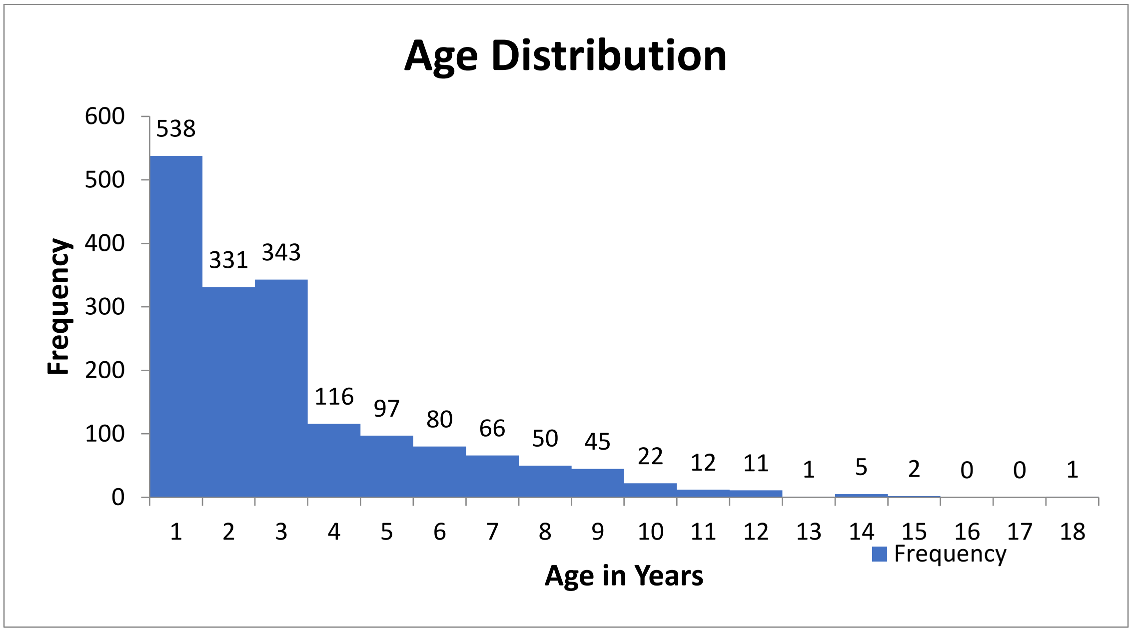

Figure 2.13 Age distribution of females scored

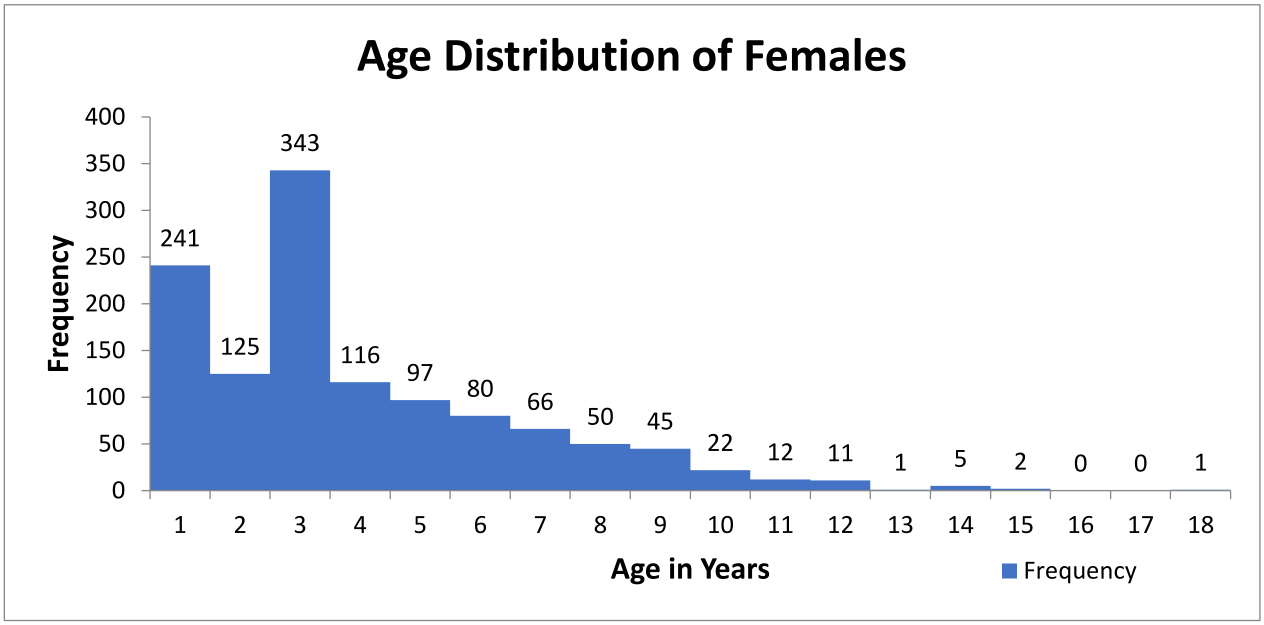

Figure 2.14 Age distribution of males scored

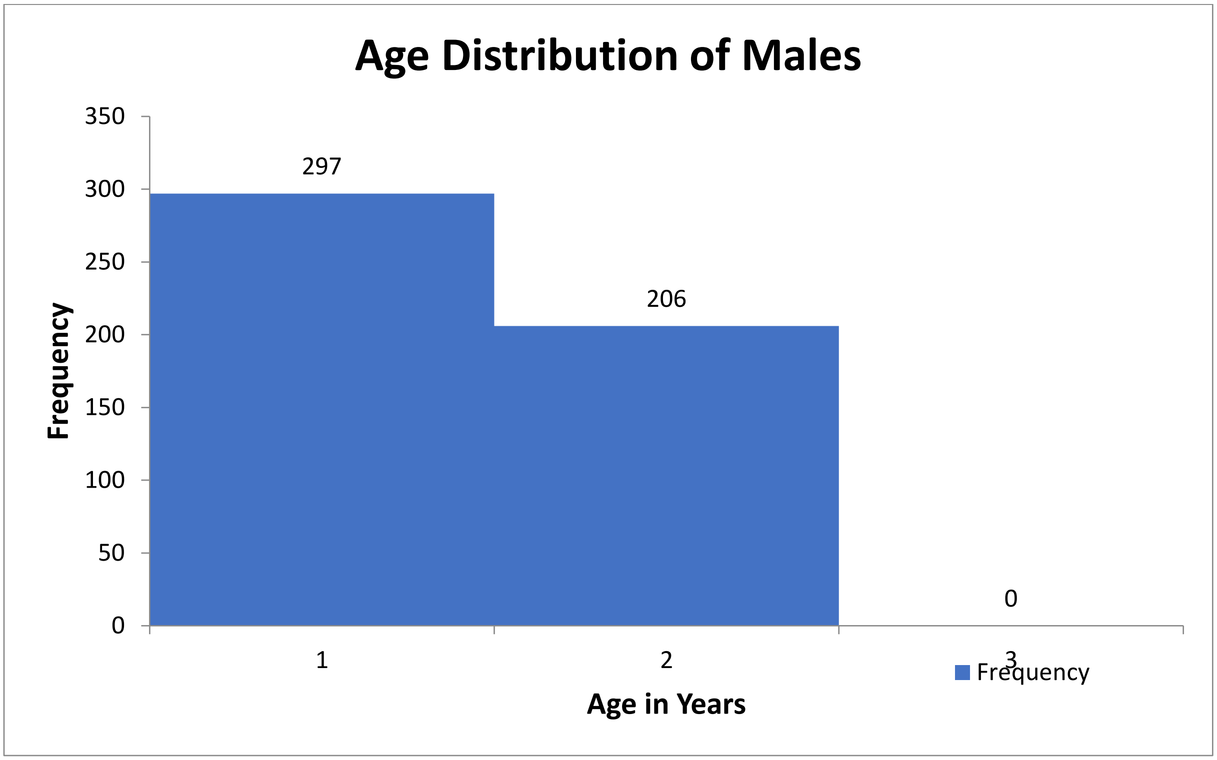

Figure 2.15 Distribution Front Hoof Angle

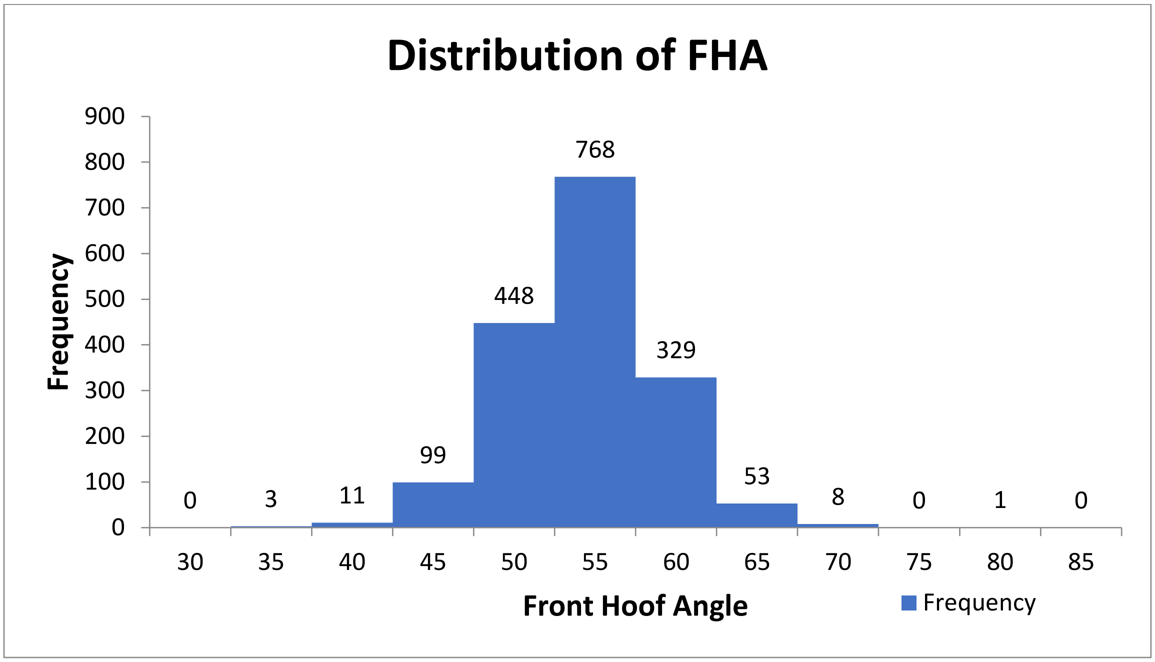

Figure 2.16 Distribution of Front Heel Depth

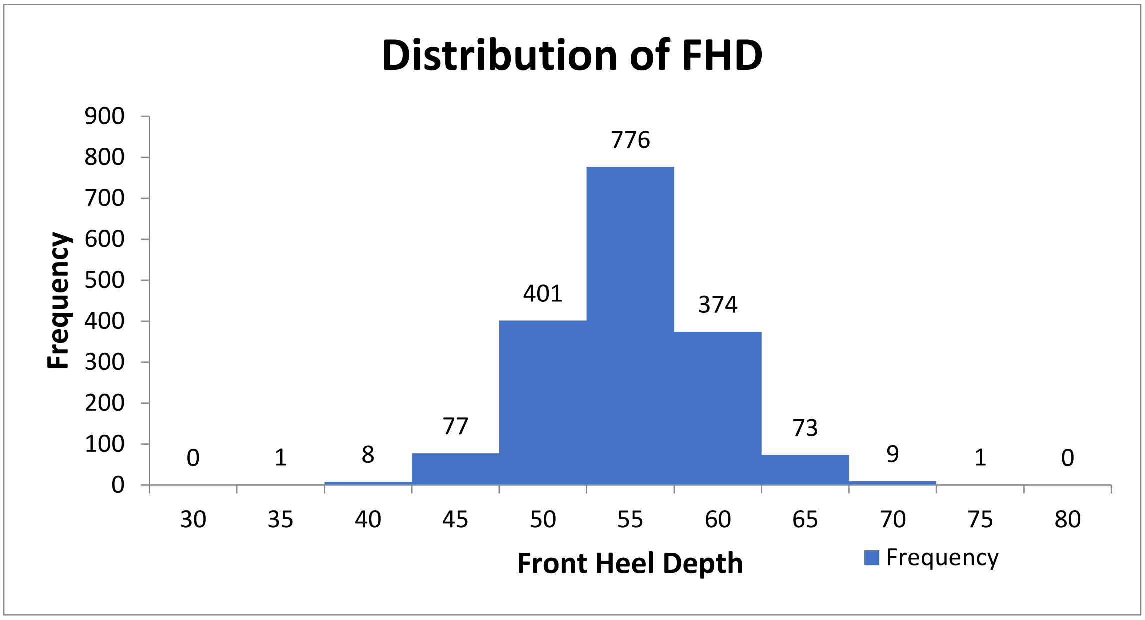

Figure 2.17 Distribution of Front Claw Shape

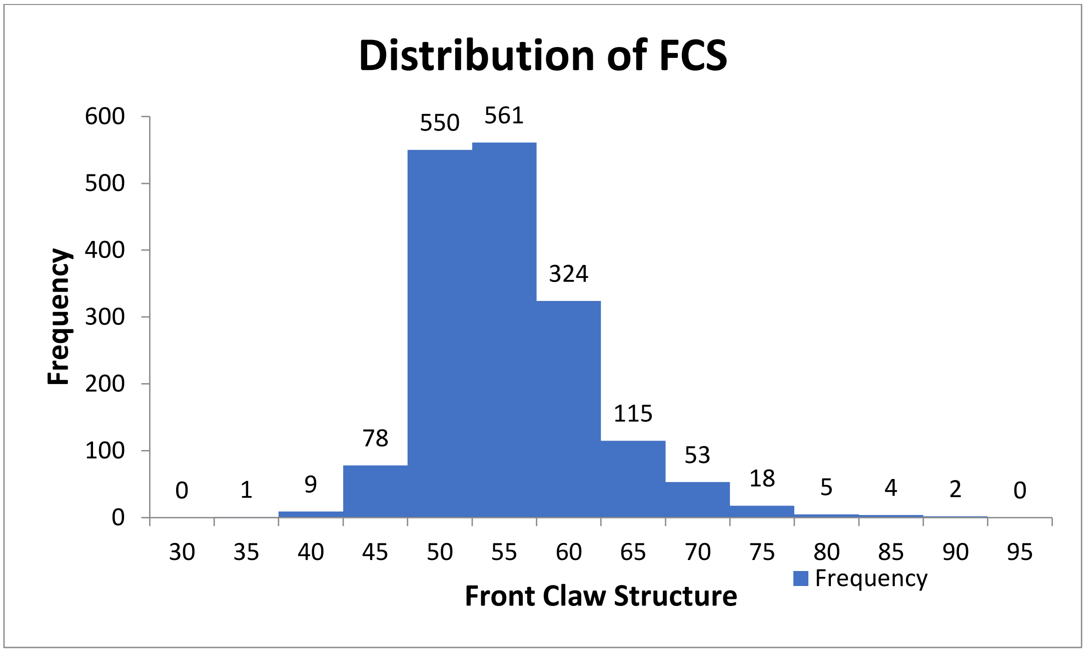

Figure 2.18 Distributions for Rear Hoof Angle

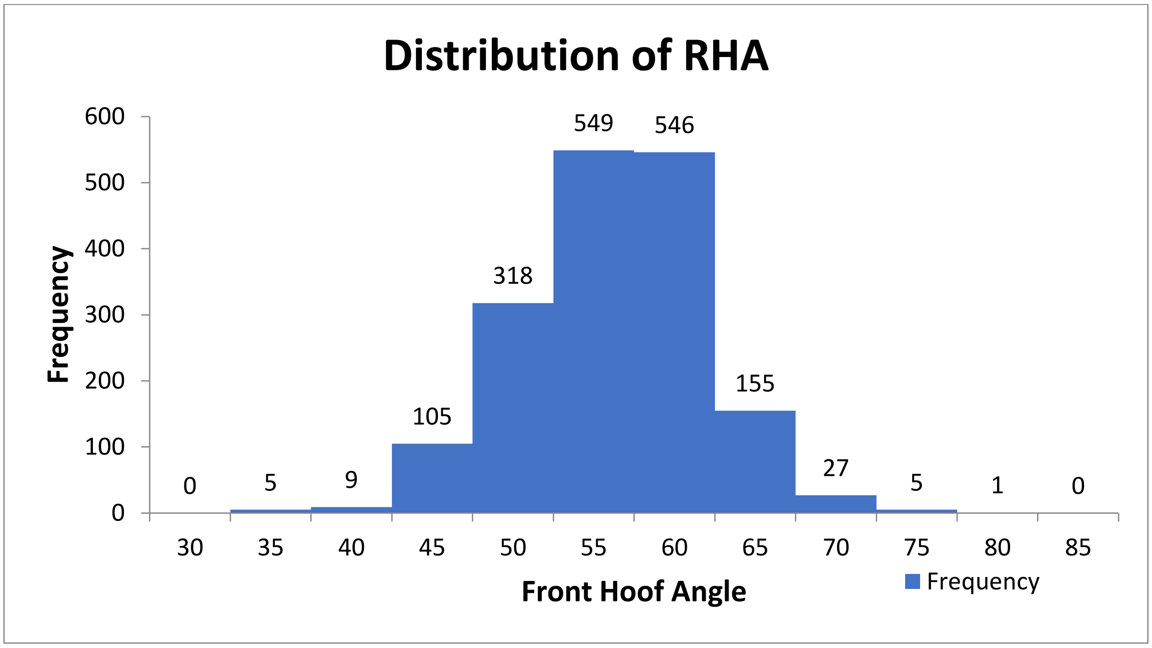

Figure 2.19 Distribution of Rear Heel Depth

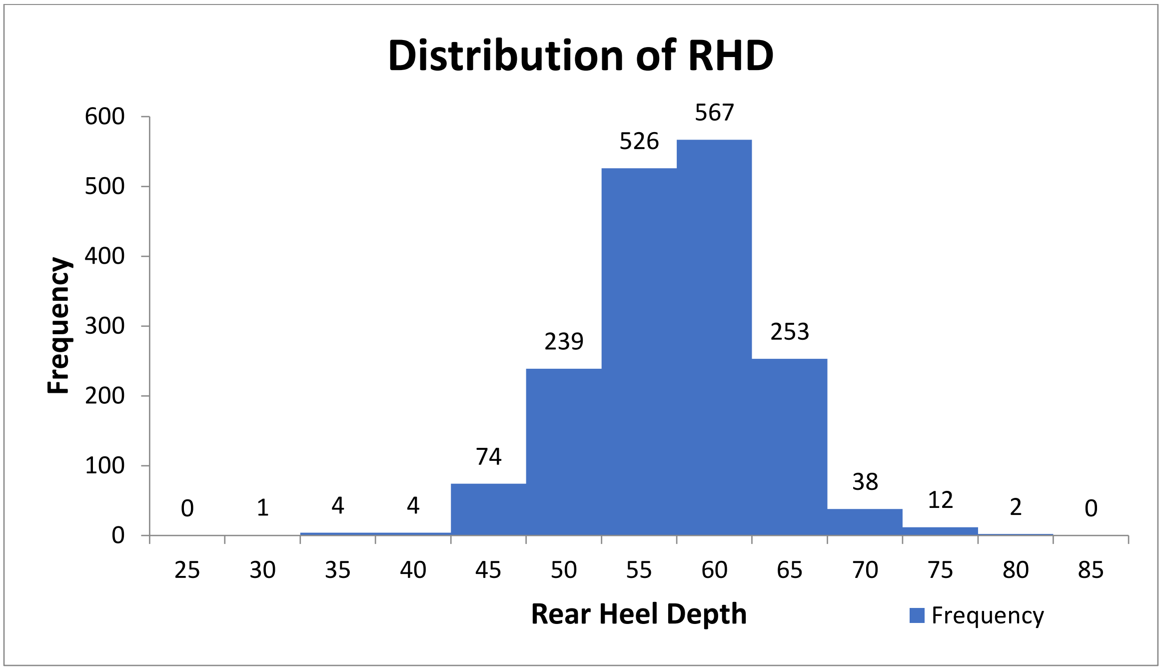

Figure 2.20 Distribution of Rear Claw Shape

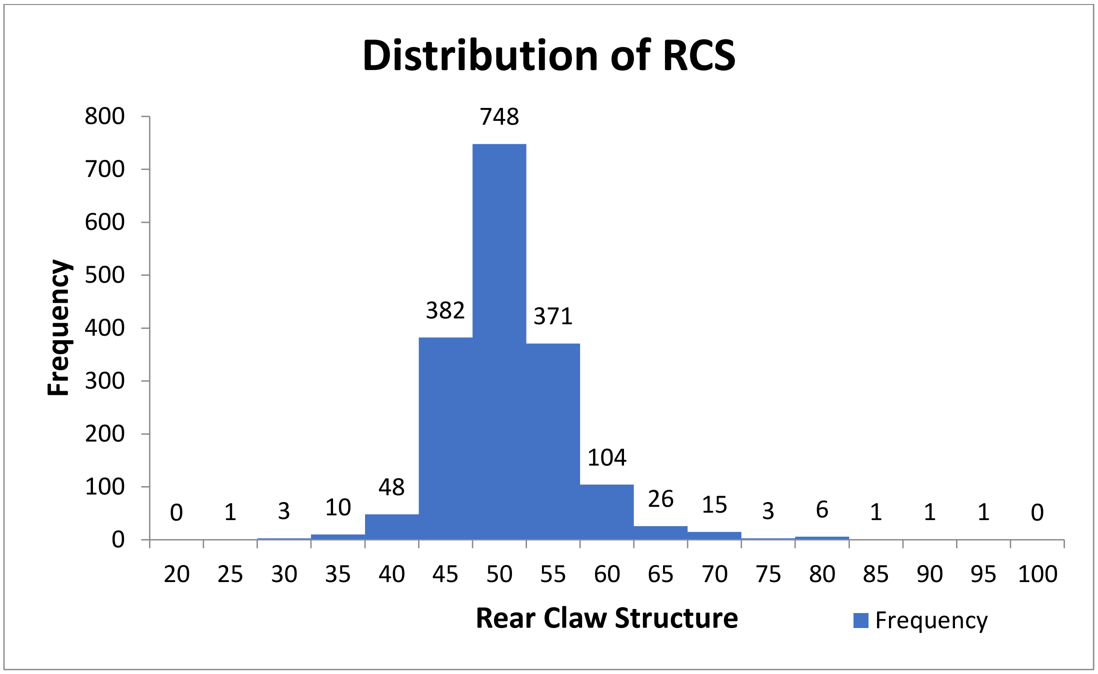

Figure 2.21 Distributions of Front Side View

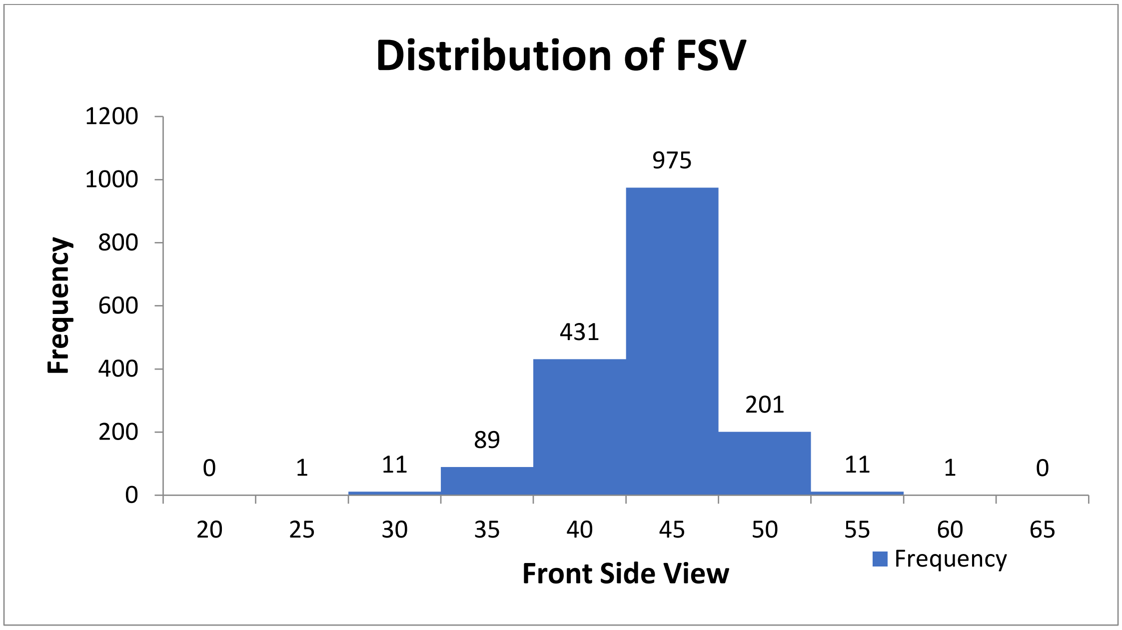

Figure 2.22 Distribution of Knee Orientation

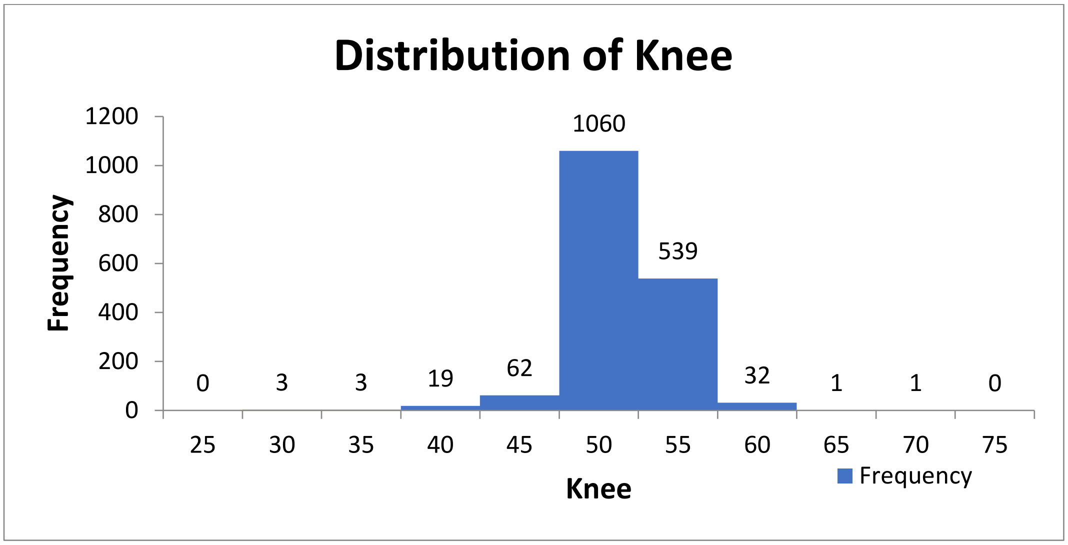

Figure 2.23 Distribution of Front Hoof Orientation

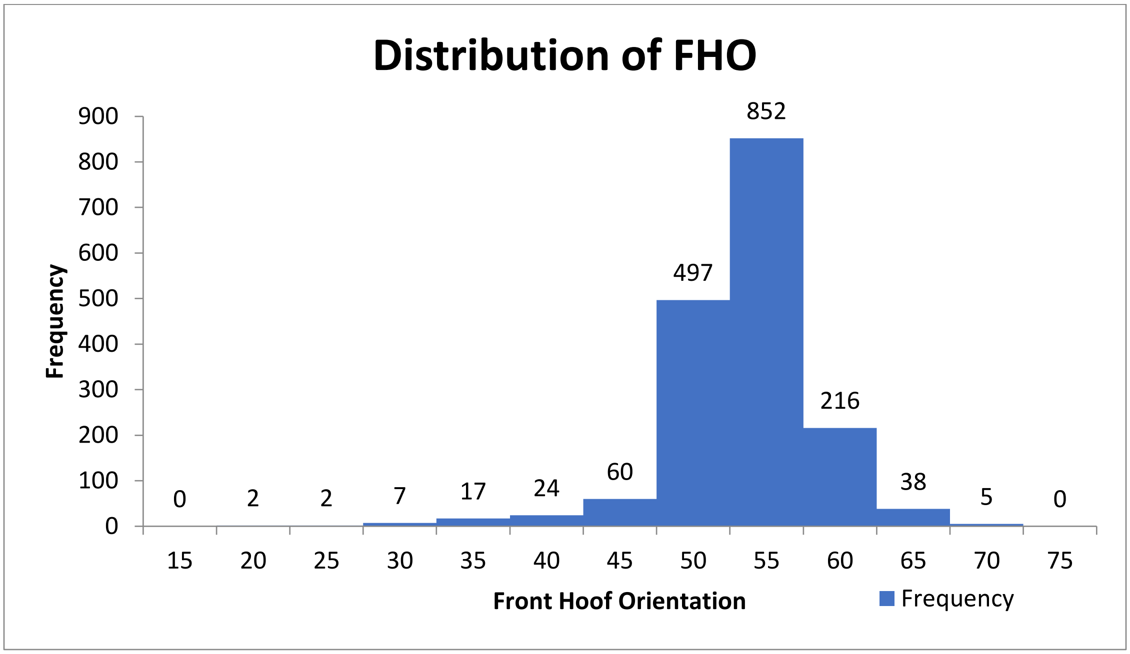

Figure 2.24 Distribution of Rear Limb Traits

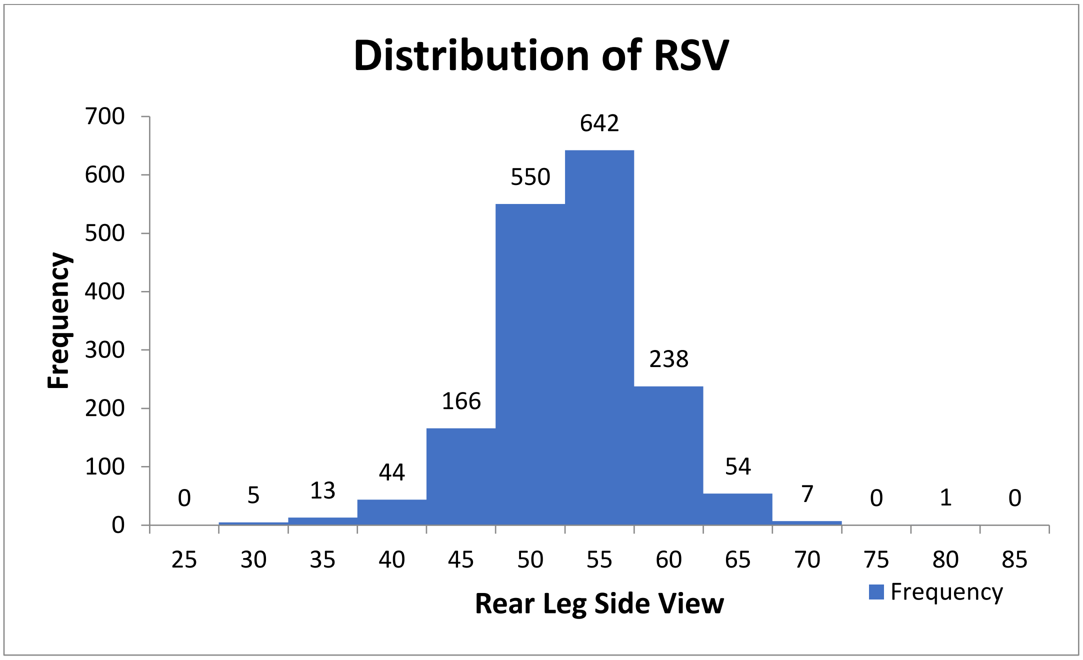

Figure 2.25 Distribution of Rear View

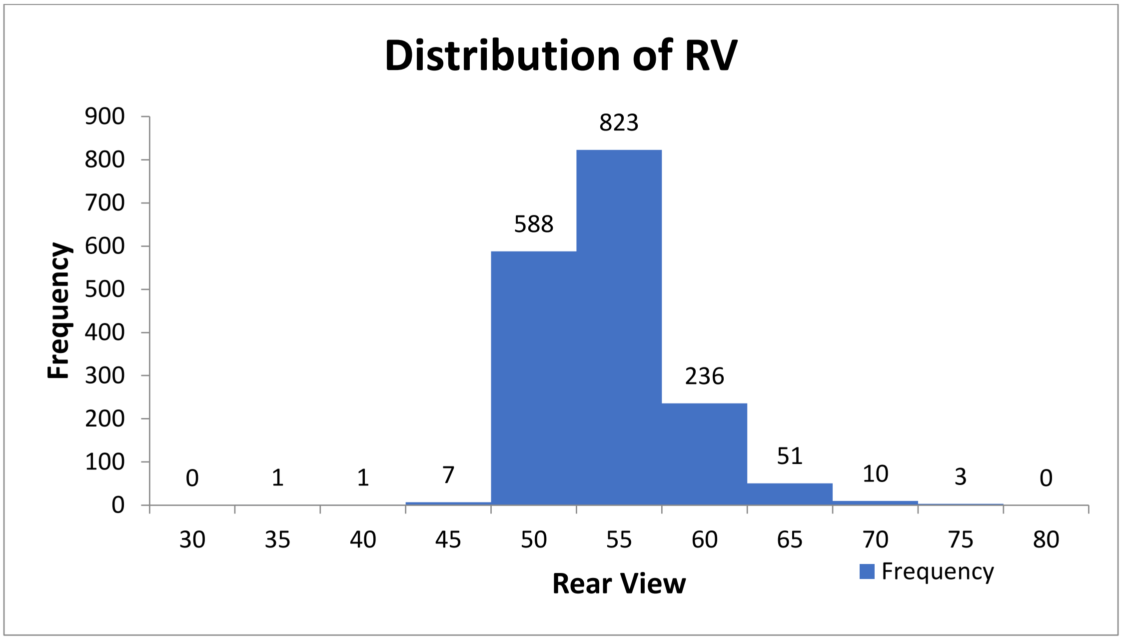

Figure 2.26 Distribution of Body Condition Score

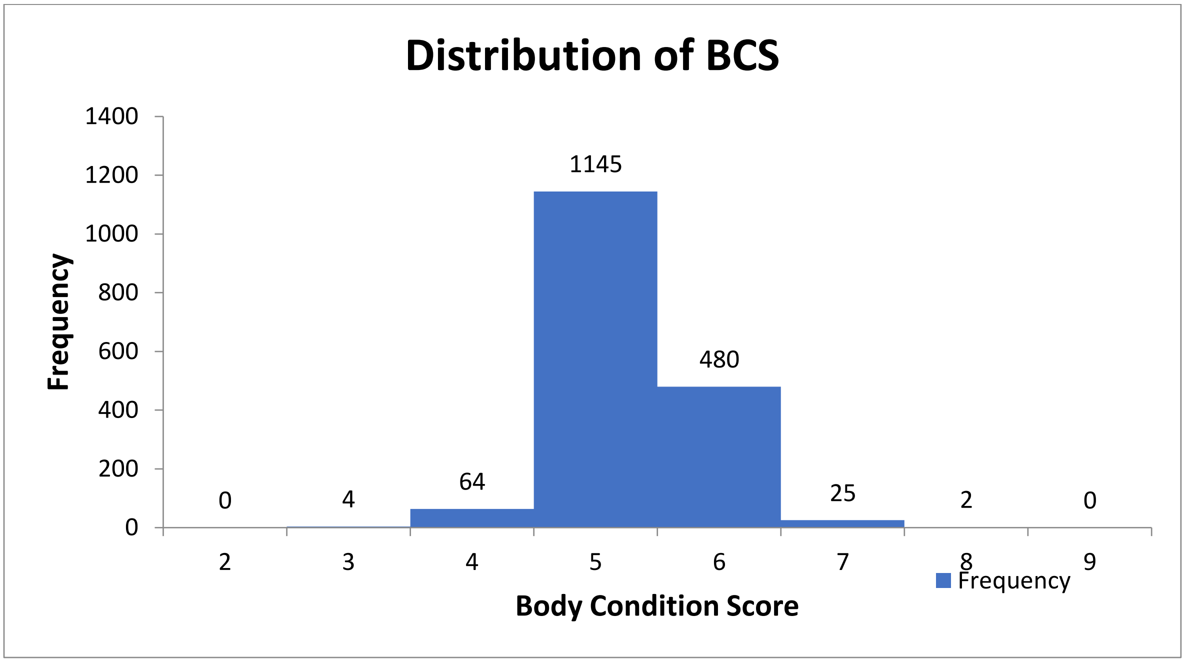

Figure 2.27 Distribution of Size of Hoof

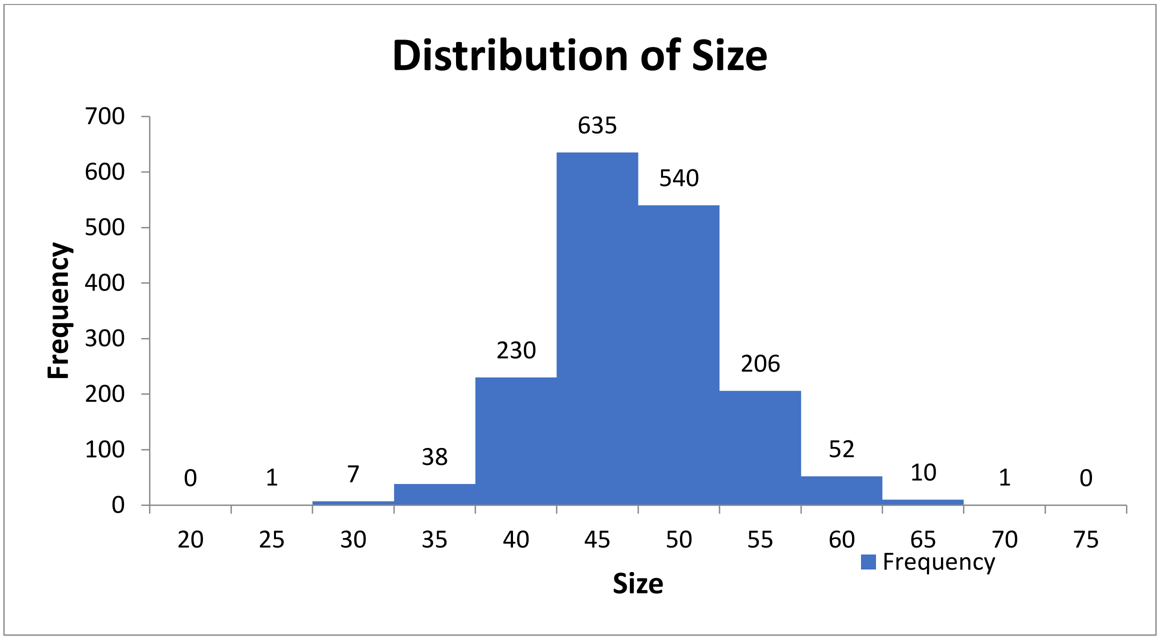

Figure 2.28 Distribution of Composite Score

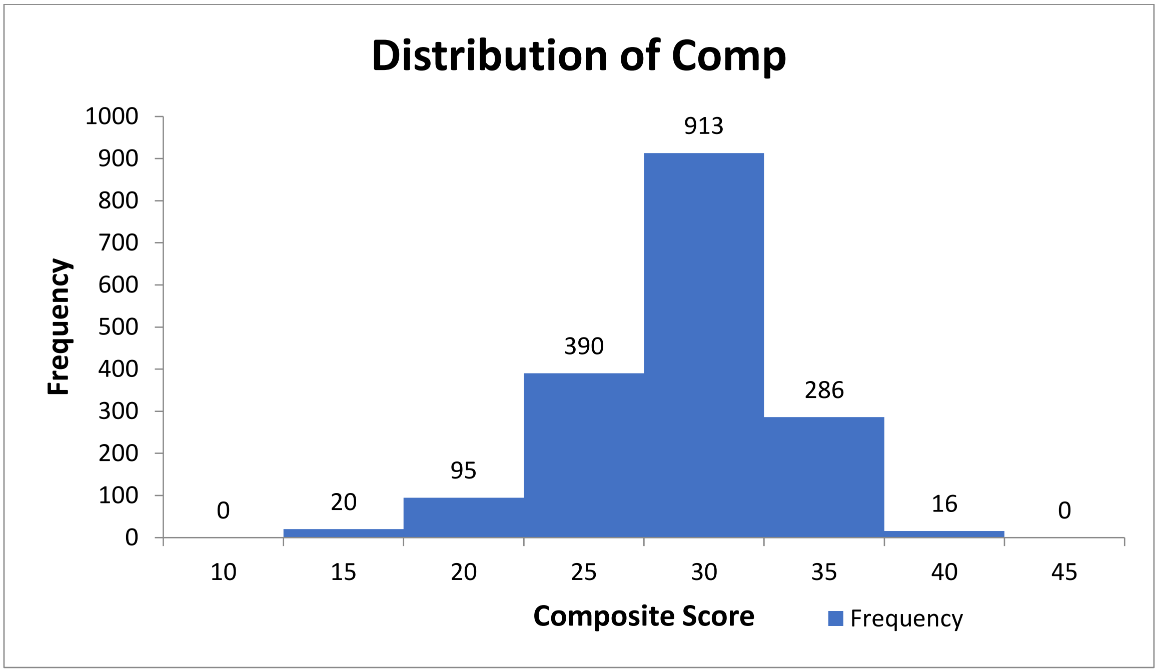

Table 2.1 Mean, Standard Deviation, Minimum and Maximum of Feet and Leg Scores

Trait	Mean	SD	Min	Max
Body Condition Score	5.65	0.52	3.70	8.55
Front Hoof Angle	56.59	4.57	38.00	82.50
Front Heel Depth	57.21	4.56	37.00	75.00
Front Claw Shape	57.47	6.43	38.00	93.50
Rear Hoof Angle	58.40	5.57	37.50	80.00
Rear Hoof Depth	59.69	5.73	34.50	83.00
Rear Claw Shape	52.76	5.76	29.50	95.33
Size of Hoof	49.63	5.35	25.50	74.00
Front Side View	46.04	3.66	29.00	61.00
Knee Orientation	53.71	2.97	32.00	70.00
Front Hoof Orientation	55.78	4.96	23.50	74.50
Rear Side View	55.17	5.43	30.00	82.00
Rear View	56.62	3.81	37.00	77.50
Composite Score	31.37	4.04	15.00	44.00

Table 2.2 Average additive genetic variance (σ_a^2), average standard error (SE), range of additive genetic variances (σ_a^2 Range), range of standard errors (SE Range)

Trait	σ_a^2	SE	σ_a^2 Range	SE Range
Body Condition Score	0.016	0.007	0.015-0.017	0.0063-0.0069
Front Hoof Angle	2.77	0.86	2.62-2.95	0.84-0.87
Front Heel Depth	2.65	0.85	2.41-3.26	0.82-0.89
Front Claw Shape	2.26	1.06	2.14-2.45	1.04-1.09
Rear Hoof Angle	3.02	0.95	2.83-3.31	0.91-0.97
Rear Heel Depth	5.20	1.39	4.77-5.52	1.34-1.42
Rear Claw Shape	4.21	1.35	4.07-4.45	1.34-1.38
Size of Hoof	7.24	1.46	7.11-7.50	1.45-1.48
Front Side View	1.88	0.60	1.79-2.06	0.58-0.62
Knee Orientation	1.43	0.48	1.25-1.52	0.45-0.48
Front Hoof Orientation	3.68	1.24	3.13-4.08	1.16-1.28
Rear Side View	7.71	2.01	7.40-7.99	1.78-4.37
Rear View	1.74	0.61	1.68-1.83	0.59-0.62
Composite Score	1.27	0.52	0.97-1.42	0.46-0.53

Table 2.3 Average residual variance (σ_e^2), average standard error (SE), range of residual variances (σ_e^2 Range), and range of standard errors (SE Range) for feet and leg traits

Trait	σ_e^2	SE	σ_e^2 Range	SE Range
Body Condition Score	0.129	0.007	0.128-0.130	0.007-0.007
Front Hoof Angle	11.36	0.77	11.22-11.48	0.76-0.78
Front Heel Depth	12.84	0.80	12.37-13.02	0.79-0.81
Front Claw Shape	23.84	1.20	23.68-23.94	1.20-1.22
Rear Hoof Angle	13.29	0.87	13.01-13.44	0.85-0.88
Rear Heel Depth	15.49	1.18	15.24-15.78	1.15-1.20
Rear Claw Shape	21.25	1.29	21.06-21.36	1.29-1.30
Size of Hoof	12.94	1.14	12.75-13.04	1.14-1.15
Front Side View	9.91	0.59	9.77-9.98	0.58-0.59
Knee Orientation	6.91	0.44	6.86-7.07	0.43-0.45
Front Hoof Orientation	18.25	1.16	17.94-18.68	1.12-1.18
Rear Side View	17.80	1.47	17.58-18.03	1.44-1.49
Rear View	10.35	0.60	10.27-10.40	0.59-0.61
Composite Score	9.26	0.53	9.09-9.98	0.52-0.58

Table 2.4 Heritability estimates and standard errors for feet and leg traits

Trait	Average Heritability	Average Standard Error	Heritability Range	Standard Error Range
Body Condition Score	0.11	0.04	0.10-0.12	0.04-0.05
Front Hoof Angle	0.20	0.06	0.19-0.21	0.06-0.06
Front Heel Depth	0.17	0.05	0.16-0.21	0.05-0.05
Front Claw Shape	0.09	0.04	0.08-0.09	0.04-0.04
Rear Hoof Angle	0.19	0.06	0.17-0.20	0.05-0.06
Rear Heel Depth	0.25	0.06	0.23-0.26	0.06-0.06
Rear Claw Shape	0.17	0.05	0.16-0.17	0.05-0.05
Size of Hoof	0.36	0.06	0.35-0.37	0.06-0.06
Front Side View	0.16	0.05	0.15-0.17	0.05-0.05
Knee Orientation	0.17	0.05	0.15-0.18	0.05-0.06
Front Hoof View	0.17	0.05	0.14-0.19	0.05-0.06
Rear Side View	0.30	0.06	0.29-0.31	0.06-0.07
Rear View	0.14	0.05	0.14-0.15	0.05-0.05
Composite Score	0.12	0.05	0.09-0.14	0.04-0.05

Table 2.5 Genetic covariances (above diagonal) and SE (below) and phenotypic covariances (below diagonal) and SE (below)

Trait	BCS	FHA	FHD	FCS	RHA	RHD	RCS	Size	FSV	Knee	FHO	RSV	RV	Comp
BCS		0.06 0.05	0.04 0.05	0.10 0.06	0.02 0.56	-0.10 0.70	0.05 0.07	0.14 0.07	0.06 0.04	-0.91 0.04	-0.15 0.06	-0.09 0.08	-0.04 0.05	0.01 0.04
FHA	-0.04 0.05		2.39 0.80	-0.54 0.69	2.75 0.78	3.35 0.90	-0.58 0.77	0.50 0.80	1.10 0.52	-0.10 0.46	-0.80 0.73	2.93 0.91	0.77 0.51	-0.61 0.48
FHD	-0.03 0.04	12.12 0.50		-0.77 0.67	2.61 0.78	3.88 0.96	-0.38 0.75	-0.23 0.81	1.07 0.53	0.09 0.45	-0.63 0.72	2.29 0.92	1.02 0.51	-0.65 0.48
FCS	0.10 0.05	1.94 0.49	2.07 0.51		0.34 0.72	-0.16 0.89	2.40 0.97	0.77 0.94	0.16 0.56	0.27 0.52	0.33 0.83	-0.05 1.03	0.33 0.57	-0.21 0.53
RHA	-0.02 0.04	7.72 0.46	7.56 0.47	2.78 0.53		3.49 1.08	-0.29 0.79	0.02 0.89	0.69 0.55	-0.09 0.48	-0.84 0.78	3.34 0.97	1.11 0.55	-0.87 0.52
RHD	-0.02 0.04	7.94 0.51	9.34 0.55	2.66 0.60	15.18 0.63		0.50 0.99	-1.50 1.03	0.60 0.66	0.02 0.55	-1.11 0.95	3.44 1.16	1.80 0.67	-1.55 0.65
RCS	0.06 0.05	0.54 0.49	1.01 0.51	9.74 0.70	3.56 0.53	4.01 0.61		-0.62 1.02	0.08 0.59	1.05 0.58	1.56 0.93	-2.16 1.15	0.36 0.57	-0.13 0.60
Size	0.40 0.05	-0.05 0.46	-0.95 0.47	0.83 0.60	0.25 0.49	-0.67 0.57	0.49 0.60		0.41 0.70	0.18 0.59	0.92 0.98	0.20 1.13	-0.62 0.70	0.97 0.66
FSV	0.17 0.03	0.89 0.34	0.71 0.35	-0.89 0.44	1.08 0.36	1.29 0.41	-0.31 0.44	3.09 0.42		-0.92 0.38	-1.80 0.63	-0.27 0.76	-0.18 0.43	1.15 0.42
Knee	-0.12 0.03	0.34 0.28	0.29 0.29	1.67 0.38	0.41 0.30	0.58 0.35	0.69 0.38	-1.46 0.35	-1.27 0.26		2.09 0.68	-1.30 0.65	0.30 0.39	0.10 0.36
FHO	-0.25 0.05	0.31 0.46	0.52 0.48	2.84 0.61	0.44 0.49	0.26 0.57	0.78 0.61	-2.82 0.57	-3.87 0.43	9.84 0.43		-2.64 1.05	0.42 0.63	-0.52 0.56
RSV	-0.23 0.05	2.99 0.52	2.88 0.54	0.05 0.67	4.96 0.57	5.35 0.64	-0.80 0.68	-0.21 0.63	1.51 0.46	1.50 0.39	1.80 0.64		1.16 0.80	-1.26 0.70
RV	-0.15 -0.03	1.34 0.34	1.81 0.35	1.15 0.45	2.59 0.37	3.25 0.42	0.92 0.45	-1.62 0.42	-1.24 0.31	2.06 0.26	3.77 0.43	5.66 0.49		-1.01 0.44
Comp	0.18 0.03	-1.83 0.32	-2.48 0.33	-5.03 0.43	-2.77 0.34	-3.45 0.40	-4.64 0.43	3.60 0.40	4.24 0.30	-0.62 0.24	-1.41 0.39	-1.03 0.43	-3.58 0.30	

Traits: Body Condition Score (BCS), Front Hoof Angle (FHA), Front Heel Depth (FHD), Front Claw Shape (FCS), Rear Hoof Angle (RHA), Rear Claw Shape (RCS), Size of Hoof (SIZE), Front Side View (FSV), Knee Orientation (KNEE), Front Hoof Orientation (FHO), Rear Side View (RSV), and Rear View (RV), and Composite Score (COMP).

Table 2.6 Genetic correlations (above diagonal) and SE (below) and Phenotypic correlations (below diagonal) and SE (below)

Trait	BCS	FHA	FHD	FCS	RHA	RHD	RCS	Size	FSV	Knee	FHO	RSV	RV	Comp
BCS		0.27 0.25	0.20 0.26	0.51 0.28	0.08 0.26	-0.04 0.24	0.19 0.25	0.40 0.19	0.38 0.25	-0.68 0.26	-0.70 0.24	-0.27 0.22	-0.26 0.26	0.07 0.29
FHA	-0.03 0.026		0.89 0.06	-0.21 0.27	0.88 0.08	0.85 0.09	-0.17 0.22	0.11 0.18	0.46 0.19	-0.05 0.23	-0.25 0.23	0.63 0.15	0.36 0.23	-0.33 0.24
FHD	-0.02 0.025	0.82 0.01		-0.31 0.27	0.85 0.10	0.94 0.06	-0.12 0.24	-0.06 0.19	0.45 0.19	0.05 0.24	-0.20 0.23	0.51 0.17	0.51 0.22	-0.36 0.24
FCS	0.05 0.025	0.10 0.03	0.10 0.03		0.13 0.28	-0.05 0.26	0.75 0.17	0.20 0.24	0.08 0.28	0.15 0.28	0.12 0.28	-0.01 0.25	0.17 0.29	-0.13 0.31
RHA	-0.01 0.026	0.51 0.02	0.47 0.02	0.14 0.03		0.86 0.06	-0.09 0.23	0.004 0.18	0.29 0.21	-0.04 0.23	-0.24 0.22	0.72 0.15	0.51 0.21	-0.44 0.22
RHD	-0.01 0.026	0.46 0.02	0.52 0.02	0.12 0.03	0.83 0.01		0.11 0.21	-0.23 0.16	0.19 0.21	0.01 0.21	-0.24 0.21	0.56 0.15	0.63 0.19	-0.57 0.18
RCS	0.03 0.025	0.03 0.03	0.05 0.03	0.38 0.02	0.18 0.03	0.18 0.03		-0.11 0.19	0.03 0.23	0.41 0.21	0.38 0.21	-0.36 0.18	0.14 0.24	-0.06 0.26
Size	0.23 0.025	-0.003 0.03	-0.05 0.03	0.04 0.03	0.01 0.03	-0.03 0.03	0.02 0.03		0.11 0.18	0.06 0.19	0.17 0.18	0.03 0.16	-0.17 0.19	0.32 0.19
FSV	0.13 0.025	0.07 0.03	0.05 0.03	-0.05 0.03	0.08 0.03	0.08 0.03	-0.02 0.03	0.02 0.03		-0.59 0.21	-0.75 0.18	-0.07 0.20	-0.10 0.24	0.87 0.19
Knee	-0.11 0.025	0.03 0.03	0.03 0.03	0.11 0.03	0.04 0.03	0.05 0.03	0.05 0.03	-0.11 0.03	-0.13 0.03		0.95 0.07	-0.38 0.19	0.19 0.23	0.07 0.26
FHO	-0.14 0.025	0.02 0.03	0.03 0.03	0.12 0.03	0.02 0.03	0.01 0.03	0.03 0.03	-0.13 0.03	-0.24 0.03	0.73 0.01		-0.46 0.18	0.16 0.24	-0.25 0.27
RSV	-0.12 0.026	0.16 0.06	0.15 0.03	0.002 0.03	0.24 0.03	0.23 0.03	-0.03 0.03	-0.01 0.03	0.09 0.03	0.10 0.03	0.08 0.03		0.31 0.20	-0.40 0.21
RV	-0.12 0.025	0.10 0.03	0.13 0.03	0.07 0.03	0.19 0.03	0.21 0.03	0.05 0.03	-0.10 0.03	-0.10 0.03	0.21 0.03	0.23 0.03	0.32 0.02		-0.64 0.18
Comp	0.15 0.025	-0.15 0.03	-0.20 0.03	-0.30 0.02	-0.21 0.03	-0.23 0.03	-0.28 0.03	0.25 0.03	0.38 0.02	-0.07 0.03	-0.09 0.03	-0.06 0.03	-0.32 0.02	

Traits: Body Condition Score (BCS), Front Hoof Angle (FHA), Front Heel Depth (FHD), Front Claw Shape (FCS), Rear Hoof Angle (RHA), Rear Claw Shape (RCS), Size of Hoof (SIZE), Front Side View (FSV), Knee Orientation (KNEE), Front Hoof Orientation (FHO), Rear Side View (RSV), and Rear View (RV), and Composite Score (COMP).

Table 2.7 Pearson correlation coefficient between front limb EPD's and production data and EPD's

	BWA	WWA	YWA	PWG	BW	WW	YW	MILK	ME	HPG	CEM	STAY	HERD	GRID
n	1710	1723	1723	1592	1727	1727	1727	1727	1727	1727	1727	1727	1727	1727
FHA	-0.04	-0.02	-0.07**	-0.07**	-0.11***	-0.05*	-0.07**	0.03	0.10***	-0.04	0.06*	-0.04	-0.02	-0.03
FHD	-0.08**	-0.07**	-0.05	-0.02	-0.18***	-0.11***	-0.15***	0.07**	0.14***	-0.09**	0.14***	-0.04	-0.02	-0.11**
FSV	-0.02	0.03	-0.01	-0.04	-0.003	0.10***	0.13***	-0.03	-0.15***	0.05	-0.13***	0.16***	0.16***	0.12***
KNEE	0.02	-0.06*	-0.09**	-0.09**	0.05*	-0.13***	-0.06**	-0.05*	-0.19***	0.05*	-0.02*	0.11***	0.07**	-0.04
FHO	0.01	-0.04	-0.09**	-0.08**	0.06*	-0.13***	-0.06*	-0.06**	-0.21***	0.08**	-0.03	0.12***	0.09***	-0.02
COMP	0.01	0.09**	0.12***	0.11***	-0.05	0.14***	0.07**	-0.01	0.26***	-0.07**	0.11***	-0.11***	-0.07**	0.01

*p <0.05
**p<0.01
***p<0.0001

Production data and EPD's: Adjusted birth weight (BWA), adjusted weaning weight (WWA, adjusted yearling weight (YWA), post weaning gain (PWG), birth weight EPD (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughter's milk EPD (MILK), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), calving ease maternal EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID).

Front Limb traits: Front Hoof Angle (FHA), Front Heel Depth (FHD), Front Side View (FSV), Knee Orientation (KNEE), Front Hoof Orientation (FHO), and Composite Score (COMP).

Table 2.8 Spearman correlation coefficient for front limb trait EPD's and production data and EPD's

	BWA	**WWA**	**YWA**	**PWG**	**BW**	**WW**	**YW**	**MILK**	**ME**	**HPG**	**CEM**	**STAY**	**HERD**	**GRID**
n	1710	1723	1592	1592	1727	1727	1727	1727	1727	1727	1727	1727	1727	1727
FHA	-0.03	-0.02	-0.06*	-0.06*	-0.11***	-0.03	-0.06**	0.05*	0.11***	-0.05*	0.07**	-0.04	-0.02	-0.03
FHD	-0.08**	-0.09**	-0.06*	-0.03	-0.17***	-0.12***	-0.17***	0.07**	0.15***	-0.10***	0.11***	-0.03	-0.01	-0.12***
FSV	-0.05*	0.04	-0.02	-0.05	-0.06*	0.12***	0.17***	-0.03	-0.12***	0.04	-0.11***	0.20***	0.23***	0.16***
KNEE	0.03	-0.04	-0.07**	-0.08**	0.05*	-0.10***	-0.04	-0.05*	-0.19***	0.06*	-0.01	0.09**	0.07**	-0.02
FHO	0.03	-0.02	-0.05	-0.06*	0.05*	-0.11***	-0.04	-0.07**	-0.21***	0.1***	-0.01	0.11***	0.09**	0.003
COMP	-0.001	0.07	0.09**	0.08**	-0.01	0.13***	0.05*	0.01	0.23***	-0.07*	0.05*	-0.09***	-0.07**	-0.01

*p <0.05
**p<0.01
***p<0.0001
Production data and EPD's: Adjusted birth weight (BWA), adjusted weaning weight (WWA, adjusted yearling weight (YWA), post weaning gain (PWG), birth weight EPD (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughter's milk EPD (MILK), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), calving ease maternal EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID).
Front Limb traits: Front Hoof Angle (FHA), Front Heel Depth (FHD), Front Side View (FSV), Knee Orientation (KNEE), Front Hoof Orientation (FHO), and Composite Score (COMP).

Table 2.9 Pearson correlation coefficients for rear limb trait EPD's and productions data and EPD's

	BWA	**WWA**	**YWA**	**PWG**	**BW**	**WW**	**YW**	**MILK**	**ME**	**HPG**	**CEM**	**STAY**	**HERD**	**GRID**
n	1710	1723	1592	1592	1727	1727	1727	1727	1727	1727	1727	1727	1727	1727
RHA	-0.01	-0.02	-0.04	-0.04	-0.07**	-0.09**	-0.07**	0.06*	-0.002	0.02	-0.01	0.004	0.004	-0.03
RHD	0.01	0.04	0.04	0.03	0.03	-0.03	-0.04	-0.01	-0.01	0.01	-0.06*	-0.06*	-0.07**	-0.05
RCS	0.03	-0.04	0.001	0.03	0.04	-0.01	-0.02	0.07**	0.06*	-0.06*	0.04	-0.12***	-0.11***	-0.03
RSV	-0.03	-0.07**	-0.08**	-0.06**	-0.07**	0.02	0.03	0.01	0.01	0.01	0.07**	0.11***	0.12***	0.05*
RV	0.01	0.04	0.04	0.03	0.03	-0.03	-0.04	-0.01	-0.01	0.01	-0.06*	-0.06*	-0.07**	-0.04
COMP	-0.01	-0.04	-0.04	-0.03	-0.03	0.03	0.04	0.01	0.01	-0.01	0.06*	0.06**	0.08**	0.05

*p <0.05
**p<0.01
***p<0.0001

Production data and EPD's: Adjusted birth weight (BWA), adjusted weaning weight (WWA, adjusted yearling weight (YWA), post weaning gain (PWG), birth weight EPD (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughter's milk EPD (MILK), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), calving ease maternal EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID).
Rear Limb traits: Rear Hoof Angle (RHA), Rear Heel Depth (RHD), Rear Claw Shape (RCS), Rear Side View (RSV), Rear View (RV), and Composite Score (COMP).

Table 2.10 Spearman correlation coefficients for rear limb trait EPD's with production data and EPD's

	BWA	WWA	YWA	PWG	BW	WW	YW	MILK	ME	HPG	CEM	STAY	HERD	GRID
n	1710	1723	1592	1592	1727	1727	1727	1727	1727	1727	1727	1727	1727	1727
RHA	-0.01	-0.02	-0.03	-0.04	-0.06*	-0.08**	-0.06*	0.07**	-0.002	0.01	-0.004	0.01	0.01	-0.01
RHD	0.02	0.05*	0.07**	0.04	0.06**	-0.01	-0.01	-0.01	-0.03	0.001	-0.08**	-0.06*	-0.09**	-0.03
RCS	0.04	-0.04	-0.004	0.03	0.03	-0.04	-0.04	0.06**	0.07**	-0.06**	0.06*	-0.14***	-0.11***	-0.02
RSV	-0.04	-0.08**	-0.11***	-0.09**	-0.1***	-0.01	0.002	0.02	0.02	0.02	0.10***	0.12***	0.15***	0.03
RV	0.02	0.05*	0.07**	0.05	0.06*	-0.005	-0.01	-0.01	-0.03	0.001	-0.08**	-0.06*	-0.09**	-0.03
COMP	-0.02	-0.05*	-0.07**	-0.05	-0.07**	0.01	0.01	0.01	0.03	0.0001	0.08**	0.06**	0.10***	0.03

*p <0.05
**p<0.01
***p<0.0001
Production data and EPD's: Adjusted birth weight (BWA), adjusted weaning weight (WWA, adjusted yearling weight (YWA), post weaning gain (PWG), birth weight EPD (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughter's milk EPD (MILK), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), calving ease maternal EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID).
Rear Limb traits: Rear Hoof Angle (RHA), Rear Heel Depth (RHD), Rear Claw Shape (RCS), Rear Side View (RSV), Rear View (RV), and Composite Score (COMP).

Table 2.11 Pearson correlation coefficients for BCS, FCS, SIZE, and COMP with production data and EPD's

	BWA	WWA	YWA	PWG	BW	WW	YW	MILK	ME	HPG	CEM	STAY	HERD	GRID
n	1710	1723	1592	1592	1727	1727	1727	1727	1727	1727	1727	1727	1727	1727
BCS	0.01	0.09**	0.19***	0.20***	0.10***	0.18***	0.14***	-0.01	0.02	-0.14***	-0.20***	-0.13***	-0.13***	0.04
FCS	0.002	0.06**	0.01	-0.01	-0.08**	0.14***	0.16***	0.05*	0.21***	0.10***	0.07**	-0.02	0.05*	0.20***
SIZE	0.24***	0.30***	0.32***	0.23***	0.19***	0.36***	0.37***	-0.09**	0.16***	0.02	-0.07**	-0.07**	-0.03	0.24***
COMP	0.02	0.11***	0.09**	0.04	0.03	0.19***	0.17***	-0.11***	0.04	0.03	-0.08**	0.08**	0.09**	0.10***

*p <0.05
**p<0.01
***p<0.0001
Production data and EPD's: Adjusted birth weight (BWA), adjusted weaning weight (WWA, adjusted yearling weight (YWA), post weaning gain (PWG), birth weight EPD (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughter's milk EPD (MILK), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), calving ease maternal EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID).
Feet and Leg traits: Body Condition Score (BCS), Front Claw Shape (FCS), Size of Hoof (SIZE), and Composite Score (COMP).

Table 2.12 Spearman correlation coefficient for BCS, FCS, SIZE, and Comp with production data and EPD's

	BWA	**WWA**	**YWA**	**PWG**	**BW**	**WW**	**YW**	**MILK**	**ME**	**HPG**	**CEM**	**STAY**	**HERD**	**GRID**
n	1710	1723	1592	1592	1727	1727	1727	1727	1727	1727	1727	1727	1727	1727
BCS	0.01	0.10***	0.19***	0.22***	0.11***	0.20***	0.16***	-0.03	0.03	-0.13***	-0.18***	-0.14***	-0.12***	0.10***
FCS	-0.02	0.05*	0.003	-0.01	-0.10***	0.12***	0.14***	0.02	0.22***	0.10***	0.06**	0.02*	0.09**	0.19***
SIZE	0.24***	0.30***	0.34***	0.27***	0.17***	0.36***	0.38***	-0.07**	0.14***	0.03	-0.05*	-0.06*	-0.01	0.25***
COMP	0.02	0.11***	0.07**	0.02	0.02	0.18***	0.17***	-0.10***	0.03	0.04	-0.09**	0.10***	0.11***	0.11***

*p <0.05
**p<0.01
***p<0.0001
Production data and EPD's: Adjusted birth weight (BWA), adjusted weaning weight (WWA, adjusted yearling weight (YWA), post weaning gain (PWG), birth weight EPD (BW), weaning weight EPD (WW), yearling weight EPD (YW), daughter's milk EPD (MILK), maintenance energy EPD (ME), heifer pregnancy EPD (HPG), calving ease maternal EPD (CEM), stayability EPD (STAY), herdbuilder index (HERD), and gridmaster index (GRID).
Feet and Leg traits: Body Condition Score (BCS), Front Claw Shape (FCS), Size of Hoof (SIZE), and Composite Score (COMP).

Table 2.13 Age Covariates for Front Limb Traits

	Covariate on Age in Months	Standard Error
Front Hoof Angle	-0.05	0.06
Front Hoof Depth	-0.07	0.06
Front Side View	0.02	0.05
Knee Orientation	0.09	0.05
Front Hoof Orientation	0.06	0.07
Composite Score	0.14	0.05

Table 2.14 Age Covariates for Rear Limb Traits

	Covariate on Age in Months	Standard Error
Rear Hoof Angle	0.26	0.06
Rear Heel Depth	-0.12	0.07
Rear Claw Shape	0.16	0.08
Rear Side View	0.25	0.08
Rear View	-0.18	0.06
Composite Score	0.20	0.05

Table 2.15 Age Covariate for BCS, FCS, Size, and Comp

	Covariate on Age in Months	Standard Error
Body Condition Score	-0.03	0.01
Front Claw Shape	-0.06	0.08
Size of Hoof	0.22	0.07
Composite Score	0.13	0.05