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Research Article

Biomechanical Parameters of Asian Elephant *(Elephas maximus)* Walking Gait

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Abstract

Quadruped animals have a unique mechanism of movement that minimizes energy use and allows muscles to work effectively. Elephants are the biggest quadruped animals on earth and how they stabilize their body and use energy are of interest. This study aimed to analyze the characteristics of kinematic gait in Asian elephants trained to work with a mahout for tourism activities in Thailand. Twenty-one healthy adult Asian elephants were recorded by 2 digital cameras while walking at normal speed (average 1.1 m s-1.) along a 15-meter, solid-soil path. The temporospatial parameters evaluated for each limb consisted of stride length (cm), stride time (sec), swing time (sec), stance time (sec) and stance time percentage, using 2D motion analysis software. The result revealed that the average stride length was varied between 192-199 cm with no significant difference between fore and hindlimbs on either side but the stride length on the right side was significantly longer than that on the left in both forelimbs (right 197.5 cm; left 192.6 cm, P<0.05) and hindlimbs (right 198.9 cm; left 193.2 cm, P<0.01). The mean gait cycle time (stride time) was varied between 2.26 and 2.34 seconds for each limb and mean stance time was varied between 1.67-1.80 seconds, with both parameters were longer on the forelimbs than hindlimbs significantly (P<0.01). Hence, swing time for the forelimb was shorter than that for the hindlimb (P<0.001). The calculated stance time percentage for each limb was 72.64-76.09%. Data from this study confirmed that elephants walk with a lateral sequence and footfall pattern, and distribute the center of mass proportionally between all four limbs. Gait analysis is a valuable tool for identifying and understanding the pathogenesis of gait abnormality.

Keywords: *Elephant, Gait cycle, Stride length, Stance time, Swing time*

Asya Filinin *(Elephas maximus)* Yürüme Biyomekanik Parametreleri

Özet

Dört ayaklı hayvanlar hareket ederken enerji kullanımını kısıtlayan ve kasların etkili bir şekilde çalışmasını sağlayan özgün bir mekanizmaya sahiptir. Filler dünyadaki en büyük dört ayaklı hayvanlar olup, vücutlarını nasıl stabil tuttukları ve enerji kullanımları hususu ilgi konusudur. Bu çalışma Tayland'da turist aktiviteleri amacıyla bir fil seyisi ile eğitilmiş olan Asya fillerinde yürüme kinematiği özelliklerini analiz etmeyi amaçlamaktadır. Yirmi bir sağlıklı ergin Asya fili sert toprak zemin üzerinde 15 metre boyunca normal hızda (ortalama 1.1 m s-1) yürürken 2 dijital kamera ile kayıt edildi. 2 boyutlu hareket analiz yazılımı kullanılarak her bir ayak için değerlendirilen temporospasyal parametreler; adım uzunluğunu (cm), adım süresini (dak), salınım süresini (dak), duraklama süresini (dak) ve duraklama süresi yüzdesini içermektedir. Ortalama adım uzunluğu her iki tarafta da ön ve arka ayaklar için anlamlı bir fark olmaksızın 192 ile 199 cm arasında kaydedildi. Ancak hem ön (sağ 197.5 cm; sol 192.6 cm, P<0.05) hem de arka ayaklar (sağ 198.9 cm; sol 193.2 cm, P<0.01) için sağ taraftaki adım uzunluğu anlamlı derecede sol taraftakinden daha uzundu. Ortalama yürüme siklus süresi (adım süresi) her bir ayak için 2.26 ile 2.34 saniye arasında değişirken ortalama duraklama süresi 1.67 ile 1.80 saniye arasında değişim gösterdi ve her iki parametre için de değerler ön ayaklar için arka ayaklardan anlamlı oranda daha uzun olarak tespit edildi (P<0.01). Ön ayaklar için salınım zamanı arka ayaklar için olandan daha kısa idi (P<0.001). Her ayak için hesaplanan duraklama süre yüzdesi %72.64-76.09 olarak belirlendi. Bu çalışmadan elde sonuçlar göstermiştir ki filler lateral sekans ve ayak basım şekli ve vücut ağırlık merkezini orantısal olarak dört ayağa yayarlar. Yürüme analizi yürüyüş bozukluklarının patogenezini tespit etme ve anlamada değerli bir yöntemdir.

Anahtar sözcükler: *Fil, Yürüme siklusu, Adım uzunluğu, Duraklama süresi, Salınım süresi*

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INTRODUCTION

The biomechanics of locomotion identifies the kinetic and kinematic mechanisms of gait, and was first introduced in veterinary practice in the late 19th century [1]. Kinetics is the study of cause of motion, which is concerned with forces applied to the body, acceleration, energy and work, whereas kinematics is the study of changes in the position of body segments in space during a specified time. Both kinetic (i.e., potential and kinetic energy) and kinematic variables (i.e., displacement of center of mass, linear and angular variables, velocity) underlie mechanisms that minimize muscular work and the metabolic cost of locomotion, which also involves neural control strategies [1]. Motion analysis has been used widely to measure normal and pathological gait. Measuring kinematic parameters can help to identify any pathologic conditions that could affect the characteristics of gait, i.e., orthopedic or neurological conditions, and the degree of gait asymmetry were found to relate to the degree of lameness [1,2].

Gait has been defined as a complex and coordinated rhythmic and automatic movement of the limbs and entire body of an animal, which results in the production of progressive movements [1,3]. The footfall pattern of a quadruped gait can be categorized into two general types; symmetrical (i.e., walk and trot) and asymmetrical (i.e., canter and gallop). The symmetrical gait pattern is found usually at slow to moderate speeds, changing to an asymmetrical pattern from moderate to high speeds, in which a suspension phase can be found in the trot, pace, canter, and gallop of horses [1]. Whereas, dogs and cheetahs have a different footfall sequence, known as the rotary gallop [4].

As elephants are the biggest quadruped animals [5], with adults weighing over 2.5 tons and being 3 meters high, their walking mechanism is of interest, particularly in terms of how they stabilize their huge body and utilize energy. Previous studies have reported the footfall pattern of elephants as a lateral sequence, when a hindlimb on one side makes contact with the ground, followed in the pendulum mechanism by the forelimb on the same side [5-7]. Unlike other quadruped animals, elephants maintain this symmetrical pattern even at faster speeds, which are increased by increasing stride frequency rather than stride length, and so they do not trot or pace [5,8]. Elephants maintain stability by using the pendulum mechanism, despite their massive bodies, and they conserve energy with effective muscular work [9,10]. They maintain movements of mass per unit distance with only one-third of the average mass-specific mechanical work of other animals [5]. To date, biomechanical studies of elephant locomotion are still limited, due to complex methodology, and costly laboratory equipment and program analysis. Hence, this study aimed to focus on the temporospatial parameter of Asian riding elephants that were trained to work with a mahout for tourism activities in Thailand. Even formerly it had been done by Hutchinson et al.[6], this study used simple methodology, did not need high technology in a laboratory setting, therefore clinicians can use this technique further for field study and the subjects in this study were riding elephants for tourism, unlike those in a zoo or the natural environment. The research knowledge and database gained from this study will add information that can be applied to monitoring lifelong elephant health management.

MATERIAL and METHODS

Ethical Approval

This study was approved by The Animal Care and Use Committee of the Faculty of Veterinary Medicine (FVM-ACUC), Chiang Mai University, Research ID 9/ 2013.

Animals

One male and 20 female adult Asian elephants (*Elephas maximus*) from the Thai Elephant Conservation Center, National Elephant Institute, Forest Industry Organization, Lampang, Thailand, were evaluated by experienced veterinarians from the Center's elephant hospital and approved as being clinically healthy, i.e., appropriate body composition score, no neurological or musculoskeletal problems, prior injuries that affected movement, and no aggressive behavior. The elephants used in this study worked as riding elephants with a harness on their back, and they were guided by their own mahout. Practice trials were conducted to ensure that the elephant and mahout were familiarized with the experimental setting and able to walk at a comfortable and normal speed.

Video Recording and Temporospatial Analysis

Markers with reflexive tape were applied to the elephant at the joint landmarks of each limb by the same veterinarian, according to procedures described by Wijesooriya [7]. The elephant subjects walked in a straight line at a normal, comfortable speed for 15 meters up a walkway before turning back. Two digital cameras (Nikon: D3300, frame size 1280×720 pixels, frame rate of 30p) were set one on each side of the walkway and 10 meters away from it to record the movement of the elephant. Temporospatial parameters that evaluated each limb consisted of stride length (cm), stride time (sec), swing time (sec), and stance time (sec). The length of stride or gait cycle corresponded to the distance between two consecutive ground contacts by the same limb. Each cycle of limb movement included the stance, the phase during which a limb made contact with the ground and the swing when the limb is not contact with the ground [1]. Stance time percentage was calculated as (stance time/gait cycle time) x 100. Velocity or speed was calculated from the average of distance divided by duration of the same limb. These parameters were digitized and calculated for three consecutive gait cycles using two-dimensional (2D) motion analysis Kinovea® software [11].

Statistical Analysis

Data were recorded as mean and standard deviation. Paired sample t-tests were used to analyze the differences of each parameter between forelimbs and hinlimbs of each side, with significant difference set at P<0.05.

RESULTS

Twenty-one elephants were enrolled into this study. Their average age was 32.7±10.2 years and weight 3.059.62±555.19 kg, and 20 of the 21 subjects were female. The demographic data are shown in *Table 1*.

The average stride length of each limb varied between 192-199 cm *(Table 2)*, with no significant difference between the fore and hindlimb on each side, but surprisingly, the average stride length on the right side was significantly longer than that on the left (right forelimb 197.45±29.06 cm vs left forelimb 192.64±28.29 cm; P<0.05; right hindlimb 198.94±29.97 cm vs left hindlimb 193.20±27.62 cm; P<0.01). Stride time or gait cycle time of both forelimbs was significantly longer than that of the hind limbs (left forelimb = 2.31±0.65 sec vs hindlimb = 2.26±0.63 sec; P<0.01 and right forelimb = 2.34±0.64 sec. vs hindlimb 2.26±0.59 sec, P<0.01). The stance time of both forelimbs was also significantly longer than that of the hindlimb (left forelimb = 1.76±0.62 sec. vs hindlimb = 1.67±0.58 sec; P<0.001 and right forelimb = 1.80±0.60 sec vs hindlimb 1.68±0.56 sec, P<0.001), which corresponded to the swing time of the forelimb being slightly shorter than that of the hindlimb, with significance on both the left and right side (P<0.001) *(Table 3)*. The stance time percentage for each limb was about 75%, with the right forelimb = 76.09%, left forelimb = 75.07%, right hindlimb = 73.28% and left hindlimb = 72.64%.

DISCUSSION

Locomotion in all animals takes place in order to transport the body, but in order to maintain such movement in various situations they need unique mechanisms with effective energy usage. Biomechanics studies of gait revealed that humans and animals use an "inverted pendulum" mechanism during walking

Table 1. *Demographic data of the Asian elephants (n =21)*

ID	Name	Age (year)	Sex	Weight (kg)	Shoulder height (cm)	Hip height (cm)	Body length (cm)	BCS
1	Jojo	25	M	4.020	267	272	420	4
2	Nue-oun	12	F	2.515	225	235	321	4
3	Prajuab	32	F	3.880	237	243	393	5
4	Kod	33	F	3.640	240	250	395	4.5
5	Pumpuang	40	F	3.970	253	258	381	5
6	Wanalee	20	F	3.090	205	207	346	4.5
7	Areena	12	F	2.280	242	238	325	3
8	Warunee	30	F	3.025	232	228	372	3
9	Taddao	35	F	3.130	312	234	340	4
10	Suwanan	33	F	3.060	257	241	356	4
11	Sankham	41	F	2.565	217	218	310	3
12	Pooky	41	F	2.930	230	227	330	4.5
13	Payom	30	F	2.590	278	273	365	3
14	Manao	24	F	2.395	332	234	340	3.5
15	Mali	41	F	2.890	253	257	344	4.5
16	Linda	32	F	2790	336	238	370	3
17	Kam-nguen	49	F	3.090	242	248	341	3
18	Kammoon	47	F	4.060	258	267	385	4.5
19	Kanjana	30	F	2.660	227	230	330	3
20	Boyo	45	F	3.155	240	240	350	3
21	Boonpeum	35	F	2.515	315	218	356	4.5
Mean		32.71		3.059.62	257.05	240.76	355.71	3.83
S.D.		10.17		**555.19**	**37.31**	**17.60**	**27.98**	**0.75**

BCS: *Body Condition Score*

Table 2. *Average stride length of the Asian elephants (n=21)*

Parameter		Forelimb (Mean ± S.D.)	Hindlimb (Mean ± S.D.)	P-value
Stride length (cm)	Left	192.64±28.29	193.20±27.62	0.64
	Right	197.45±29.06	198.94±29.97	0.20
P-value		0.03	0.005	

Paired samples t-test; significance level at P-value <0.05

Table 3. *Stride, swing, and stance time of the Asian elephants (n=21)*

Parameter		Forelimb (Mean ± S.D.)	Hindlimb (Mean ± S.D.)	P-value
Stride time (sec.)	Left	2.31±0.65	2.26±0.63	0.002
	Right	2.34±0.64	2.26±0.59	0.003
Swing time (sec.)	Left	0.55±0.06	0.59±0.06	<0.001
	Right	0.54±0.06	0.58±0.06	<0.001
Stance time (sec.)	Left	1.76±0.62	1.67±0.58	<0.001
	Right	1.80±0.60	1.68±0.56	<0.001
Stance time percentage (%)	Left	75.07	72.64	
	Right	76.09	73.28	

Paired samples t-test; significance level at P-value <0.05

gait [3,12-15]. Each limb generates ground force patterns that cause the fore and hind quarters to vault over their respective stance limbs, like inverted pendulums. This mechanism is a fundamental system that bipedal, quadrupedal, and even hoppers, like kangaroos, use to minimize muscular work and the metabolic cost of locomotion, with an effective exchange between potential gravitational and kinetic energy during the gait cycle. It is a cyclic exchange between gravitational potential energy and kinetic energy within each stride, aimed to maintain movements of the center of mass per unit distance [3-5,13,14]. At the start of a step, the center of mass becomes high; kinetic energy is converted into potential gravitational energy, and then moves forward and downward during the second half of a step, when potential gravitational energy is converted back into kinetic energy. Alternate transference of these two forms of energy results in some energy loss, but in the stance phase, leg performs like a pendulum that the hip moves along an arc and no moment acts, so with the knee kept rigid, muscles do not work. This inverted pendulum contributes to effective energy exchange, in which up to 70% of energy can be recovered [3,12,15].

In terms of the kinematic mechanism of an elephant, walking and running differ in the mechanics of center of mass motion [13]; walking and running types of gait are identified by several factors: duty factors (fraction of the stride duration in which each foot remains on the ground), Froude number (dimensionless speed parameter), phase relationship between kinetic and potential energies, and the slope of the vertical ground reaction force [5,13]. During running gaits, such as trotting, hopping and galloping, potential energy and kinetic energy are converted into elastic strain energy of a bouncing mechanism, like a mass-spring system [3,12-14]. A duty factor above 0.5 has been used to indicate walking, with feet on ground for more than half of each stride cycle, and a duty factor of below 0.5 indicates running [5].

Analysis of elephant locomotion is limited, however, the studies of Hutchinson et al.[6], Ren et al.[16], and Genin et al.[5] clarified the locomotor kinetic and kinematic characteristics of Asian elephants. They revealed that elephants, as with other quadrupeds, use a lateral sequence footfall pattern during walking to achieve the objectives of effective energy expenditure and minimal muscular work [5,6,16]. The temporospatial parameters reported in this study were consistent with those found in previous literature, even though all of the subjects were riding elephants guided by their own mahout and trained to work in tourism activities. The stride length of each limb was approximately 200 cm, ranging from 192.6 to 198.9 cm, with no significant difference between the fore and hindlimb on each side at a comfortable walking speed of average 1.1 ms^{-1}. This may confirm that elephants walk with a lateral sequence footfall pattern, and distribute their center of mass proportionally across all four limbs, as reported in previous studies [5-7,16].

It was somewhat surprising that in this study the average stride length on the right side was significantly longer than that on the left (P<0.05 for both fore limbs and hind limbs). Most of the subjects were adult elephants ridden by mahouts; and as domesticated Asian elephants, unlike zoo-captive elephants, their gait characteristics may have been influenced from a young age by training or developing lateralization behavior for a preferred side, as indicated by Haakonsson and Semple [17], who stated that left-side trunk movement bias was associated with feeding, swinging and self-touching. Thus, stride length in this study might reflect the lateral preference of Asian elephants.

With temporal parameters, the stride or gait cycle time of the forelimb was significantly longer than that of the hindlimb on both sides (P<0.01). Average stance time of all four limbs was between 1.67 and 1.80 sec., with the stance time of the forelimb significantly longer than that of the hind limb (P<0.001), as reflected in a shorter swing time of both fore limbs when compared to the hind limbs (P<0.001). The stance time percentage for each limb was about 75% (ranging from 72.64 to 76.09%). Temporal data from this study were consistent with those in the studies of Genin et al.[5] and Wijasooriya et al.[7] in that elephants may bear more weight on their forelimbs in order to support their massive body weight. This study also confirmed that Asian elephants spend a single limb swing phase of only approximately 25%, and distribute their body weight to the other three legs in order to maintain stability while accelerating the body forward. Therefore, even with their huge bodies, elephants are able to consume energy, reduce muscular work, and maintain their stability effectively.

The temporospatial parameters from this study confirmed those from earlier data, in that the bio-mechanics of the Asian elephant's low-speed walking is similar to that in other quadruped mammals. This study used simple technology and equipment, including two digital cameras, which veterinarians or researchers apply to field study. Understanding the biomechanics of elephant locomotion also can be used as objective measurement in clinical care and research. However, the normal kinematic parameter should be continued to study and compare walking in lifelong daily work, since it might provide other health parameters for elephant welfare and management.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Authors' Contribution

Kongsawasdi S. was a major contributor, who designed, conducted, collected, and statistical analyzed the data in this study. Mahasawangkul S. and Boonprasert K. arranged in the process of evaluation of eligible subjects and data collection. Pongsopawijit P., Chuatrakoon B., Thonglorm N., and Kanta-in R. assisted in data collection. Tajarernmuang T. assisted in data analysis using Kinovea® software for motion analysis. Pongsopawijit P. and Nganvongpanit K. provided advice and support of information for discussion. Kongsawasdi S. wrote the manuscript and Pongsopawijit P. assisted in the discussions and writing of the manuscript.

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