FULL PAPER
Surgery

Functional assessment of the gluteus medius, cranial part of the biceps femoris, and vastus lateralis in Beagle dogs based on a novel gait phase classification

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ABSTRACT. In humans, walking analysis based on the gait phase classification has been used for interpretation of functional roles of different movements occurring at individual joints, and it is useful for establishing a rehabilitation plan. However, there have been few reports on canine gait phase classification, and this is one of the reasons for preventing progress in canine rehabilitation. In this study, we determined phases of the canine gait cycle (GC) on the basis of the phase classification for human gait. The canine GC was able to be divided into initial contact (IC) and the following 5 phases: loading response (LR), middle stance (MidSt), pre-swing (PSw), early swing (ESw), and late swing (LSw). Next, the hind limb joint angles of the hip, stifle and tarsal joints and results of surface electromyography of the gluteus medius (GM), cranial part of the biceps femoris (CBF) and vastus lateralis (VL) muscles in relation to the gait phases were analyzed. The activities of three muscles showed similar changes during walking. The muscle activities were high in the LR phase and then declined and reached a minimum in the PSw phase, but they increased and reached a peak in the LSw phase, which was followed by the LR phase. In conclusion, the multiphasic canine GC was developed by modification of the human model, and the GC phase-related changes in the muscle activity and joint angles suggested the functions of GM, CBF and VL muscles in walking.

KEY WORDS: dog, gait analysis, gait phase classification, rehabilitation, surface electromyography

Rehabilitation and physical therapy are effective for recovery of body functions from various disorders of orthopedic and neurological origins. Appropriate physical therapy methods are generally selected on the basis of an individual patient's abnormal movement in human medicine [18, 32]. In therapy for gait disorders, physical therapists detect abnormal movements by comparison with normal movements based on phases of the gait cycle (GC). The GC is measured between the first contact of a leg with the ground and the second contact of the same leg with the ground. The human GC is divided into two major phases: stance and swing phases. The stance phase is further divided into the following 5 subphases: initial contact, loading response, mid stance, terminal stance and pre-swing. The swing phase is also divided into the following 3 subphases: initial swing, mid swing, and terminal swing. Thus, the human GC consists of eight phases [31, 39, 46]. Kinesiological data such as data for kinematics, kinetics, and electromyography can be integrated for each gait phase by using gait phase classification. Classification of gait phase is useful for interpretation of a kinesiological function of different motions generated by an individual joint [4]. Physical therapists estimate the causes of the patient's abnormal movement by referring to the functional role of kinesiological data in each phase of the GC [31, 36]. Therefore, the establishment of normal GC phases has markedly contributed to the development of rehabilitation and physical therapy in humans.

Attention has recently been given to rehabilitation for companion animals such as dogs. As in humans, gait analysis is considered to be indispensable for judging the status of gait and assessing the effectiveness of rehabilitation for companion animals [5, 25, 33, 34, 38, 44, 45]. Analysis of canine gait has been attempted on the basis of methods that have been used in humans

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[14, 29, 35, 45]. There have been some studies on classification of canine GC phases, but the number of phases has remained controversial. Some studies have suggested a two-phase classification consisting of stance and swing phases [7, 8, 15, 17, 23, 30], while others have indicated a three-phase or four-phase model [6, 8]. The two-phase model is simple and is clearly defined by contact of the leg with the ground and lifting of the leg from the ground. However, the two-phase model is not appropriate for precise walking analysis because the number of phases is insufficient to explain the complex movements of the limbs. Although there is a three-phase model consisting of two stance phases and one swing phase, the criteria for dividing the stance phase into two phases have not been described [8]. In a four-phase model consisting of two stance phases and two swing phases, each stance phase and each swing phase is automatically divided into two equal durations [6]. Therefore, it is thought that a three-phase model or four-phase model is not based on actual walking events. The functional roles of limbs change depending on the walking event such as braking with hind limb contact or propulsion with a single hind limb support [21, 44]. The sequential roles of limbs during walking should be categorized according to the actual walking events, not simply defined in time. Although joint angles, ground reaction forces, and muscle activities were described in detail in previous reports [21, 22], there have been few attempts to examine canine gait movements by comprehensively integrating data. If kinesiological data are inclusively interpreted on the basis of a detailed classification as in humans, it would be possible to clarify the functional role of each limb at each walking event. Thus, for the development of canine rehabilitation for walking, the establishment of an accurate canine gait phase classification and an understanding of the functions of different motions occurring at individual muscles and joints are needed.

In dogs, there are large numbers of patients suffering from hind limb diseases such as patella luxation and rupture of the cranial cruciate ligament. Therefore understanding a hind limb muscular function is essential to establish appropriate rehabilitation and physical therapy for these patients. The purpose of this study was to determine the canine hind limb gait phase and to assess the functions of three main hind limb muscles, such as gluteus medius (GM), cranial part of the biceps femoris (CBF) and vastus lateralis (VL) in each gait phase.

MATERIALS AND METHODS

Dogs

Eight beagles (3 females and 5 males) owned by Rakuno Gakuen University were used in this study. The dogs were aged from 4 to 8 years (5.6 ± 0.6 years). Their body weights ranged from 10.0 to 14.7 kg (12.3 ± 0.6 kg) and their body heights (measured from the ground to the dorsal aspect of the scapula) ranged from 37.0 to 40.5 cm (38.7 ± 0.5 cm). All of the dogs were healthy and free of orthopedic and neurologic abnormalities as determined by results of orthopedic and neurologic examinations. All procedures were approved by the Experimental Animal Research Committee of Rakuno Gakuen University (VH17B7).

Measurement procedure

All experiments were performed on a treadmill (AF 1900; ALINCO, Osaka, Japan). After the dogs had become habituated to walking on the treadmill for 3 days (20 min habituation session twice a day), we acquired data for 10 valid GCs. The treadmill speed was set at 0.7 m/sec with reference to a previous study using beagles [1]. At this treadmill speed, beagles can walk smoothly and with good coordination.

Gait phase classification of the canine hind limb

There are morphological differences between human lower limbs and canine hind limbs. However, walking for both humans and dogs is characterized by the inverted pendulum model, which is a cyclic exchange between gravitational potential energy and kinetic energy [27]. In addition, the locus of the vertical ground reaction force when walking is represented by an M-shaped graph for both human lower limbs and canine hind limbs [8, 16, 44]. Other previous studies showed that a walking dog behaves like two humans walking in front and behind because there are similarities of kinetics during walking between human and canine forequarters or hindquarters [2, 3, 27]. Therefore, the gait phase classification for humans is possible to apply for dogs. In this study, only the canine hind limb gait phases were defined for simplification. Based on a comparison with walking events observed in humans [31, 39] (Fig. 1), classification of canine gait phases was performed. Walking events in canine hind limbs were similar to those in humans [8, 16, 44] (Fig. 1). However, unlike humans, dogs walk without touching their heels on the ground and the terminal stance related to heels was excluded. We also excluded mid swing due to the anatomical differences in the ranges of motion for the canine hind limb and the human lower limb. Therefore, canine gait phases were considered to be initial contact (IC) and five following phases: loading response (LR), middle stance (MidSt), pre-swing (PSw), early swing (ESw), late swing (LSw) (Fig. 1).

Calculation of phases of the GC

We used a KinemaTracer three-dimensional motion analysis system (Kissei Comtec Co., Ltd., Matsumoto, Japan) in this study. The KinemaTracer is included in a computer for recording and analysis, and four CCD cameras were set up around a treadmill; image size was 640 × 480, frame rate was 60 fps, and shutter speed was 1/96. Using double-sided adhesive tape (Kabetakku sponge double-sided adhesive sheet, Nichiban Co., Ltd., Tokyo, Japan) and kinesiology tape (Battlewin tape, Nichiban Co., Ltd.), 10 color markers (each 20 mm in diameter) were attached to anatomical landmarks of the hind limbs of each dog (Fig. 2). The anatomical landmarks were the iliac crest, greater trochanter of the femur, femorotibial joint between the lateral epicondyle of the femur and the fibular head, lateral malleolus of the distal portion of the tibia, and distal lateral aspect of the fifth metatarsal bone [30]. Kineanalyzer software (Kissei Comtec Co., Ltd.) was used to analyze video images. All video images were analyzed frame-
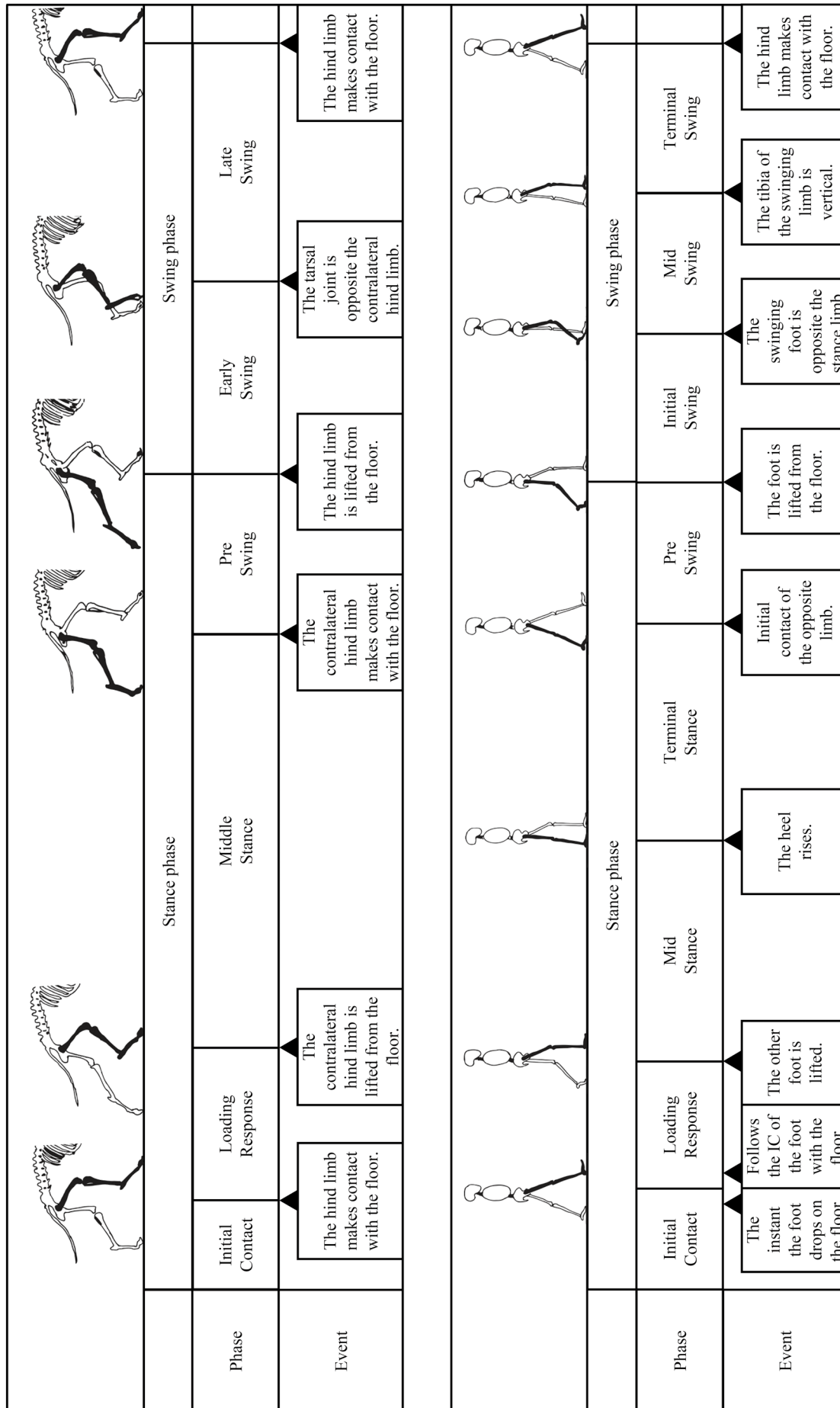
Fig. 1. Classifications of gait phases in canines and humans. The top panel is the canine hind limb gait phase classification and the bottom panel is the human gait phase classification [31].
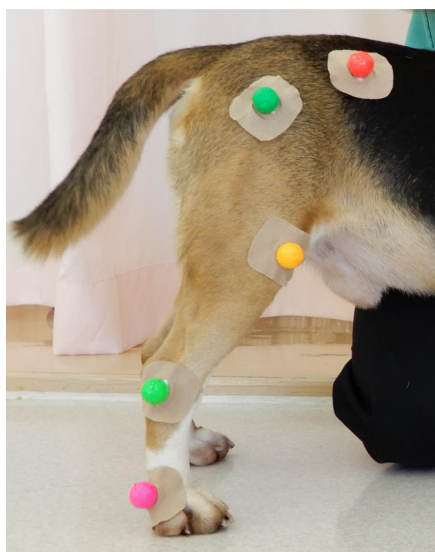
Fig. 2. Positions of color markers on anatomical landmarks of the canine hind limb: the red marker is the iliac crest, the green marker at a high position is the greater trochanter of the femur, the yellow marker is the femorotibial joint between the lateral epicondyle of the femur and the fibular head, the green marker at a low position is the lateral malleolus of the distal portion of the tibia, and the pink marker is the distal lateral aspect of the fifth metatarsal bone.
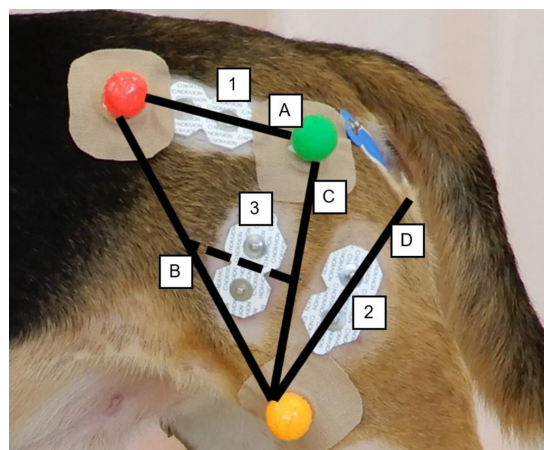

Fig. 3. Placement of surface electrodes over 1) the gluteus medius, 2) cranial part of the biceps femoris, and 3) the vastus lateralis. The solid lines represent (A) the line between the iliac crest and greater trochanter, (B) distance between the iliac crest and the patella, (C) distance between the patella and greater trochanter connection of their midpoints, and (D) the line between the patella and ischium tuberosity. The dotted line represents the junction between the middle of line B and line C.

by-frame by one person to divide all GCs into defined phases (Fig. 1). Relative duration of each gait phase at a walking speed of 0.7 m/sec was calculated as the average and standard error of the mean (SEM) of data for 10 GCs [(time between the IC and gait phase events) / (time between the IC and the following IC)] × 100%.

Recording of hind limb joint angles and GM, CBF and VL muscle activities

Measurements were conducted using 6 of the 8 dogs (3 females and 3 males). Muscle activities were sampled at 1,500 Hz using a telemetric unit (Telemyo 2400T G2, Noraxon USA, Inc., Scottsdale, AZ, USA) with kinematic measurements using a KinemaTracer three-dimensional motion analysis system (Kissei Comtec Co., Ltd.). The sampled muscle activity signals were filtered using a 20–500 Hz band-pass filter to remove any movement artifacts [35]. Self-adhesive surface electrodes with a distance between the electrodes of 20 mm (HEX Dual Electrodes, Noraxon USA, Inc.) were attached to the skin. The ground electrode was attached over the ischium tuberosity. The skin fur was clipped and shaved. A skin preparation gel (Skin Pure, Nihon Kohden, Tokyo, Japan) was used for achieving minimal skin impedance and then the skin was cleaned with sanitary cotton moistened with 80% ethanol. To ensure that the electrodes were attached at the same positions in all dogs, the electrodes were placed following a specific procedure by the same person (Fig. 3). For the GM muscle, the electrodes were placed at the midpoint of the distance between the iliac crest and greater trochanter [6, 8, 43]. For the CBF muscle, the electrodes were placed in the middle third of the distances between the ischial tuberosity and patella [6, 43]. For the VL muscle, the distances between the iliac crest and patella and between the patella and greater trochanter were measured. The midpoints of these lines were connected, and the electrodes were placed in the center of the resulting line [6, 43]. The electrodes were attached to the dogs when they were standing with their feet positioned squarely underneath the body [8].

Data normalization

Data normalization was performed to reduce variability and to improve reproducibility of the kinematic and surface electromyography (sEMG) data. This procedure made it possible to compare the data from individual dogs. Methods for normalization of kinematic and sEMG data have already been described [8, 13, 15]. In brief, time-normalized stride average data of kinematics and sEMG were generated from 10 valid GCs from each dog. The duration of each GC was standardized to 100 frames as the rate of the stride duration. The amplitude of sEMG was normalized by the following three steps. First, the amplitude of sEMG in each 10 valid GC was recorded and the maximum amplitude in each GC was appointed. Second, the average of the 10 appointed maximum amplitudes was calculated and considered as 100%. Third, each sEMG amplitude was indicated as a percentage of the maximum amplitude (%EMG).

Statistical analysis

Intraclass correlation coefficients (ICC) were used to determine intra-rater reliability of the timing of gait phase events (Model 1,

k). Data from the first to tenth GCs were used, and the SEM was calculated. We used a previously reported scheme based on ICC values: high reliability; 0.90 to 0.99, good reliability; 0.80 to 0.89, fair reliability; 0.70 to 0.79, and poor reliability; 0.69 and below [51, 52]. Statistical analysis was conducted using R version 3.6.1 software (R software, Vienna, Austria).

RESULTS

Gait phase classification of the canine hind limb and its validity

At a walking speed of 0.7 m/sec, the mean durations of the GC phases (one GC considered to 0–100%) were 0% to $13.6 \pm 0.3\%$ for LR, $13.6 \pm 0.3\%$ to $48.4 \pm 0.4\%$ for MidSt, $48.4 \pm 0.4\%$ to $63.9 \pm 0.4\%$ for PSw, $63.9 \pm 0.4\%$ to $81.3 \pm 0.3\%$ for ESw, and $81.3 \pm 0.3\%$ to 100% for LSw. ICC values for gait phase event classification were 0.86 (LR to MidSt), 0.71 (MidSt to PSw), 0.91 (PSw to ESw), and 0.88 (ESw to LSw) (Table 1). The relatively high ICC values (over 0.71) indicated the validity of this gait phase classification.

Kinematics based on gait phase classification

Hip joint (Fig. 4; upper panel): The hip joint at IC was flexed with a mean posture of 88°. During LR, the hip angle was relatively stable, but it extended progressively during MidSt. In PSw, the hip extension reached a peak and hip flexion began. The hip flexion continued in the first half of LSw. A subtle extension of the hip joint during the second half of LSw contributed to the final hip position just prior to IC.

Stifle joint (Fig. 4; middle panel): The stifle joint at IC extended with a mean posture of 138°. Following the onset of LR, the stifle had a steady flexion by the first half of PSw, and then rapid stifle flexion began. In ESw, the stifle reached a maximum flexion and then extension began. The stifle extension continued until the end of LSw.

Tarsal joint (Fig. 4; lower panel): During a GC, the tarsal made 4 arcs of motion. The first 2 arcs occurred in LR and PSw, and the later 2 arcs occurred in the swing phase of ESw and LSw. The tarsal flexion initiated by IC continued for the first half of LR and then reversed toward an extension. During MidSt, extension of the tarsal joint continued and reached a maximum in PSw, and then flexion began. The tarsal flexion continued during ESw, and extension began after maximal flexion had been reached. The tarsal extension continued, and a slight tarsal flexion was attained before the end of LSw.

sEMG based on gait phase classification

GM muscle (Fig. 5; upper panel): The GM was activated at the onset of IC, and its activity rapidly decreased toward the end of LR. From the onset of MidSt, the activity of the GM decreased gradually toward PSw, but its activity increased slightly in ESw and increased rapidly in LSw.

CBF muscle (Fig. 5; middle panel): The CBF muscle exhibited one peak activity during the transition between the swing and stance phases. The CBF was strongly activated at the onset of IC, and then its activity decreased until the end of MidSt and reached a minimum during PSw and the first half of ESw. In the latter half of ESw, the CBF activity increased rapidly and a high level of activity was maintained until the end of LSw.

VL muscle (Fig. 5; lower panel): The VL muscle showed high activity at IC, and then its activity decreased towards the end of LR. Moderate activity of the VL muscle was maintained until the first half of MidSt, however, it decreased from the latter half of MidSt and reached a lower peak at ESw. The activity increased from the end of ESw to LSw.

DISCUSSION

In this study, we classified canine gait phases based on human gait phases and evaluated the validity of the canine gait phase classification using intra-rater reliability of the timing of gait phase events. We also estimated the functional roles of muscles (GM, CBF and VL muscles) in relation to the gait phases using the results of simultaneous recording of hind limb muscle activities and joint angles.

We classified canine hind limb gait phases based on human gait phases. However, a comparison of human walking with canine walking showed that canine gait phases could not be classified in the same way as that for humans because humans are plantigrade and canines are digitigrade. In humans, IC (0 to 2% of the whole GC) includes the instant the foot makes contact with the ground

Table 1. Relative duration of each gait phase event at a walking speed of 0.7 m/sec

		Mean (%)	SEM	ICC
LR to MidSt	The contralateral hind limb is lifted from the floor.	13.6	0.3	0.86
MidSt to PSw	The contralateral hind limb makes contact with the floor.	48.4	0.4	0.71
PSw to ESw	The hind limb is lifted from the floor.	63.9	0.4	0.91
ESw to LSw	The tarsal joint is opposite the contralateral hind limb.	81.3	0.3	0.88

LR: loading response, MidSt: middle stance, PSw: pre-swing, ESw: early swing, LSw: late swing, SEM: standard error of the mean, ICC: Intraclass correlation coefficients (0.90 to 0.99, high reliability; 0.80 to 0.89, good reliability; 0.70 to 0.79, fair reliability; and 0.69 and below, poor reliability [51, 52]).
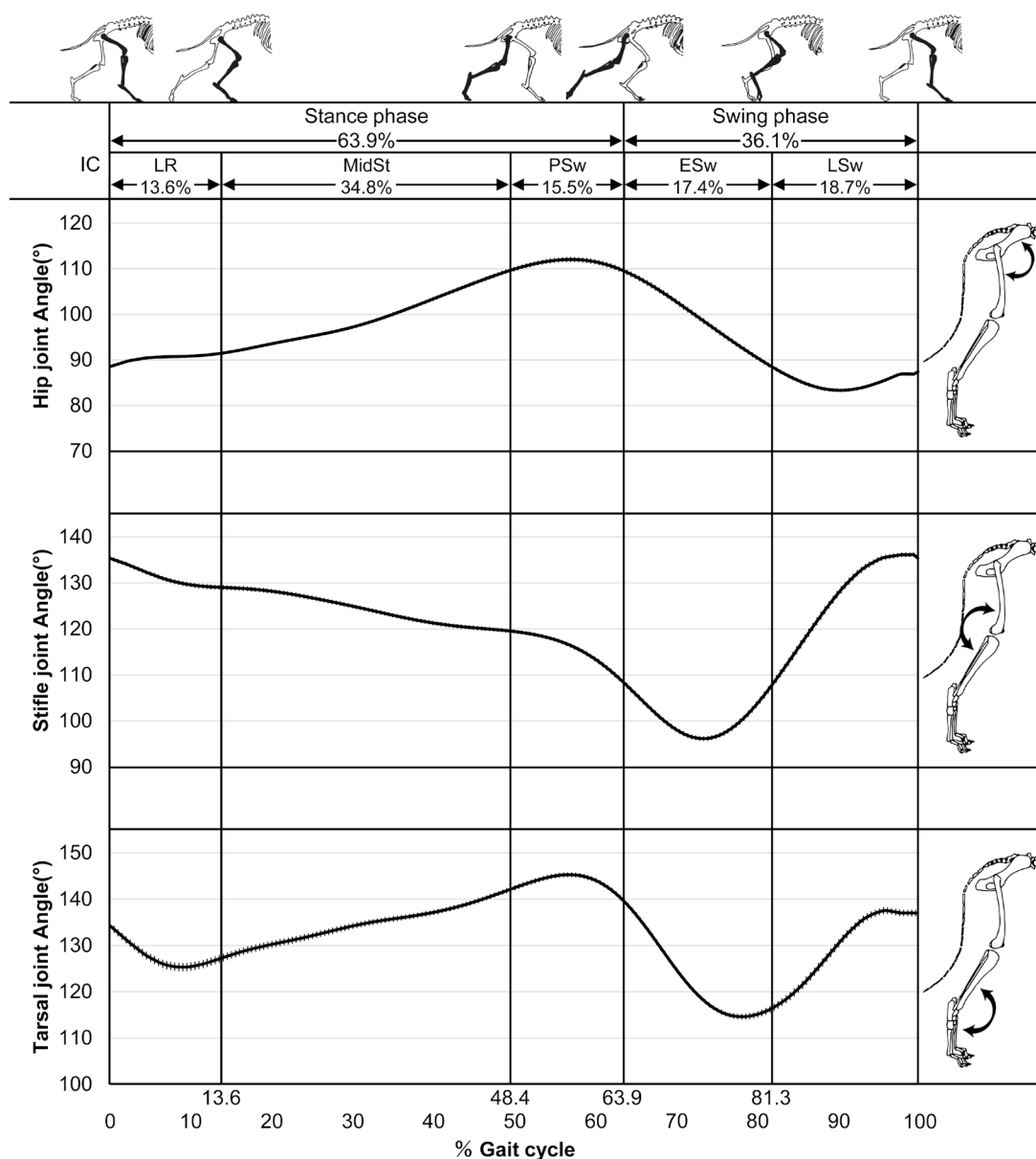
Fig. 4. Joint angle patterns of the hip (upper panel), stifle (middle panel) and tarsal (lower panel) when walking on a treadmill at a speed of 0.7 m/sec. The plot shows the mean (solid line) ± SEM (vertical lines) of joint angle data from all dogs. The x-axis represents the gait cycle (GC) in percent (%GC). Abbreviations are initial contact (IC), loading response (LR), middle stance (MidSt), pre-swing (PSw), early swing (ESw), and late swing (LSw). The y-axis represents the degree for each joint angle indicated by an arrow. Each joint angle changed depending on each gait phase.

and the immediate reaction to the onset of body weight transfer [31], but the definition of the end of this phase was unclear in the case of dogs. Therefore, in this study, IC was defined as the point (0% GC) when the foot was grounded. We also divided the swing phase into 2 phases by the event of "the tarsal joint being opposite to the contralateral hind limb". We assessed the validity of the canine gait phase classification using intra-rater reliability and confirmed high and good intra-rater reliability except for MidSt to PSw period. The ICC value (0.71) in MidSt to PSw period was the lowest among the GC periods but this value indicated the fair reliability in the reference classification [51, 52]. Although the reason for the low ICC value observed in MidSt to PSw period was not clarified at present, but individual difference in dog walking might be a possible factor. The phases of canine GC determined in this study provide an understanding of gait by integrating kinesiological parameters as in humans and are useful for detailed gait analysis of dogs.

In this study, we chose the GM, CBF, VL muscles for sEMG measurements because they are major stabilizers of the hip and stifle during weight-bearing [19, 26, 43]. Following cranial cruciate ligament transition and repair, a decrease in the thigh girth mainly due to atrophy of antigravity muscles such as quadriceps and biceps femoris has been reported [24, 37]. The focus of the early phase of rehabilitation in orthopedic patients (such as patients with cranial cruciate ligament rupture and patellar luxation) and neuromuscular
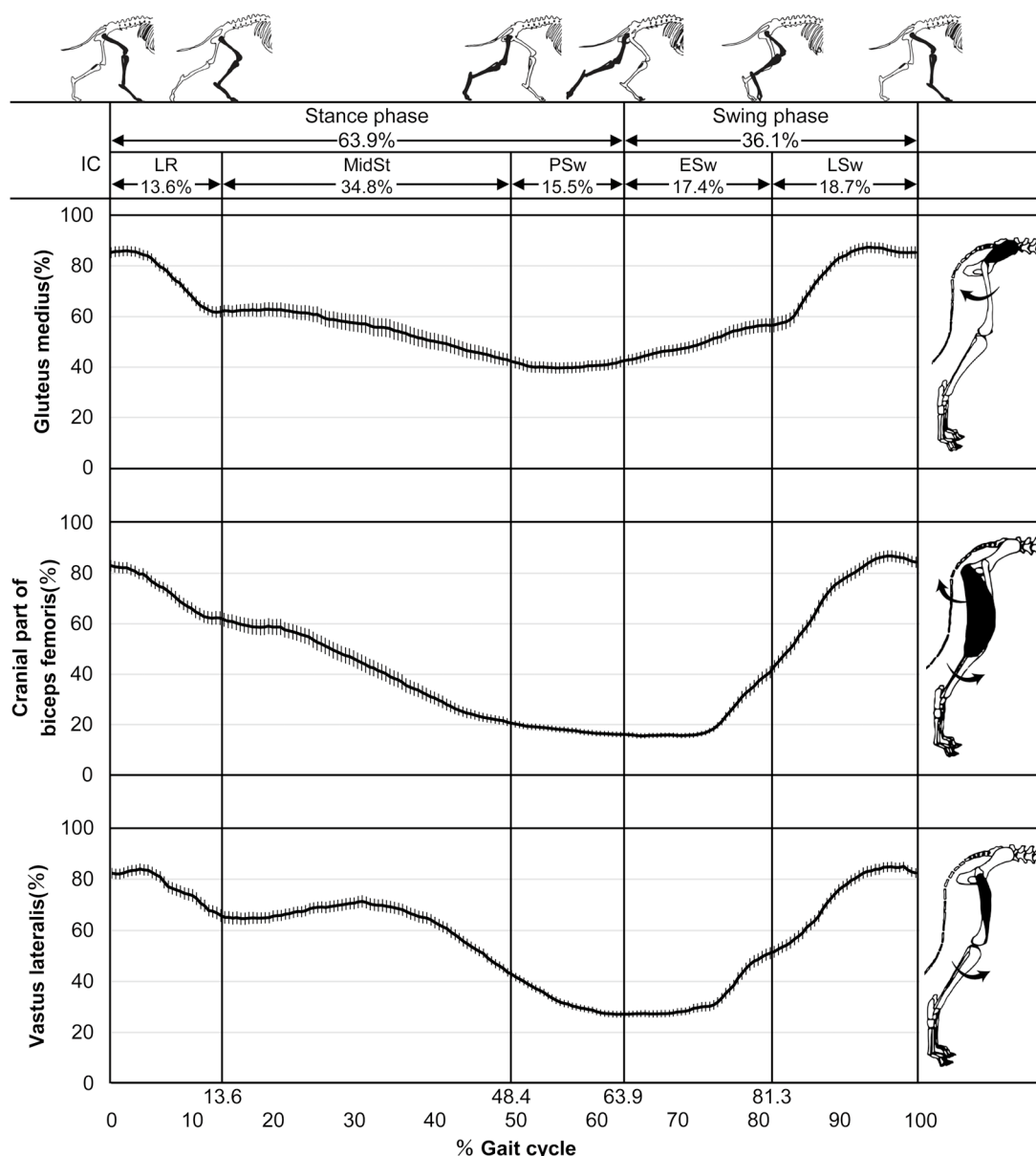
Fig. 5. Activities of the gluteus medius (GM), cranial part of the biceps femoris (CBF) and vastus lateralis (VL) muscles when walking on a treadmill at a speed of 0.7 m/sec. The plot shows the mean (solid line) ± SEM (vertical lines) of sEMG data from all dogs. The x-axis represents the gait cycle (GC) in percent (%GC). The y-axis represents the sEMG percentages of the GM muscle (upper panel), CBF muscle (middle panel) and VL muscle (lower panel), which is based on the average of the maximum activity obtained from each of 10 valid GCs. The gait phase-related changes in the muscle activities were observed in every skeletal muscle.

patients is improvement of weight-bearing and mass of anti-gravity muscles [44]. The biceps femoris muscle consists of cranial and caudal parts. It has been suggested that the cranial part functions in hip extension and stifle extension and that the caudal part functions in hip extension and stifle flexion [9, 19, 44, 50]. We chose the cranial part of the biceps femoris in the present study because we focused on the anti-gravity function, which is important in the beginning of rehabilitation. Since the studies on sEMG measurements in dogs have been limited, the validity of the muscle activities obtained in this study is considered by comparison with results of previous studies. The function of the GM muscle has been thought to be hip extension [19, 48]. Bockstahler *et al*. [6] and Breitfuss *et al*. [9] reported that sEMG of the canine GM indicated 3 peaks of activity in early stance, late stance and early swing phases. On the other hand, Schilling *et al*. [15] found that the GM had two activity peaks in the late swing phase and early stance phase using an electrode implanted in the muscle. Since an implanted electrode is surgically and directly placed on the muscle, it can provide more accurate muscle activity than sEMG electrode [20]. Our results for the GM activities were similar to the results obtained by implanted electrodes [15]. Therefore, we considered that the GM has two activity peaks during walking. The muscle function of the CBF has been suggested to be primarily hip extension and stifle extension [9, 19, 44, 48, 50]. In previous studies, it was found that the CBF muscle showed one peak activity at the transition between the swing and stance phases and that the activity

decreased until the end of the stance phase [6, 9, 15]. We obtained the same results that the CBF muscle was activated at the late swing and early stance phases (Fig. 5). The function of the VL muscle is stifle extension [19, 48]. Previous studies [6, 9, 23, 49] showed VL muscle activity started in the late half of the swing phase and lasted through most of the stride cycle. Our results for VL muscle activity are almost the same as the results of previous studies [6, 9, 23, 49].

Previous kinetic studies of canine walking have shown ground reaction forces in vertical and craniocaudal directions [8, 10, 11, 16, 41, 42]. The vertical force representing weight-bearing peaks at about 20% of the stance period and then decreases slightly. At about 80% of the stance period the vertical force reaches the second peak, and then rapid decrease is observed, resulting in a classic M-shaped waveform in the stance period [11, 16, 41]. Regarding the force in the craniocaudal direction, the cranial force shows propulsion (acceleration) and the caudal force shows braking (deceleration). The forces during 0 to 34% of the stance phase were used for braking in the caudal direction, and the forces during 34% to 100% of the stance phase were used for propulsion in the cranial direction [11]. These kinetic findings suggest maximum weight-bearing and braking are reached during LR (double hind limb support), propulsive power increases from the latter half of MidSt (single hind limb support), and those forces are significantly reduced during PSw (double hind limb support). Since the hip joint angle during LR was relatively stable, the hip extension muscles of GM and CBF are thought to play a role in the maintenance of hip joint position against the strong vertical force and deceleration forces associated with weight-bearing. Since the stifle joint showed flexion movement during LR, activities of the CBF and VL muscles are thought to play a role in the prevention of excessive stifle flexion with eccentric activity against the strong vertical force and deceleration forces of weight-bearing. Since the hip joint performs extension movements during MidSt, it is thought that the GM and CBF contributed to the propulsion of the body by extending the hip joint. Since the stifle joint during MidSt showed flexion movement, activities of the CBF and VL muscles are thought to be involved in prevention of excessive stifle flexion with eccentrical activity and in maintenance of propulsion of the body. During the swing phase, the hip flexion continued in the first half of LSw and indicated a subtle extension of the hip joint during the second half of LSw. Activities of the hip extensor muscle of GM and CBF are thought to be involved in slowing down the hip flexion speed with eccentric activity during ESw and in preparation for shock absorption of IC during LSw. Since the stifle joint during late ESw and LSw showed extension movement, activities of the CBF and VL muscles are thought to play a role in stifle extension with concentric activity and prepare the limb for stance.

There are several limitations in this study. First, the three-dimensional motion analysis system using markers attached to the skin might to contain noises of skin movement [6, 22, 47]. Fluoroscopic analysis should be performed to obtain more strict information [22, 40]. Second, sEMG is a non-invasive method of attaching electrodes on the surface of the body to reduce the stress of recording, but there is a possibility of "crosstalk" among the target muscle and other nearby muscles [6, 8, 12, 28, 43]. Third, only the function of three muscles were investigated in this study. In order to clarify the functional roles of the hind limb based on the phases of GC, only evaluation of activities of the hip and stifle extension muscles is not sufficient. In this study, the transition of the range of motion of the tarsal joint was clarified on the basis of gait phase classification, but activities of the muscles involved in the movement of the tarsal joint were not measured. In future, by investigating various muscles of the hip, stifle and tarsal joints, functional roles of the hind limb based on gait phases of the GC will be clarified.

In conclusion, we developed an original canine gait phase classification and estimated features of joint angles and functional roles of the GM and CBF and VL muscles in dogs based on this classification. Changes in muscle activities during walking suggested that the function of LR is weight-bearing stability, the function of MidSt is advancement of the body, and the function of late ESw and LSw is preparation of the limb for stance. The canine gait phase classification should be useful for interpreting the functional significance of different motions occurring at each joint. The present canine gait phase classification will be useful for determining appropriate rehabilitation and physical therapy.

POTENTIAL CONFLICTS OF INTEREST. The authors have nothing to disclose.

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