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Gait Analysis and Biomechanics of Quadruped Motion for procedural Animation and Robotic Simulation

Z. Bhatti, A. Waqas, A. W. Mahesar, M. Karbasi,

***Abstract* – In this paper, a detailed overview of the animal motion and analysis of various gaits of each quadruped character is discussed. The three animal characters under study are Lion, Cat and Tiger, where all three belong to the same family and thus have the same anatomical structure and gait aesthetics. In order to conduct the study of various gaits of locomotion and propulsion employed by an animal during the execution of any of its regular gaits, various video footages of live animal motion are used as the primary source. Each gait and its footfall patterns were studied from the extracted frame-by-frame footage of each animal type and are analyzed. For each locomotion, its gait footfall sequence diagram and gait graph is drawn to provide an understanding and timing information of the cadence of each leg. This study will greatly aid the animators of movie and game industry to understand the quadruped motion and animate their four-legged creatures correctly.**

***Index Term* – Quadruped, Biomechanics, Animation, Quadruped Gaits, Footfall patterns, Gait graphs Introduction.**

I. INTRODUCTION

Computer generated animation has become extremely popular in current era, not only in movies and games, but mainstream television, education, scientific visualizations, sports are just few noteworthy areas of its applications. Two major types of animation techniques are used in the general industry; namely key-frame and motion capture techniques. However, there are few other techniques of generating animation through procedural programming techniques and physics based rules. In this paper a study has been conducted to understand the biomechanics of quadruped motion and their gait patters, so it can be effectively used by the animators to produce believable motions in applications like movies, 3D animations, Games, Virtual reality and augmented reality, etc.

The locomotion knowledge of quadrupeds has always been of keen interest among the researchers in the field of biomechanics, robotics and especially in Animation and 3D Games. It has been observed that motion gaits of most of the quadruped characters have same symmetrical patterns for both right and left legs. The deference, however, is that the gait footfall sequence between both right and left leg occurs with different time shifts and phases [1] [2]. Thus, consequently same motion pattern is shared between legs containing varying time shift parameters. The earliest research done by Alexander provided valuable information of various gaits and their analysis of quadruped characters, [3][4]. The hypothesis developed by him in particular regarding the relationship between size, speed, mass and various forces is still being used to analyze the quadruped motion [5][6]. This theory, known as Froude number, is commonly used concept and also adopted by many in their research work. According to this, any animal regardless of its size and weight, will tend to change gaits as equal Froude number between 2 and 3 [7], [2], [8].

Zeeshan Bhatti and Abdul Waheed Mahesar are with Institute of Information and Communication Technology, University of Sindh, Jamshoro. Ahmad Waqas and Mostafa Karbasi are with International Islamic University Malaysia.
Email: zeeshan.bhatti@usindh.edu.pk, waheed.mahessar@usindh.edu.pk, ahmad.waqas@iba-suk.edu.pk, karbasi_mostafa@yahoo.com. Manuscript received on Sep 06, 2017 revised on Nov 07, 2017 and accepted on Dec 15, 2017.

II. MOTION ANALYSIS

For the analysis of quadruped motion, live animal motion clips were obtained from various sources over the Internet. Each animal was analyzed individually from the video feeds and from within these multiple footages the gait information was extracted as also discussed in [9].

A. Motion Extraction from Video Footage

For the motion footage analysis, the key sources explored were 5 major on-line re-sources containing hundreds of image and video references of quadruped motions, 10 DVD documentaries on quadrupeds, and 4 movies were explored to obtain the motion dataset. The videos were first characterized into motion types and then frame-by-frame breakdown was done of each gait type. Figure 1 illustrates the walk motion of female lioness broken down into frame-by-frame reference. The reference image consists of 35 frames, because after this, the motion starts to cycle and repeat itself, with 30 frames per second (fps). Then, the key phases of walk motion are timed, extracted and numbered frame by frame.

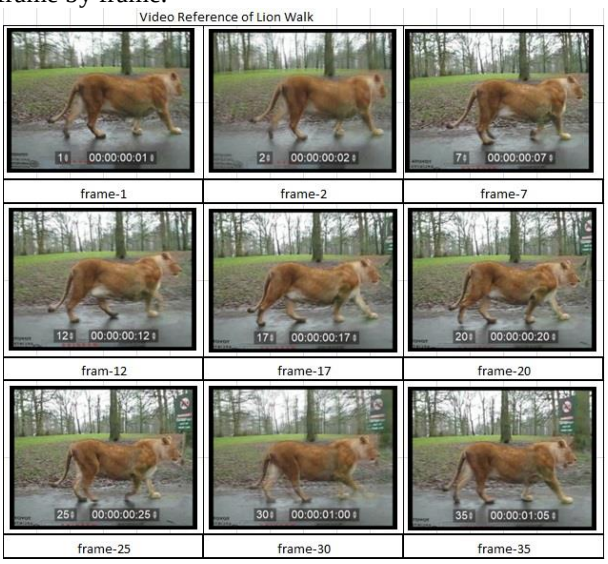

Fig. 1 Frame by Frame motion of Lion Walk [9]

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The male Lion's fast Gallop motion, is based on 17 frames after which the motion cycles repeats itself. Here, again the key frames from the motion where the limb positions changes, has been recorded and illustrated in Figure 2.

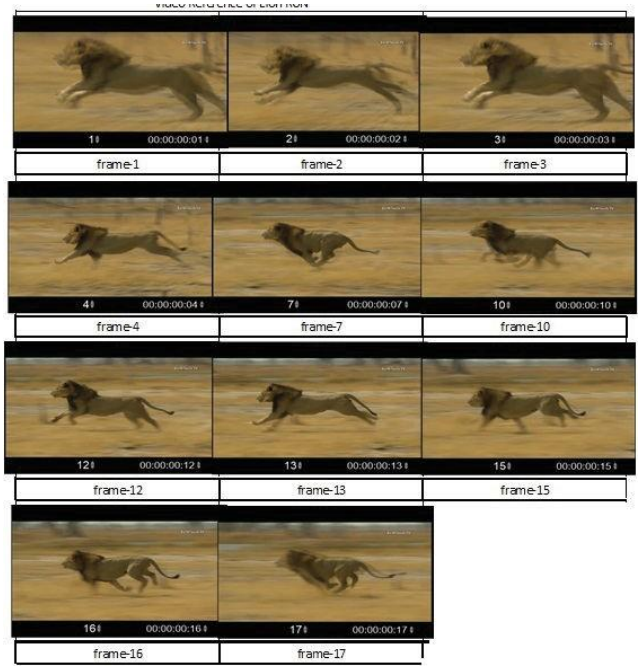

Fig. 2 Frame-by-frame breakdown of Lion Fast Gallop motion

The locomotion of Tiger is also classified and a frame-by-frame dataset is created from various video footages of live Tiger motion. Figure 3 illustrates the walk gaits of Tiger over 42 frames with speed of 30 frames per second.

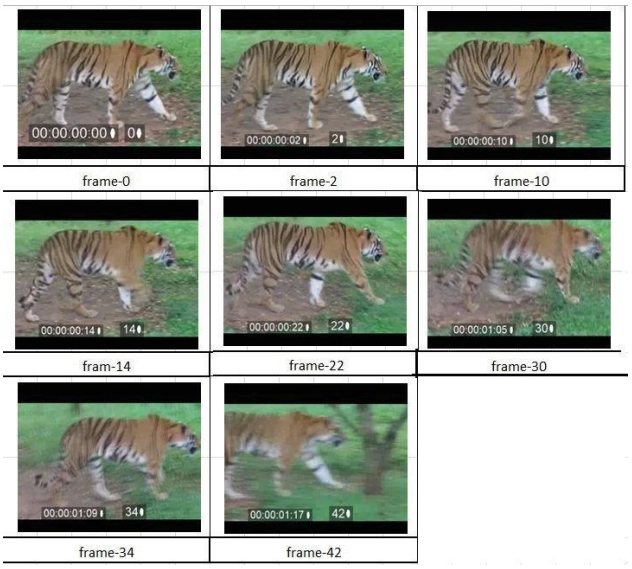

Fig. 3 Frame-by-frame motion of Tiger walk

The motion references of the understudy animals was also obtained from the book of Edward Maybridge [10], [11] as shown in Figure 4. The various gaits of a house Cat are illustrated in Figure 4, where topmost frames are of cat walk, then fast walk or trot motion, then gallop and last frames are of fast running motion.

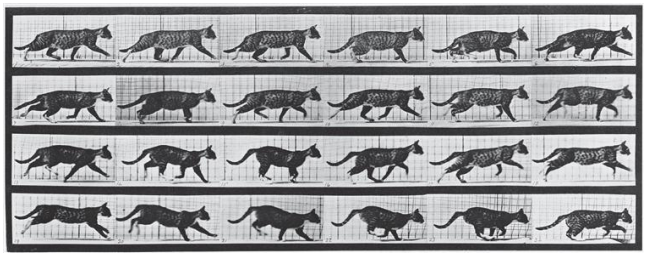

Fig. 4 Frame-by-frame sequence of cat in Walking, trotting and Running (courtesy of E. Muybridge [10]).

A. Gait Graphs and Footfall Pattern

After analyzing the motion video footages and segregating each gait with frame-by-frame sequence of images, the gait graphs and footfall patterns for each locomotion types is generated. The animal gaits change according to their speed and so the Froude number aids in developing a control cyclic algorithm for each gait type. While keeping the speed of each gait type constant, for each animal, will tend to increase the accuracy of the generated animation. Gait graphs typically represent the timing information of each leg during motion. The timing information is calculated according to the stance phase and swing phase of each leg. The stance phase determines how long the leg was static and planed on the ground; whereas the swing phase calculates the time each leg was in swing motion.

B. Phases of Quadruped Motion

A four-legged animal in forward motion demonstrates progressive and retrogressive actions with relation to their body. For any quadruped, as they move, their weight initially is shifted away from the swing leg and balanced on the stance/planted slegs. The head is normally raised with neck and back as the weight is shifted throughout the motion. This weight shift allows the animal to balance his body and not to fall over. The normal pattern of contact phases for legs has been categorized in 4 phases as shown in Figure 5. The first phase is when all four legs are on the ground and in stance phase. The second phase occurs when one leg is in swing phase and the remaining three legs are planted on the ground in stance phase. The third phase begins when any of the two legs are in motion while two are in constant contact with ground. The final phase is when at least one leg is in contact with the ground and the remaining 3 are in swing phase.

C. Symmetrical and Asymmetrical Gait Types

The motion Gaits of quadrupeds are generally classified in two categories, "symmetrical" and "asymmetrical". This categorization is centered on various patterns of limb movements and has nothing to do with left-right symmetry. The gait is said to be symmetrical if both the right and left legs alternate in motion, whereas the asymmetrical gait is formed when both legs move together in same pattern, in suspended phase and so often termed as "leaping gaits" [12],

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[13],[14]. For the purpose of understanding each gait and its type, we generate gait graphs of each motion type as shown in Figure 6, for symmetrical gaits and Figure 7 illustrates the asymmetrical gait graph for Rotary & Transverse Gallop and Bound motion types. The gait graphs are drawn and illustrated using the style of Hildebrand. Dark colored areas indicate time of contact and leg in stance phase, whereas bottom axis is % of cycle. The two main factors and variables involved in the gait analysis are, Stride Length and Swing Phase. These two parameters control the relational phase shift time between each of the four legs of quadruped.

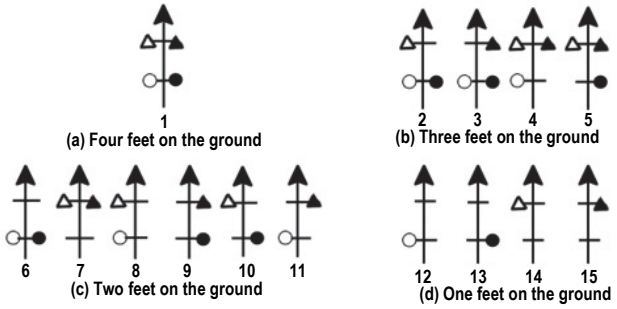

Fig. 5 Typical 4 Phases of Quadruped motion showing various possible footfall patterns

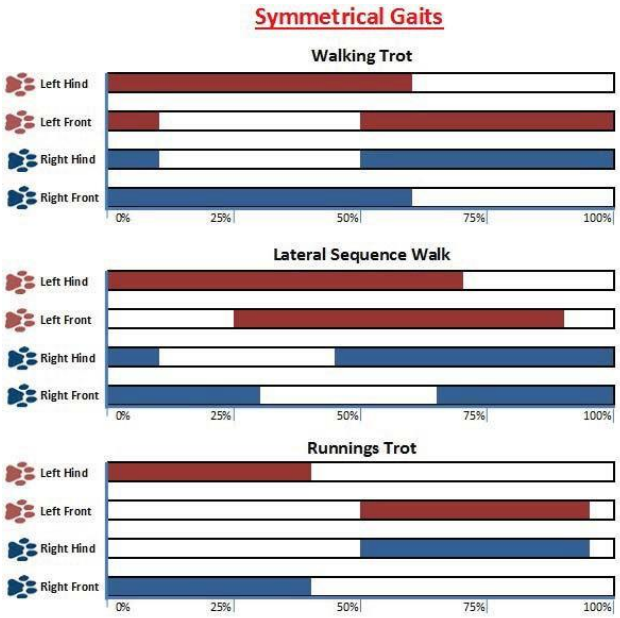

Fig. 6 Symmetrical Gait graphs

Similarly, the symmetrical and asymmetrical footfall sequence of each leg in motion was determined and categorized, as shown in Figure 8. The two symmetrical sequences of footfall gaits are Diagonal footfall pattern and Lateral footfall pattern. In diagonal footfall, each leg motion occurs in diagonal sequence. For example, if left front (LF) leg moves first, then the second leg to follow the motion would be right hind (RH), then right front (RF) and finally left hind (LH). Whereas, in lateral symmetrical footfall, the sequence follows the reverse or clockwise pattern. For example, if LF moves first, then the second leg to follow the motion is LH (instead of RH as in diagonal sequence), followed by RF and finally RH moves. The asymmetrical footfall sequence has 4 types of patterns (c) Diagonal direct footfall pattern, (d) Diagonal converse footfall pattern, (e) Lateral direct and finally (f) Lateral converse footfall pattern. The asymmetrical sequence adopts the pattern of transferring motion pattern from front left to front right and hind left to hind right and vice versa throughout the locomotion. For example, in diagonal direct sequence, if LF leg moves first, then RF leg moves following the LF leg, after which LH is moved which followed by RH leg. Contrary to this the Lateral direct asynchronous footfall sequence illustrates a square pattern with sequential follow through each leg. For example, if LF moves first, then RF follows, after which RH moves and finally LH and cycle is repeated.

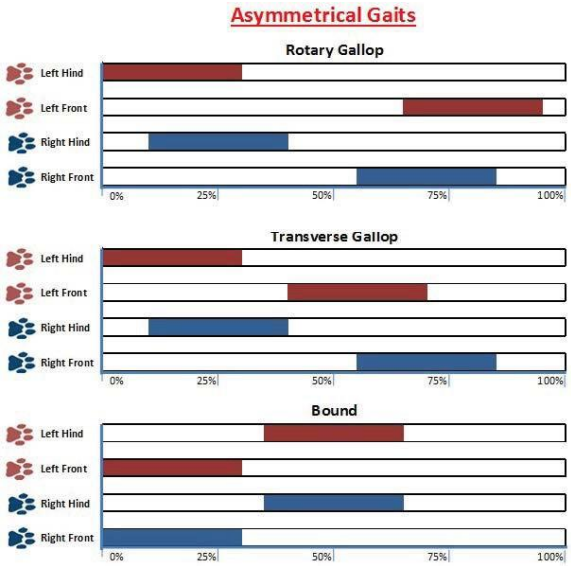

Fig. 7 Asymmetrical Gait graphs

III. GAIT PATTERN ANALYSIS

Each quadruped character can generate various patterns of locomotion, from walk, trot, gallop, canter, ample, pace etc. for this study only the 6 most common type of motion gaits have been studied and analyzed. Generally quadruped gait have been segregated in two-beat and four-beat gaits [15].

A. Synopsis of Walk Gait

Walk gait is the most basic type of natural gait exhibited by all animal types. A walk gait of a quadruped consists of 4 even beats per stride with three legs always on the ground in stance phase forming a triangle and fourth leg will be in swing phase. It has a symmetrical sequence of footfall pattern. The walk itself has several variations from ordinary walk, to collected or extended walk [12] however, the sequence of footsteps remains same and unchanged. The analysis of walk gait for all types of characters under study (Horse, Lion, Tiger & Cat) was done and Figure 9 shows the footfall pattern of Lion walk gait. The footfall pattern of

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Tiger and Cat was generated and their motion was analyzed. In quadruped walk, each foot leaves and strikes the ground at different times, thus referred as 4-beat gait. There is no particular order of leg starting the walk motion. Any leg can be used to start the motion and the footfall sequence will be synchronous as discussed in previous section and already illustrated in Figure 7. In Figure 9, the frames 1 and 35 represent identical gait when all four legs are on the ground and mark start of the walk gait cycle. Frames 2, 7, 20 and 25 mark the phases when each leg leaves the stance phase and enters swing phase, whereas the in-between frames correspond to the secondary motion of the legs in a single motion cycle. Frames 2, 12, 20 and 30 highlight the triangular footfall support base system during walk gait. The swing phase and footfall timing of each leg was derived from this footfall pattern diagram and swing phase timing was calculated using Figure 10.

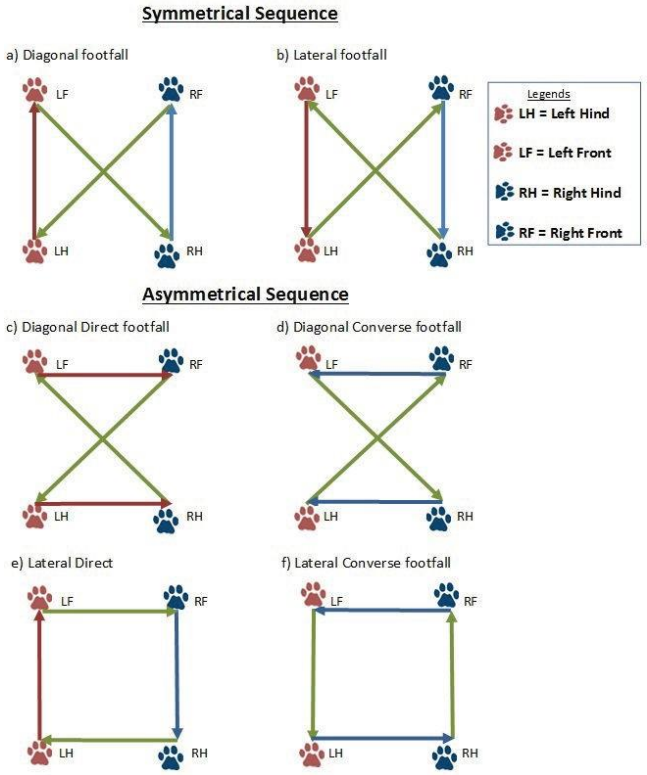

Fig. 8 Symmetrical and Asymmetrical footfall sequence of quadrupeds

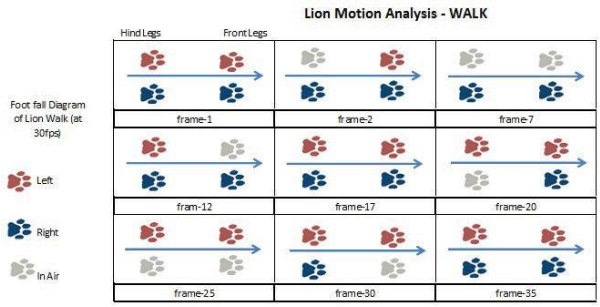

Fig. 9 Walk footfall pattern of Lion Character

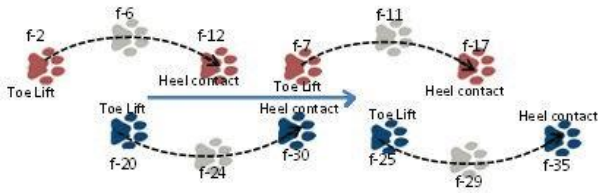

Fig. 10 Foot swing phase during Lion's walk motion

The timing information of walk gait is obtained through the Gait graph shown in Figure 11, generated from the video footage analysis and footfall pattern diagram. The solid colored bars indicate the leg in swing motion whereas the white space in-between indicates the leg in stance phase. The gait graph illustrates the time for the feet contact and swing time for each leg.

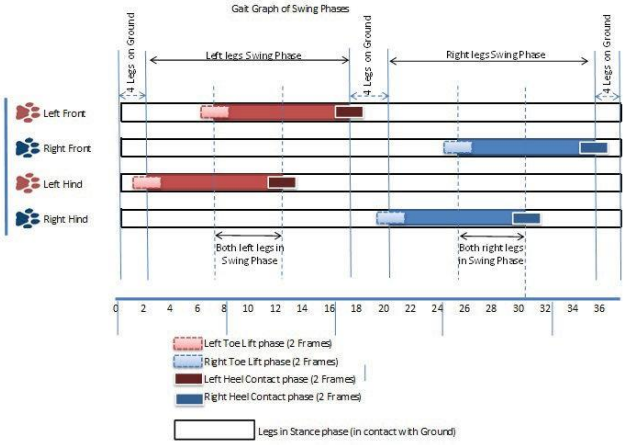

Fig. 11 Gait graph of Walk motion of a Lion

B. Synopsis of Trot Gait

Trot Gait is a steady, natural, 2 beat gait with diagonal leg footfall pattern. The diagonal gait pattern allows the legs to be raised before the other diagonal pair of legs would touch the ground with suspension of all four feet's. The natural footfall sequence of trot gait is left front (LF) + right hind (RH) legs in a left diagonal pattern with 1st beat, whereas, the 2nd beat footfall is normally right front (RF) + left hind (LH) legs in a right diagonal pattern. This leg sequence is evident in the footfall diagram of Tiger motion given in Figure 12, where the asymmetrical diagonal direct gait pattern is visible in each phase of the gait. The timing information of this asynchronous trot motion is obtained through generating the gait graph, as illustrated in Figure 13. As it can be seen the LF and RH move together in same sequence and for same time in left diagonal sequence, whereas the RF and LH move together in right diagonal sequence.

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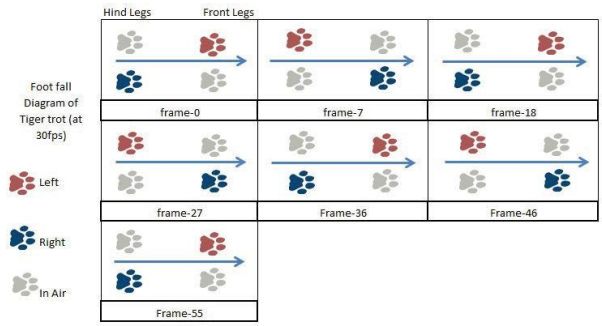

Fig. 12 Footfall pattern of Tiger's Trot gait

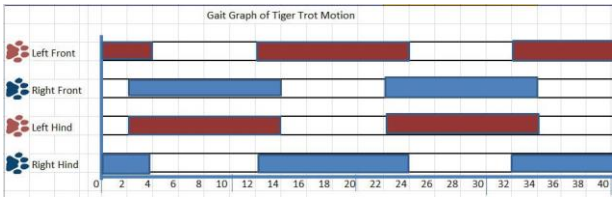

Fig. 13 Gait graph of tiger Trot motion

Trot gait has a variation which alters the timing of the legs slightly to produce a suspension in motion. This suspension results in all four legs being in the air for a very brief moment. Sometimes this gait is referred to as Running Trot or Fast Trot. The timing graph for this gait type is shown in Figure 14. Contrarily, the slow Trot is often referred to as the Jog gait.

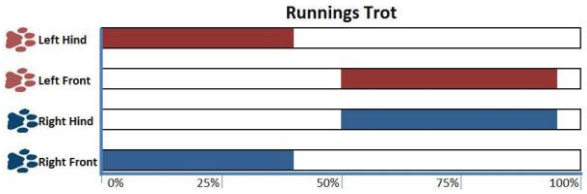

Fig. 14 Timing graph of running Trot gait

C. *Canter Gait*

The Canter is a 3 beat gait, considered as restrained or collected gallop motion. The leg support and footfall alternates from one leg to, two diagonal legs and then back to one leg footfall cadence. This is also a very common and natural gait found in most of the quadruped animals. The leg motion has both left and right lead sequences, depending usually on the previous gait phase and gait transition as illustrated in Figure 15.

The footfall sequence of each leg is illustrated in Figure 16, showing the left lead foot sequence in four simple phases. In a Left Lead phase, the RH enters stance phase first as 1st beat, with LH and RF following in 2nd beat, finally LF falls on ground as 3rd beat as illustrated in Figure 17(a). The suspension phase occurs when the LF foot leaves the ground, starting swing phase. Similarly in Right Lead phase, the LH leads the 1st beat, followed by RH and LF as 2nd beats, with lastly followed by RF landing on ground as 3rd beat, illustrated in Figure 17(b). Here, the period of suspension is observed after the RF leaves the ground and enters swing phase. Hence, there is a period of suspension where all four legs are in air with swing phase, after each stride.

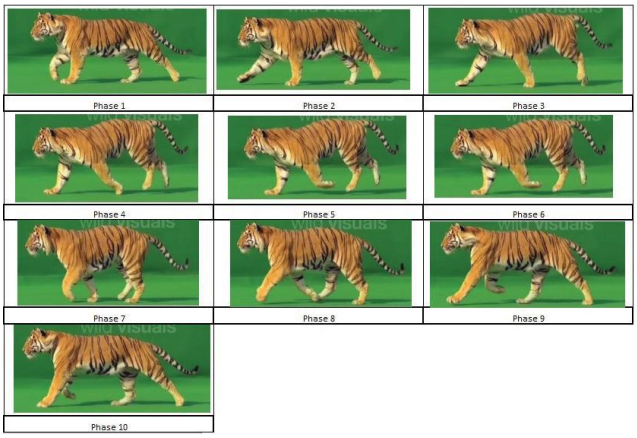

Fig. 15 Frame-by-frame breakdown of Tiger Canter gait with right lead

Fig. 16 Canter gait footfall sequence with left lead

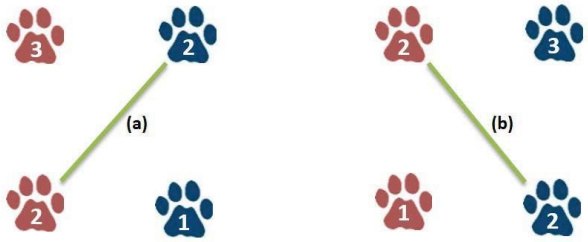

Fig. 17 Canter Gait of Horse motion (a) Left Lead Canter sequence (b) Right Lead Canter sequence

Canter is a natural gait especially to horses which usually is considered a slightly faster than the normal Trot gait, however, slower than the gallop gait. The faster the speed of motion in a straight direct, longer will be the suspension phase between the three beats. The gait graph of canter motion is given in Figure 18, where solid colored bars indicates that time leg is in stance phase (in contact with ground), and white area indicates leg in swing motion (in air).

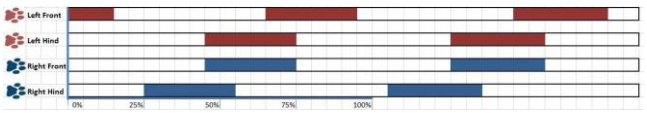

Fig. 18 Canter Gait Graph where solid bars show the leg in stance phase, and white area indicates leg in swing motion

D. *Gallop Gait*

A Gallop is one of the famous gait types for quadrupeds with 4 beat patterns, moving with a fast speed. It is similar to Canter gait type, but the diagonal paired motion of legs do not follow exact sequence, neither do they land or enter the swing phase at the same time. Normally extending to two beat motions, in gallop the hind foot of quadrupeds, touches the ground slightly before the diagonal front foot. Gallop

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motion has got left and right lead motions similar to Canter gait, with suspension phase occurring after the last front foot leaving the ground. Some of the faster animals have a very short stance phase time with longer swing phase time as legs remain in air for longer period of time and just briefly touch the ground to gain momentum and speed. Generally these patterns have been classified into two types, Transverse Gallop and Rotary Gallop. In transverse gallop the footfall sequence succeed a cross pattern as shown in Figure (19:Top). Whereas, in rotary gallop, the footfall sequence succeeds in a clockwise or anticlockwise rotative pattern illustrated in Figure (19: Bottom).

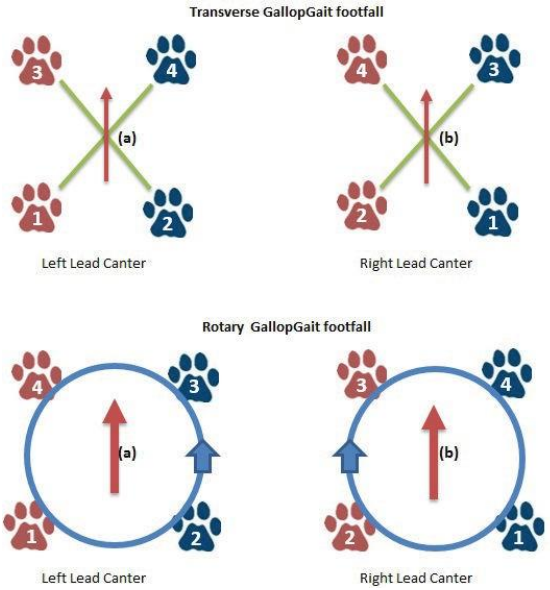

Fig. 19 Transverse (Top) and Rotary Gallop gait footfall symmetry

Footfall sequence of the transverse gallop gait of quadruped is illustrated in Figure 20. Similarly, Figure 21 shows the timing pattern of each legs swing phase in colored bar, where white area indicates leg in swing motion.

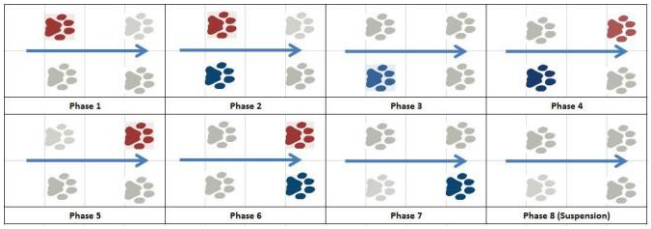

Fig. 20 Transverse Gallop gait footfall sequence of quadrupeds

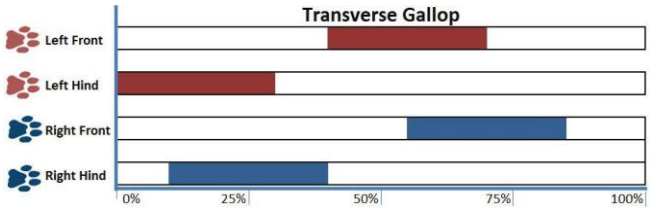

Fig. 21 Gait graph of Transverse Gallop footfall timing

The footfall pattern of rotary gallop gait is illustrated in Figure 22. Similarly, Figure 23 shows the timing pattern of rotary gallop for each legs swing phase in colored bar, where white area indicates leg in swing motion.

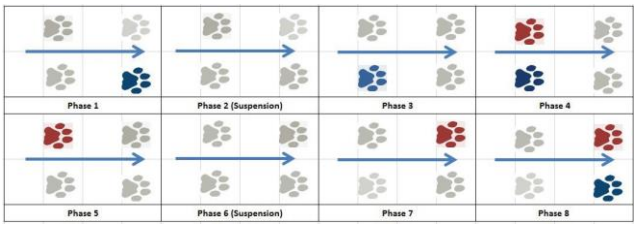

Fig. 22 Rotary Gallop gait footfall sequence of quadrupeds

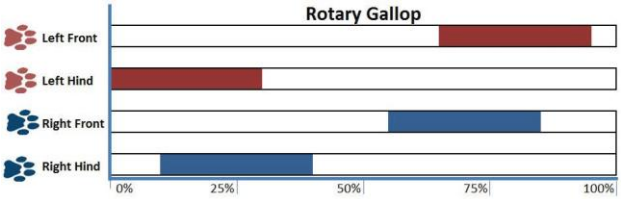

Fig. 23 Gait graph of Rotary Gallop footfall timing

E. Running or Pace Gait

The running motion gait referred to as Pace gait, is a lateral two-beat gait. During this running gait, the two legs on the same side of the quadrupeds move forward together, unlike the trot, where the two legs which are diagonally opposite from each other move forward together. In both the pace and the trot, two feet are always off the ground. The footfall pattern of pace gait is illustrated in Figure 24 where the two feet are always on the ground in contact phase.

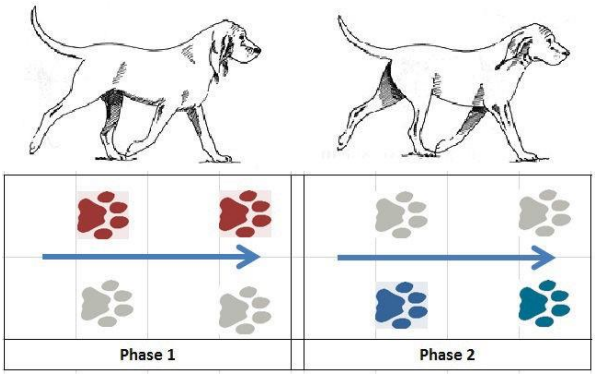

Fig. 24 Footfall pattern of Pace gait

F. Ambling Gait

A quadruped generally has a several types of 4 beat gaits which are considered as intermediate gaits, having varying speed with different footfall patterns. Therefore, historically they were once grouped together and collectively referred to as the "amble" and this gait continuum is illustrated in Figure 25. Ambling gaits are usually faster than a walk but normally slower than a canter. The amble gait is generally lot smoother in motion as compared to trot or a pace gaits, and so can easily be continued for a longer period of time.

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Fig. 25 Amble gait continuum

IV. CONCLUSION AND DISCUSSION

This paper discussed the motion analysis of various gaits of the quadruped characters, Horse, Lion, Tiger and Cat. A detail analysis was done to understand the gait behaviors and footfall sequence of each locomotion type. A footfall pattern was illustrated of each gait for each character type. Then gait timing graph was created to understand and calculate the time of each legs stance phase and swing phase. Based on this motion analysis, various motion equations are formulated and different gait patterns are generated as discussed [16], [17]. The motion analysis study done in this work, shows that the gaits of a quadruped animals move with a periodic cyclic pattern in a symmetrical rhythm, as the four legs are already located in format symmetry. The symmetrical coupling of the four legs is represented in the Figure 26, where solid bars show the lateral and dotted lines show the diagonal synchronization. A cycle is represented by the interval between successive foot strikes of the same foot, from where the sequence is repeated [18].

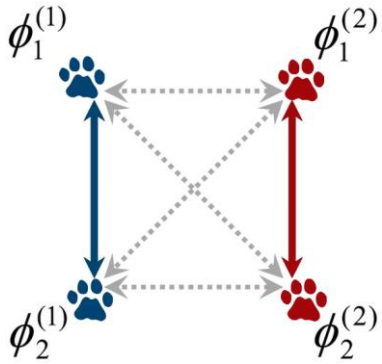

Fig. 26 The Lateral and Diagonal couplings are represented by the solid and dotted lines, respectively for a quadruped gait.

The motion of quadruped phenotypes produces two variants of gait phases, where the legs are out-of-phase (walking or running) or in-phase (jumping or hopping), with some gaits having a more complex behavior of the relative phase [4][18].

V. ACKNOWLEDGMENT

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